INTERNATIONAL TELECOMMUNICATION UNION

CCIR

INTERNATIONAL
RADIO CONSULTATIVE
COMMITTEE

RECOMMENDATIONS AND REPORTS OF THE CCIR, 1986

(ALSO QUESTIONS, STUDY PROGRAMMES, RESOLUTIONS, OPINIONS AND DECISIONS)

XVIth PLENARY ASSEMBLY
DUBROVNIK, 1986

VOLUME II

SPACE RESEARCH AND RADIOASTRONOMY

Geneva, 1986

CCIR

1. The International Radio Consultative Committee (CCIR) is the permanent organ of the International Telecommunication Union responsible under the International Telecommunication Convention "... to study technical and operating questions relating specifically to radiocommunications without limit of frequency range, and to issue recommendations on them..." (International Telecommunication Convention, Nairobi 1982, First Part, Chapter I, Art. 11, No. 83).

2. The objectives of the CCIR are in particular:

a) to provide the technical bases for use by administrative radio conferences and radiocommunication services for efficient utilization of the radio-frequency spectrum and the geostationary-satellite orbit, bearing in mind the needs of the various radio services;

b) to recommend performance standards for radio systems and technical arrangements which assure their effective and compatible interworking in international telecommunications;

c) to collect, exchange, analyze and disseminate technical information resulting from studies by the CCIR, and other information available, for the development, planning and operation of radio systems, including any necessary special measures required to facilitate the use of such information in developing countries.

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PLAN OF VOLUMES I TO XIV
XVITH PLENARY ASSEMBLY OF THE CCIR

(Dubrovnik, 1986)

VOLUME I	Spectrum utilization and monitoring.
VOLUME II	Space research and radioastronomy.
VOLUME III	Fixed service at frequencies below about 30 MHz.
VOLUME IV-1	Fixed-satellite service.
VOLUMES IV/IX-2	Frequency sharing and coordination between systems in the fixed-satellite service and radio-relay systems.
VOLUME V	Propagation in non-ionized media.
VOLUME VI	Propagation in ionized media.
VOLUME VII	Standard frequencies and time signals.
VOLUME VIII-1	Land mobile service. Amateur service. Amateur-satellite service.
VOLUME VIII-2	Maritime mobile service.
VOLUME VIII-3	Mobile satellite services (aeronautical, land, maritime, mobile and radiodetermination). Aeronautical mobile service.
VOLUME IX-1	Fixed service using radio-relay systems.
VOLUME X-1	Broadcasting service (sound).
VOLUMES X/XI-2	Broadcasting-satellite service (sound and television).
VOLUMES X/XI-3	Sound and television recording.
VOLUME XI-1	Broadcasting service (television).
VOLUME XII	Transmission of sound broadcasting and television signals over long distances (CMTT).
VOLUME XIII	Vocabulary (CMV).
VOLUME XIV-1	Information concerning the XVIth Plenary Assembly: Minutes of the Plenary Sessions. Administrative texts. Structure of the CCIR. Lists of CCIR texts.
VOLUME XIV-2	Alphabetical index of technical terms appearing in Volumes I to XIII.

All references within the texts to CCIR Recommendations, Reports, Resolutions, Opinions, Decisions, Questions and Study Programmes refer to the 1986 edition, unless otherwise noted; i.e., only the basic number is shown.

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DISTRIBUTION OF TEXTS OF THE XVITH PLENARY ASSEMBLY OF THE CCIR IN VOLUMES I TO XIV

Volumes I to XIV, XVIth Plenary Assembly, contain all the valid texts of the CCIR and succeed those of the XVth Plenary Assembly, Geneva, 1982.

1. Recommendations, Reports, Resolutions, Opinions, Decisions

1.1 *Numbering of these texts*

Recommendations, Reports, Resolutions and Opinions are numbered according to the system in force since the Xth Plenary Assembly.

In conformity with the decisions of the XIth Plenary Assembly, when one of these texts is modified, it retains its number to which is added a dash and a figure indicating how many revisions have been made. For example, Recommendation 253 indicates the original text is still current; Recommendation 253-1 indicates that the current text has been once modified from the original. Recommendation 253-2 indicates that there have been two successive modifications of the original text, and so on. Within the text of Recommendations, Reports, Resolutions, Opinions and Decisions, however, reference is made only to the basic number (for example Recommendation 253). Such a reference should be interpreted as a reference to the latest version of the text, unless otherwise indicated.

The tables which follow show only the original numbering of the current texts, without any indication of successive modifications that may have occurred. For further information about this numbering scheme, please refer to Volume XIV-1.

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162	III	377, 378	I	485, 486	VII
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(1) Published separately.

1.3 *Reports (cont.)*

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1.3.1 *Note concerning Reports*

The individual footnote "Adopted unanimously" has been dropped from each Report. Reports in this Volume have been adopted unanimously except in cases where reservations have been made which will appear as individual footnotes.

1.4 *Resolutions*

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20	VIII-1	64	X-1	86, 87	XIV-1
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33	XIV-1	74	VI	96	XI-1
39	XIV-1				

1.5 *Opinions*

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42	VIII-1	67-69	VI		

1.6 *Decisions*

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43	X/XI-2	60	XI-1	72	X-1 + XI-1

1.6.1 *Note concerning Decisions*

Since Decisions were adopted by Study Groups, use was made of the expression "Study Group . . . , Considering" and the expression "Unanimously decides", replaced by "Decides".

2. **Questions and Study Programmes**

2.1 *Text numbering*

2.1.1 *Questions*

Questions are numbered in a different series for each Study Group: where applicable a dash and a figure added after the number of the Question indicate successive modifications. The number of a Question is completed by an *Arabic figure indicating the relevant Study Group.* For example:

- Question 1/10 would indicate a Question of Study Group 10 with its text in the original state;
- Question 1-1/10 would indicate a Question of Study Group 10, whose text has been once modified from the original; Question 1-2/10 would be a Question of Study Group 10, whose text has had two successive modifications.

2.1.2 *Study Programmes*

Study Programmes are numbered to indicate the Question from which they are derived, if any, the number being completed by a capital letter which is used to distinguish several Study Programmes which derive from the same Question. The part of the Study Programme number which indicates the Question from which it is derived makes no mention of any possible revision of that Question, but refers to the current text of the Question as printed in this Volume. Examples:

- Study Programme 1A/10, which would indicate that the current text is the original version of the text of the first Study Programme deriving from Question 1/10;
- Study Programme 1C/10, which would indicate that the current text is the original version of the text of the third Study Programme deriving from Question 1/10;
- Study Programme 1A-1/10, would indicate that the current text has been once modified from the original, and that it is the first Study Programme of those deriving from Question 1/10.

It should be noted that a Study Programme may be adopted without it having been derived from a Question; in such a case it is simply given a sequential number analogous to those of other Study Programmes of the Study Group, except that on reference to the list of relevant Questions it will be found that no Question exists corresponding to that number.

References to Questions and Study Programmes within the text are made to the basic number as well as for other CCIR texts.

2.2 *Arrangement of Questions and Study Programmes*

The plan shown on page II indicates the Volume in which the texts of each Study Group are to be found, and so reference to this information will enable the text of any desired Question or Study Programme to be located.

VOLUME II

SPACE RESEARCH AND RADIOASTRONOMY

(Study Group 2)

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Report 721	Attenuation by hydrometeors, in particular precipitation, and other atmospheric particles	V
Report 722	Cross-polarization due to the atmosphere	V
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Report 883	Attenuation of visible and infra-red radiation	V
Report 885	Propagation data required for evaluating interference between stations in space and those on the surface of the Earth	V
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Report 1010	Propagation data for bi-directional coordination of earth stations	V
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Report 893	Solar power satellites and the ionosphere	VI
Study Programme 25E/6	Radio propagation through the solar and other extra-terrestrial ionized media	VI
Opinion 72	Time dissemination using meteorological satellites	VII
Report 1050	Technical and operational considerations for a radiodetermination satellite service in bands 9 and 10	VIII-3
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SPACE RESEARCH AND RADIOASTRONOMY

STUDY GROUP 2

Terms of reference:

To study questions relating to:

1. systems for the space research service, the Earth exploration-satellite service, including the meteorological-satellite service and their associated technologies, as well as general principles of systems for the operation of spacecraft:

2. systems for the radioastronomy service and for radar astronomy, with particular reference to associated interference problems.

1982-1986-1990 *Chairman:* F. HORNER (United Kingdom)
Vice-Chairman: H. G KIMBALL (United States of America)

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 2

1. Objectives

As services considered by the Study Group continue to develop, the Reports on their characteristics need to be up-dated, and the main changes in each section of the Report are outlined below. However, much of the revision which is being carried out is concerned with protection and frequency-sharing problems, with improvement in the clarity of presentation, and with the elimination of material which is no longer essential. The logic of the presentation continues to be to separate the various aspects of the treatment of each service into the following topics:

(a) characteristics and telecommunication requirements,

(b) preferred frequencies,

(c) protection criteria, and

(d) frequency sharing.

Topic (a) provides a general insight into the service, (b) is of special significance at conferences competent to change frequency allocations; and (c) and (d), while relevant to conferences, also provide information needed for engineering studies, especially when sharing problems arise.

As a guide to the available texts in these categories, the Tables of Annex I have been compiled. Table I identifies the relevant Reports and Recommendations in so far as it is possible at present to classify them according to the above guidelines. Complete conformity is not yet practicable because some Reports still cover several aspects of a service, and others relate to more than one service. Nevertheless the Table is useful in identifying texts of interest and in the planning of future Study Group activities. Table II is a further breakdown of the texts on frequency sharing with other services.

One important facet of the Study Group work which is not covered by the tables is that of interaction between services through spurious emissions, since this is not strictly a sharing problem. Information is presented in Section 2B, but there are also important and relevant texts relating to each of the services and contained in other sections. It is for consideration whether Reports on such problems should be presented in a more cohesive manner, depending on the degree of commonality between the problems of the different services.

The changes introduced at the XVIth Plenary Assembly will result in a substantial reduction in the size of Volume II, despite the introduction of Reports on new topics. The general lay-out follows the sequence of Table I of Annex 1. Where material has been deleted, in the interest of brevity, references have been given to earlier versions of the Reports containing more details which are still considered to be relevant.

2. Propagation data used by Study Group 2

Study Group 2 needs data on propagation through the troposphere, largely available from Reports of Study Group 5. Even if derived from other sources there should be consistency with Study Group 5 Reports unless there are good reasons for differences, provided that comparable data are contained in these Reports. Annex II outlines the Study Group 5 Reports which form the basis of the required data and indicates where such data are applied in Study Group 2 texts. A summary of this sort can be expected to lead to a better understanding of the sources of information, to clarify the relationships between the Reports of the two Study Groups, to highlight any inconsistencies, to help in up-dating Reports when necessary, and to indicate to Study Group 5 what further information is needed.

Although it is impracticable to ensure that Study Group 2 takes into account all the most recent changes in Study Group 5 data, because the output of a Study Group 5 meeting is not available if Study Group 2 meets at about the same time, a clear statement of the common ground between the two Study Groups will help to keep texts as up-to-date as possible.

Dependence of Study Group 2 texts on data from Study Group 6 is on a much smaller scale, but should be examined in future in a similar way.

3. Main changes to Volume II

3.1 *Section 2A — Research in space technology*

Much long-standing text has been deleted, as having served its purpose but some new advances have been recorded. In particular the use of lasers in the control of satellite location and attitude is discussed in additions to Report 546. Report 543 has been shortened by elimination of some technical details of a particular system. A need in future work is for Reports on antenna patterns to be reviewed and, where necessary, correlated with similar work by other Study Groups.

3.2 *Section 2B — Topics of general interest*

A subject which is becoming of considerable interest is that of spurious emissions from space stations, and this is examined under Study Programme 19-1/2 and in collaboration with Study Group 1, a new Report 980 has been prepared. A note to Study Group 1 comments on the work of that Group (see Annex III to this Introduction).

The Report on radio propagation through plasmas (Report 222) has been reduced to the essential background and conclusions, reference being made to earlier versions if detailed analysis is needed. The phenomena are taken into account in current operational techniques and it is for consideration whether Recommendation 367 still serves a purpose.

Report 679, on transmission of power from satellites, has been condensed because work on such systems is not being pursued on an important scale.

A new Report 981 on sharing is included in this general section because it concerns several of the services covered individually in later sections. It discusses the power limits which may be necessary for satellite emissions to avoid interference to radio-relay systems in shared bands near 2 GHz.

3.3 *Section 2C — Space operations*

Report 845 has been updated with a discussion of the relevant merits of providing space operation functions in mission and in space operation bands, and by improving the presentation of data on typical systems.

Minor changes to Recommendation 363 have been made.

3.4 *Section 2D — Data relay satellites*

A new Annex has been added to Report 848 to describe new systems currently at the planning stage.

Report 847 has been extended to include more material on sharing with feeder links for the broadcasting-satellite service. With reference to sharing with the radiolocation service near 14 GHz, initial calculations indicate that use of more recent propagation data would lead to amendment of the coordination distances in the Report, and this needs further examination.

Recommendation 510 on sharing between data relay satellites and other services is maintained without change, but it is noted that the Recommendation does not include guidelines for sharing with feeder links to broadcasting satellites, a topic which is discussed in Report 847.

Report 690 has been suppressed, as no longer relevant and the associated Recommendation 511 has also been suppressed.

A new Report 983 provides information on frequency sharing between data relay satellites. Another new Report 982 consists of the material formerly in Annex I to Report 692-1 of Section F. It is appropriate that this should be in the data relay section, but further work is needed to clarify the similarities and differences between the data relay requirements for space research and Earth exploration satellites.

3.5 *Section 2E – Space research*

The rationalization of texts on deep-space research was largely accomplished at the XVth Plenary Assembly and a similar exercise is being carried out for near-Earth space research. Report 548 has been separated into different topics, the new version with this number dealing only with telecommunication requirements for near-Earth missions, while new Reports 984 and 985 deal specifically with preferred frequencies and protection criteria respectively. Correspondingly, Recommendation 364 has been restricted to preferred frequencies, while a new Recommendation 609 deals with protection criteria.

In the deep-space field, Report 536 has been updated, and Report 685, on protection criteria and sharing, has been re-written to provide more information and improve clarity, with a new Annex on interference susceptibility. A new Report 986 explains the reasoning behind a new Recommendation 610 for a re-classification of deep-space distances.

Report 456 and Recommendation 513, on beacon transmitters have been modified to take account of the new and more thorough treatment of geodesy and geodynamics in Section 2F.

Report 688 has been suppressed because it relates to a sharing situation which is no longer relevant. Reports 544 and 545 have also been suppressed, with the essential elements having been included in other Reports.

Report 684 has been curtailed, with the essential features of the Annex being incorporated in other Reports.

3.6 *Section 2F – Earth exploration satellites*

An important addition to this section is a new Report 988 on geodesy and geodynamics. Techniques for studying orbits of satellites and their relationships to specific locations on the Earth's surface have many applications, but it is now considered that only those measurements of the highest accuracy currently attainable are useful in advancing our knowledge of geodesy. The new Report deals with such matters, absorbing relevant material from other Reports, but not those aspects of satellite tracking and space research (for example observations of the ionosphere) for which measurements of lower accuracy are useful. Report 535 has been revised to exclude geodesy and geodynamics applications and to update other aspects, and Report 538 has been revised to place less emphasis on precise location techniques and more on the data-collection requirement.

As mentioned under Section 2D, an Annex to Report 692, on data relay satellites has been transferred to that section.

Report 850, on sharing between passive sensors and other services has been extended following further studies of compatibility with radio-relay systems and the effects of terrain shielding.

A new Report 987 discusses potential interference to passive sensors by unwanted emissions from services in other frequency bands.

Report 395, on meteorological satellites, has been reduced in length by concentrating more on essential frequency requirements, which are common to many satellite systems, and less on the descriptions of individual satellites and on historical surveys.

3.7 *Section 2G – Radioastronomy and radar astronomy*

Reports on radioastronomy have undergone thorough revisions in recent years and have required little up-dating for the XVIth Plenary Assembly, except in one important respect. The new texts reflect both the continuing need for currently-allocated bands and increasing interest in the use of higher frequencies. The latter trend has resulted in revision of Report 852 and Recommendation 314.

Concern about potential interference from transmitters which are operating nominally in other bands has led to several new and modified texts, mainly to emphasize the special risk of interference from large numbers of geostationary satellites. Additions to Reports 224 and 697 highlight this problem, and a new Recommendation 611 has been agreed concerning such spurious emissions.

Report 853 on interference from power satellites, has been shortened to reflect the diminished interest in such systems for the time being. Some corrections have been made to data on microwave oven emissions in Report 854, and a need for further review of Table II of that Report is noted.

Report 696 is maintained without change, but is recognized as a candidate for shortening in the near future.

3.8 *Questions and Study Programmes*

Apart from editorial and other minor changes, the following proposals for modifications have been agreed.

Question 1-1/2: Study Programme 10/2 has been modified and extended to specify more completely the factors to be taken into account in studies of sharing.

Question 7-2/2: § 1.3 has been deleted together with Study Programme 7A/2 as no longer needed.

Question 10-1/2: has been modified to exclude items relating to geodesy and geodynamics (see Question 12-2/2).

Question 12-2/2: a new Study Programme 12E/2 has been added to promote studies of geodesy and geodynamics.

Question 23/2: has been deleted as its relevance to Study Group 2 was not clear and it seemed unlikely to give rise to any contributions.

4. Terminology

The Study Group discussed an input document from its representative on the CMV and approved a paper which would serve as a brief for him at the CMV Final Meeting. Comments on the main issues of interest were as follows.

The Study Group re-affirmed its desire to re-define "deep-space" with a lower distance limit of 2×10^6 km, as indicated in Report 986 and Recommendation 610. It also agreed that for the time being the term "near-Earth" will continue to be used with an upper limit approximately at the distance of the Moon. The existence of an undefined volume between "near-Earth space" and "deep space" is not considered to pose an immediate problem but needs further study.

The Study Group does not regard either the existing definition of "feeder link" or various proposed modifications (e.g. as suggested in a note from the Chairman of the CMV) as entirely satisfactory, but as it makes little use of the term, other Study Groups seemed more appropriate for discussion of any changes.

The term "spreading loss" has been used with various meanings and an effort has been made to achieve a logical and uniform definition within the Study Group. However, the term is used more widely and the views of the Study Group have been conveyed to the CMV.

Another term which is not used consistently is "global", and its use is being avoided in favour of "world-wide" when this is intended.

Previous views on a definition of "remote-sensing satellite" have been modified, as it is considered undesirable to limit its meaning to satellites with sensors which operate only at radio frequencies.

Comments on the definition of a data relay satellite have been conveyed to the CMV, but further consideration of terms of this kind is necessary before an agreed opinion can emerge.

The response to the CMV included all the significant comments which the Study Group wished to make on the request from the Chairman of the CMV regarding Recommendations 573, 662 and Report 666.

5. Preparations for radio conferences

Preparations for the Conference Preparatory Meeting (CPM) for the WARC ORB-85 and participation in both the CPM and the conference were noted. IWP 2/2 had been set up for this work, by Decision 61 of the Interim Meeting. This lapsed automatically on completion of the work.

The Study Group has given due consideration to a paper from the Director, CCIR, on inter-sessional studies for the Second Session of the WARC-ORB conference. It has been decided that no Interim Working Party on this matter should be initiated by the Study Group, at least for the present, and that the extent of participation in the proposed Joint Interim Working Party should be decided in the light of the programme and objectives of that Working Party when these are more clearly stated. In view of the fact that the WARC-ORB conference would mainly relate to other services, some concern has been expressed that undue effort on the conference agenda might detract from necessary work by the Study Group in its normal programme. It has been agreed that decisions on participation will be made by the Chairman and Vice-Chairman, taking into account the views which have been expressed.

The planned Radio Conference for the Mobile Services (Resolution 933 of the Administrative Council) has been discussed and the possibility of marginal, though perhaps important, effects on other services was noted. Particular concern has been expressed that there might be changes to use of the bands 1610-1626.5 MHz and 1646-1660 MHz which could have a serious effect on observations of the OH radical by radioastronomers in the bands 1610.6-1613.8 MHz and 1660-1670 MHz. It is considered essential that the Study Group should be fully cognizant of any proposed changes and be able to assess the technical implications for the radioastronomy service.

ANNEX I

TABLE I – *Classification of some Reports and Recommendations of Study Group 2*

Service or activity	Characteristics	Preferred frequencies	Protection criteria	Sharing and interference
Space operations	Report 845	Recommendation 363	Recommendation 363	Report 396 Report 678 Report 981
Data relay satellites	Report 848 Report 982			Recommendation 510 Report 983 Report 846 Report 847 Report 981
Near-Earth space research	Report 548 Report 456 Report 684	Recommendation 364 Recommendation 513 Report 984	Recommendation 364 Recommendation 609 Report 985	Report 687 Report 981
Deep-space reseach	Recommendation 610 Report 536 Report 986	Recommendation 576 Report 683 Report 849	Recommendation 578 Report 685	Recommendation 578
Earth exploration satellites (general)	Report 535 Report 538 Report 988	Recommendation 514 Report 692		Report 540 Report 981
Meteorological satellites	Report 395	Recommendation 362		Report 541 Report 851
Earth exploration satellites (sensors)		Recommendation 515 Recommendation 577 Report 693		Recommendation 516 Report 694 Report 850 Report 987 Report 695
Radio and radar astronomy	Report 852 Report 699 Report 226		Recommendation 314 Recommendation 479 Report 224 Report 539	Recommendation 517 Recommendation 611 Report 696 Report 697 Report 853 Report 854

TABLE II – *Study Group 2 texts on frequency sharing*

Study Group 2 service or activity	General	Fixed and mobile	Fixed satellite	Broadcasting	Broadcasting satellite (including feeder links)	Radiolocation	Aeronautical radio-navigation	Mobile satellite	Aeronautical mobile	Inter-satellite
Space operations		Report 396 Report 981	Report 396	Report 396		Report 396				
Data relay satellites		Recommendation 510 Report 847 Report 981 Report 982	Report 847 Report 982		Report 847	Report 847				
Near-Earth space research	Report 456 Report 548	Report 687 Report 984								
Deep-space research	Recommendation 578 Report 685									
Earth exploration satellites (general)		Report 540 Report 981 Report 982	Report 540 Report 982							
Meteorological satellites			Report 694 Report 850				Report 694			Report 694
Earth exploration satellites (sensors)		Report 694 Report 850	Report 694 Report 850		Report 694	Recommendation 516 Report 694 Report 695	Report 694	Report 694		Report 694
Radioastronomy		Report 696	Report 696	Report 696	Report 696	Report 696	Report 696		Report 696	Report 696

ANNEX II

STUDY GROUP 5 REPORTS USED BY STUDY GROUP 2

1. Of the many relevant Reports of Study Group 5, the following have been found the most useful in the solution of Study Group 2 problems. The versions of the Reports cited are those approved by the XVth Plenary Assembly (Geneva, 1982) but many existing references in Study Group 2 Reports are to earlier versions. The short notes indicate the topics but are not the formal Report titles.

1.1 *General information*

Report 238-4	Propagation for trans-horizon radio-relay systems
Report 563-2	Basic radiometeorological data
Report 564-2	Physical factors in tropospheric propagation
Report 569-2	Interference between stations on the Earth's surface

Note. – A corresponding Report 885 deals with interference between space and surface stations, but this has not yet been applied to Study Group 2 problems.

Report 718-1	Effects of large-scale tropospheric irregularities
Report 881 (Geneva, 1982)	Effects of small-scale tropospheric irregularities
Report 336-2	Propagation on the Moon

1.2 *Absorption*

Report 719-1	Absorption in gases
Report 721-1	Absorption by hydrometeors
Report 883	Attenuation at frequencies in the visible and infra-red ranges

1.3 *Noise emissions*

Report 720-1	Emissions from natural sources

2. Study Group 2 requirements

The Study Group needs data on the expected transmission loss on Earth-space links, on variations in this loss which affect the reliability of the links, on the natural background noise with which the signal must compete, on variations in propagation delay and on the various factors which may lead to interference between services. Most data are presented for zenithal paths and this is so in the following notes except where otherwise stated.

2.1 *Absorption*

Identical curves of absorption through the atmosphere are presented in Reports 700-1 (SETI) and 683-2 (deep space) for the frequency range 1-20 GHz, for clear weather and for rain conditions (32 mm/h). The data are said to be based on information in cited Reports of Study Group 5. For example, Study Group 5 Reports which provide data are 719-1 (clear air) and 721-1 (precipitation).

Corresponding curves for the range 10-150 GHz are given in Report 849 (deep space). In this case a rather higher rain intensity (55 mm/h) is assumed. The reference given is Report 719 for clear air. Report 456-3 mentions absorption in atmospheric gases in this frequency range, without reference to Study Group 5 Reports.

Data are also given in Report 852 (radioastronomy) for the frequency range 1-350 GHz based on new studies. They relate to a water vapour concentration of 7.5 g/m^3 at the surface. New curves for frequencies up to 1000 GHz are also presented, for both dry and humid atmospheres, but relating to high-altitude locations. This information goes beyond what is recorded in Study Group 5 Reports but several of those Reports are cited. A new Report 984 contains data on attenuation along paths of 5° and 20° elevation from 1 to 350 GHz.

Report 693-2 (Earth exploration satellites) also presents curves for 10-350 GHz, with 7.5 g/m^3 of water vapour at the surface. No reference to Study Group 5 Reports is given. An additional set of curves for 1-150 GHz shows the zenith attenuation from sites at various heights above the surface (up to 16 km) to space. Clear-air and water vapour concentration 7.5 g/m^3 at the surface are assumed. Reference is made to Report 719.

For the infra-red and visible ranges, curves are given in Fig. 1 of Report 681-2, which is reproduced from Report 883. The wavelength range is 1-20 μm (15-300 THz). The curves are for clear air and for stations at sea level and at 4 km altitude. Data are also given for transmission through a hazy atmosphere (λ = 0.4-4.0 μm).

2.2 *Sky noise*

As in the case of absorption, Reports 700-1 (SETI) and 683-2 (deep space) present identical curves of sky-noise temperature in the range 1-20 GHz, in clear weather and with 32 mm/h of rain. References are made to Reports 720 and 564.

Noise temperatures in the range 10-120 GHz are given in Report 849-1 (deep space) for a 30° angle of elevation from an earth station. Temperatures are given for clear-air conditions and for 55 mm/h of rain. Reference is made to Report 720.

A new Report 984 provides data on sky-noise temperature at 5° elevation angle and frequencies from 0.1 to 350 GHz. Rain conditions are included.

2.3 *Fading and scintillation*

Scintillation is mentioned in the two main Reports on deep space (Reports 683-2 and 849-1) but no data are presented. References are made in Report 683-2 to Reports 564, 718 and 881, but none are given in Report 849. A new Report 584 refers to Report 564-2 as a source of information on scintillation, which is said to be negligible at frequencies above 10 GHz in clear air and at angles above 10°.

2.4 *Phase delays in ranging systems*

Phase delays leading to ranging errors are mentioned in Reports 683-2 and 849-1, but only those caused by ionization along the path. An appropriate reference for delays in the troposphere is Report 564-2 (§ 9) but there is also mention in Reports 718-1 and 721-1.

2.5 *Site shielding*

In interference studies described in Report 396-5 (Annex VI) use is made of site-shielding information, attributed to Report 724, but Report 569-3 contains a fuller treatment.

2.6 *Interference and sharing studies*

In Report 696-1, Report 238-4 is used as a basis for comments on sharing with trans-horizon radio-relay systems; Report 539, on protection of radioastronomical observations on the Moon, makes reference to Report 336.

Study Group 5 has produced Report 724-1, dealing specifically with the role of propagation factors in coordination. It is not listed in § 1.1 of this Annex because, in principle the information therein stems from other Reports and, with the exception of § 2.5 above, it is not referenced in Study Group 2 Reports. However, the Study Group has an important interest in the Report, both as a user and as a contributor to its findings regarding the Study Group 2 services.

ANNEX III

NOTE TO THE CHAIRMAN OF STUDY GROUP 1
SPURIOUS EMISSION LIMITS

Study Group 2, at its 1985 Final Meeting, has taken note of the urgent need for CCIR studies of limits of spurious emissions from space stations, as prescribed in Recommendation No. 66 of the WARC-79 and amplified in CCIR Administrative Circular 252. The current relevant Study Group 2 findings are given in Reports 697, 844, 980 and 987 and Recommendation 611. Study Group 2 interference criteria are given in Recommendations 363, 364, 578, 514, 314 and 611 as well as Reports 694 and 224. Having further noted the specific proposals in Doc. 1/88(Rev.1), Study Group 2 provides the following comments with regard to the establishment of limits for spurious emissions.

1. The general emission limits proposed in Document 1/1024 are suitable, with minor modifications, for initial establishment of guidelines. It is noted that there are no Reports deriving these limits and that Report 697 indicates that they may provide insufficient protection in some cases. Modifications to the proposed limits are suggested in § 2 below. General suggestions with regard to the further development of criteria on limits are made in § 3 to 6 below.

2. The following specific comments are made with regard to the draft revision of Note 13 of Recommendation 329-4 as proposed in Document 1/1024.

2.1 The required spurious emission suppression is vaguely expressed. The specified 50 dB of harmonic suppression, relative to the power of the fundamental, should have an associated reference bandwidth. Such a reference bandwidth could be as small as 1 Hz for the protection of phase locked loop receivers or as large as 1 MHz or more for the protection of wideband video and digital receivers. The proper choice is dependent on the frequency band under consideration. As it stands, the 50 dB relative suppression might be associated with the total power of all spurious emission components or with each particular component, excluding intermodulation components. It is suggested that the initial Recommendation should specify the necessary bandwidth as the reference bandwidth for both the "fundamental" and spurious emission.

2.2 Space station thermal noise emissions in adjacent bands should be excluded from the stated 50 dB relative limit. The input S/N of a spacecraft transponder might be of the order of 20 dB to 40 dB in many cases. Consequently, where only frequency translation and retransmission are involved, the noise is re-broadcast at about the same relative in-band levels. The associated spurious emissions may be subject to intentional or inherent filtering in the transponder, but must be considered separately in much the same manner as close-in intermodulation components. It appears to be reasonable to include thermal noise under the 30 dB suppression limit for intermodulation.

2.3 The 50 dB relative suppression for all spurious emissions except intermodulation may not adequately prevent harmful interference in all cases. However, it is noted that this level of suppression has been applied for many years by at least one administration using hundreds of earth and space stations without any reports of significant interference. The attribution of interference problems to spurious emissions is exceedingly difficult for a variety of reasons, including the fact that the interference is often intermittent and of too low a level to facilitate diagnosis.

2.4 The postulated specification of 30 dB suppresion for intermodulation emissions falling outside the allocated band, with a 4 kHz reference bandwidth, is acceptable for the present time but this matter requires further study.

3. In the long term, the specification of limits for spurious emissions from space services under Note 13 of Recommendation 329-4 may be inappropriate. Many additional necessary provisions could be identified in the future work, such as those described below. A more prominent specification may be desirable, perhaps in the form of a separate Recommendation delineating the considerations that are unique to the space services.

4. The protection required by potentially-affected services in adjacent and harmonically-related bands will differ significantly. A single set of limits applying to the whole of one of the ranges, 960 MHz to 17.7 GHz, specified in Article 8 of the Radio Regulations, may be too general to protect effectively the various potential victims and, at the same time, minimize the constraints placed on the space services. Also, a limit that is practicable at one end of this broad frequency range (e.g. 960 MHz) may be unreasonable at the other end (e.g. 17.7 GHz) because of the variation in filter capabilities. Consideration should be given to the long-term establishment of limits for particular smaller frequency bands and the extension of the limits beyond 17.7 GHz.

5. The specification of separate categories of limits is appropriate for:

– intermodulation and thermal noise types of spurious emissions; and

– all other types.

From the perspective of required protection, limits of the first category are most strongly affected by adjacent band and in-band allocated services, whereas the other category is dependent upon allocated services in harmonically-related bands. From the perspective of constraints on the space services in meeting these limits, the means for conformance with each category of spurious emission limits are different (e.g., harmonic filters and bandpass filters/frequency assignment plans).

6. A single set of emission limits applying to both earth stations and space stations may not be appropriate. The sensitivities of a particular victim service to earth and space station spurious emissions are likely to differ significantly. This is primarily due to the differences in the interference paths and antenna couplings that are generally encountered with space stations and earth stations.

SECTION 2A: RESEARCH IN SPACE TECHNOLOGY

Recommendations and Reports

REPORT 672

A FORECAST OF SPACE TECHNOLOGY

(Question 15/2)

(1978)

1. Introduction

During 1975 the United States National Aeronautics and Space Administration conducted a planning study entitled "Outlook for Space". An important aspect of this study was a forecast of advances in space technology which could be expected to occur between 1980 and 2000 [NASA, 1976].

2. The forecasts

Between now and the year 2000 a great number of advances are expected to occur in technology applicable to space activities. These advances will bring about the feasibility of complex missions and systems of benefit to mankind. The more important areas where advances are expected, and should be encouraged, are listed below, and the expected advances are summarized in the remainder of this Report.

These advances will not occur spontaneously, but will be achieved by deliberate emphasis on research and development in particular areas where advances will have the greatest impact on space capabilities. Therefore, the summary in this Report covers both needs and anticipated advances.

- Instruments and sensors
- Data interpretation
- Precision navigation
- End-to-end information management
- Communication elements
- Space energy converters
- Very-long-life components and systems
- Large-scale, reliable microcomponent utilization
- Large, controllable lightweight structures
- Low-cost Earth-to-orbit transportation
- Nuclear space power and propulsion
- Advanced propulsion
- Autonomous spacecraft and vehicles
- Lunar resource recovery, processing and space manufacturing
- Planetary environmental engineering
- Closed ecological life-support systems
- Long-flight physio-psycho-socio implications

2.1 *Instruments and sensors*

The requirement for increasing the effectiveness and capacity of remote sensing systems stems both from the global nature of the measurements, and from the extraordinary difficulty of achieving some of the required measurement parameters.

Particle, optical and microwave sensing systems, both active and passive, will continue to be developed with particular emphasis on frequency selection and low-cost designs. Instrument capabilities may be greatly enhanced by technological advancement in space cryogenics, large lightweight optical systems, and large space-erectible antennae.

Lightweight optical systems, employing continuously adaptable optical surfaces formed of multiple elements, will permit extraordinary growth in the light-gathering capacity for both astronomical and remote sensing applications.

Due to increased sensor system capability, data handling needs will grow substantially. For example, by the year 2000, imaging devices on Earth application satellites will be capable of returning a thousand times more data than in 1975, that is, an increase from about 10^{10} bits/day to about 10^{13} bits/day.

2.2 *Data interpretation*

The level and sophistication of theoretical models for the design and interpretation of remote sensing techniques needs to be upgraded. As an example, the capabilities of radar and microwave radiometry to measure desired quantities are only understood with any precision in a small number of areas and, even in those, there are requirements for enhancement of modelling precision (e.g., temperature sounding).

Upgrading measurement conception, data interpretation, and modelling are necessary in order to permit quantitative interpretation of remote sensing data in terms of quantities, and phenomena of interest to the user.

2.3 *Precision navigation*

High accuracy, in-orbit, position knowledge is intrinsic to many missions. Order of magnitude improvements are required in gravity models, station location accuracies, and in atmospheric density effects, with companion efforts in multilateration techniques for Earth orbit determination.

For interplanetary navigation, very-long-baseline-interferometry techniques will be utilized with extra-galactic radio sources, eventually permitting angle measurements to spacecraft of 0.01 second of arc.

2.4 *End-to-end information management*

The steady and rapid growth in the amount of data collected in space and returned to the Earth will necessitate radical improvements in the technology for acquiring, processing and disseminating this information at low cost.

Many Earth-oriented activities, for example, those involving meteorological, agricultural, and marine observations, will require major advances in information management systems to be put into operation on a global scale. Future space information systems devoted to these applications will benefit significantly from the miniaturization of processing and storing capabilities; from more sophisticated on-board software systems; from more economical and efficient data distribution facilities; and from advanced methods for human-machine interaction.

There will be a need for very advanced, reliable, economical, and high-capacity systems capable of transferring information at gigabit/second rates, processing it as received, or as needed, preserving it in large memories in flight or Earth-based systems, or making it available to users in a form that enables them to make timely and effective use of it on a national scale.

2.5 *Communication elements*

Low-cost, large antenna apertures will be developed for use on Earth and in Earth orbit. These antenna apertures will be required for a wide spectrum of space missions, ranging from radio instrument sensing at high resolution, and spacecraft tracking throughout the solar system, to inter-stellar communication and the search for extra-terrestrial intelligent life.

In addition to employment of classical large-dish reflector antenna techniques, development of low-cost methods of arraying integrated dipole elements for achieving the required antenna aperture size will be pursued in light of continued advances in LSI technology and microprocessors. In addition to the need for large-aperture antennae, special antenna designs will be developed (in Bands 9 and 10) for radio sensing and satellite communications. These designs will emphasize special coverage patterns, side lobe control and multiple frequency and polarization operation. Lens antenna technology and small-element array technology will be used to a large degree to provide these classes of antennae.

Large scale integrated circuit technology will be exploited to develop compact, integrated communication systems composed of receiver amplifiers and transmitter power amplifier elements connected to their respective antenna dipole array elements.

Development of complex, high-data-volume, real-time digital processors is contemplated for a number of information transfer applications such as radar imaging, random access satellite communications, and detection of interstellar microwave signals in a search for extra-terrestrial intelligence (SETI). For SETI * applications, spectral resolution to 0.1 Hz is necessary to detect weak, highly monochromatic signals.

2.6 *Space energy converters*

The attractiveness of collecting solar power in space and beaming it back to Earth depends on the development of either low-cost photovoltaic solar arrays or solar energy concentrators with thermal converters deployed on extremely lightweight structures. In the case of photovoltaic arrays, the high voltages and multi-gigawatt power levels imply that the structural array must have extraordinary insulating properties. The complete structure should be adaptable to space assembly and subsequent maintenance-free operation for many years. Considerations of efficiency, radiation susceptibility, temperature, weight reduction and cost reduction; all present challenges for new technology. In the case of the concentrators with thermal converters, the problems of orientation, shape, thermal stability, and rigidity of large-scale structures are keys to the development of space energy conversion.

2.7 *Very-long life components and systems*

Many candidate objectives warrant the utilization of space techniques only if the capitalization cost of the missions or systems can be amortized over a long period of time, requiring little maintenance or resupply. For example, a solar-power station in space might achieve a competitive position with alternative stations on Earth, not only as a consequence of a reduction in the cost of the energy conversion system and the space transportation costs to orbit, but also simply through the station's operation over many maintenance-free years in space.

Systems properly designed for the environment of space often find space to be a benign environment. Thus, the unique environment of space itself offers the opportunity for space application systems to compete with Earth-based systems. Concomitantly, deep space missions, by the very nature of their long flights to their targets, demand long-life systems lasting for decades.

2.8 *Large-scale, reliable microcomponent utilization*

The miniaturization of components will continue, altering the whole architecture of space and Earth information systems leading, for example, to distributed systems with balanced use of standardized and customized processor elements, arrayed in optimum fashion for their tasks.

Ultra-high-density microelectronics for information storage is an example of a necessary prerequisite to an expanded and enhanced information management capability. Mass memory of 10^7 bits will be stored on a silicon chip less than one square cm in area; present devices can hold less than 10^4 bits/chip.

The potential use of such large quantities of active devices places extraordinary demands on designing reliable systems. These must be either component fault-free, heavily redundant, self-repairing, or a combination of all of these attributes.

2.9 *Controllable lightweight large-scale structures*

A complete new technology is required for such structures so that they can be delivered into space, unpacked, assembled, and maintained with the required precision in orientation, shape, thermal stability and rigidity. Some of these structures will have dimensions of the order of kilometres and in many cases the shapes of their surfaces will have to be controlled by servo-mechanisms to within centimetres or millimetres. Examples of such structures include very large microwave reflectors, microwave antennae, solar-energy collectors, radiators, solar sails, telescopes and enclosures for farms and habitats.

In additional to structural integrity and shape control, the dynamic interactions involved in the pointing control of such structures are unprecedented.

2.10 *Earth-to-orbit transportation-larger scale, lower cost*

Space transportation technology advancement continues as a dominant need for certain missions to make them cost-effective. The Shuttle transportation system can be expanded to full capability to give both improved flexibility and lower cost for a variety of missions envisioned for the next 10 to 15 years. For more advanced missions such as large orbital power plants, nuclear waste disposal, and assembly and processing operations in

* See Report 700.

space, and eventually bases or outposts in space, a new heavy lift vehicle can provide a factor of three or more reduction in the cost of lifting massive quantities of material to low Earth-orbit. Other options include a number of heavy lift vehicles which could prove feasible, such as a winged, single-stage-to-orbit vehicle or vertical takeoff vertical landing vehicle. These designs could potentially lower launch costs to 50 dollars per kilogram.

2.11 *Nuclear space power and propulsion*

High levels of operational power must be supplied for long durations for missions where solar energy is not available in sufficient quantities. One cost-effective solution is the employment of nuclear energy storage converted to tens of kilowatts to megawatts of electric power in space. The shielding, safety and waste disposal aspects of nuclear power in space are amenable to solution.

Radioisotopes provide a very efficient mechanism for storing energy. When used at power levels below 10 kW_e*, in conjunction with thermoelectric or thermionic conversion, radioisotopes provide electrical energy on a mass-per-unit energy basis three to four orders of magnitude more favourable than electrochemical batteries. Projected improvements in thermoelectric or thermionic converters and in isotopic fuel will significantly reduce costs from today's levels.

For higher powers, 100 kW_e to multi-megawatt, nuclear fission reactors will hold the same level of mass-per-unit energy stored and reduce energy storage costs one to two orders of magnitude below that possible with radio-isotropes. A fission nuclear power system of 100 to 500 kW_e could be developed in the last decade of the century. If nuclear propulsion is to be used for high-load transportation such as placement of solar power stations in synchronous orbit, multi-megawatt systems must be developed.

2.12 *Advanced propulsion*

Storing and use of energy for propulsive purposes is a major cost factor in missions requiring high energy provision (i.e., to the edge of the solar system and beyond, out of the ecliptic plane, to landings and returns from extra-terrestrial bodies) and missions requiring transportation of very large amounts of matter (i.e., nuclear waste disposal, solar or nuclear power stations in space and bases in orbit or on the Moon).

The high costs associated with heavy loads and long flight durations can be dramatically reduced by the use of systems which accelerate the exhaust mass to very high velocity by electric or magnetic means, and which employ energy stored in the nuclear states of matter or collected from the solar radiation in space. The development of solar and nuclear-fission electric propulsion is expected in the next 20 years.

Even more advanced propulsion concepts, which would be brought into operation after the turn of the century, offer the prospect of system mass per unit power levels two to three orders of magnitude less than solar and nuclear electric propulsion. Systems utilizing gas core nuclear fission, fusion microexplosion and metastable hydrogen rockets could provide such propulsion.

2.13 *Autonomous spacecraft and vehicles*

Already, we have seen the early steps in a technology to develop remote, adaptive human supervisory control of space machines having some degree of autonomy. The use of semi-autonomous robots will require on-board capabilities approximating those of present-day minicomputers, plus visual, manipulative and analytical instrumentation, sufficient to permit a real-time (except for propagation delay) and high-level interaction between humans and machines. These capabilities imply kHz to MHz channel rates, megabit on-board storage, microsecond operation times, and four- to ten-level hierarchical command structure. The high-density data storage and end-to-end data management technologies mentioned earlier contribute to achieving these capabilities in semi-autonomous spacecraft. To perform even the simplest tasks autonomously, machines must be given the ability to acquire data from their environment, build models of them that incorporate prior knowledge, physical laws and "common sense", and use these models for task execution and problem solving.

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* W_e refers to electrical Watt.

In deep space, on missions requiring fast reaction time, round trip propagation times make Earth-based navigation and control impractical. As such remote locations, machine autonomy is required to move safely from one location to another, determine present location, implement control sequences and provide a desired set of dynamic states independent of unexpected internal or external forces, equipment failures or other unexpected occurrences.

2.14 *Lunar resource recovery, processing and space manufacturing*

At some point in the future, it is estimated that it will become cost effective to process some minerals into products on the Moon and transport them to facilities in Earth orbit or possibly on Earth. The obtaining of such resources from space would ease the pressure on the demand for energy and minerals obtainable on the Earth.

Materials present on the Moon are: oxygen for life support and propulsion; metals (e.g., Al, Mg, Fe, Ti) for structural materials and propulsion; ceramics and glasses for construction; silicon for photovoltaic devices and thorium for nuclear breeder reactor fuels. The manufacturing and assembly of small components or modules into large structures in orbit could become a reality by using lunar materials. The special requirements of resource recovery and processing in the lunar environment need to be examined now and developed over the next one or two decades to prepare for potential opportunities near the turn of the century.

2.15 *Planetary environmental engineering*

Much of the monitoring of our environment's subtle changes is available only through space activities. Efforts to control future damage to the environment, and repair the damage already done, will be greatly enhanced by the availability of global environmental information gathered from space. This enhancement may well become crucial for the successful preservation of our environment.

Ultimately, once we have learned to preserve our own biosphere, the ability to shape nearby planet biospheres as benign environments for human beings could become a reality.

2.16 *Closed ecological life-support systems*

At a certain crew size and duration in space, the cost, mass and complexity associated with a closed life-support system become less than that of resupplying expendables from Earth. A number of attractive space objectives will ultimately reach this trade-off point and, since the development lead time is very long, it is advocated that this general technology advancement begin with the last quarter of this century.

Even though it might not be possible to guarantee long-term fully closed operation, a vigorous pursuit of this technology will permit substantial reductions in resupply.

Monitoring and control systems need to be developed for temperature, humidity and probably for CO_2, particulate and bacterial matter, and trace contaminants, even if major recycling is accomplished biologically.

2.17 *Long-flight physio-psycho-socio implications*

As human beings in greater numbers spend more time in space, the physiological implications must be understood and dealt with.

Consideration has to be given also to the appropriate forms of social order for large space ventures. Though the form that this order might take in a small and isolated community is now unknown, its components include communications, aesthetics, education, law, entertainment, work products and other such elements that are recognized as the hallmarks of successful human communities on Earth.

It will be necessary to translate our knowledge of social and political science to the space environment and to understand the special problems and opportunities provided by this environment.

3. Conclusion

The next 25 years will find mankind reaching further into space for not only purely scientific investigations, but also for Earth-oriented applications such as solar energy production, space processing and space mining.

The growth and variety of future space operations is a precursor of the diversity of the frequency-use needs of the space services.

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REPORT 546-3 *

SPACE SYSTEMS TECHNOLOGY IN THE SPACE RESEARCH SERVICE: ATTITUDE CONTROL TECHNOLOGY

(Question 15/2)

(1974–1978–1982–1986)

1. Introduction

The determination and maintenance of proper spacecraft orientation is essential to the fulfilment of nearly all space research and other missions. The accuracy and reliability of a spacecraft's attitude control system (ACS) affects many other satellite subsystems: above all, narrow beam antennas must be properly aimed in order to function effectively; solar panels will operate most efficiently when oriented normal to the sun line and sensors must be precisely pointed to fulfil their proper functions. Earth-oriented satellites, with continuous orientation of narrow beams toward specific locations on Earth require precise attitude stabilization.

This Report describes various techniques for attitude control and discusses some of the factors that affect the accuracy of control systems.

2. Background

The majority of satellites must be attitude oriented with respect to the Earth. Some experimental communication satellites make use of high-gain narrow beam antennas which must be directed toward and "locked" onto specific areas of the surface of the Earth. The Communication Technology Satellite (a joint United States and Canadian project), for example, makes use of two steerable spot-beam antennas which can, on command, be pointed independently anywhere within the field of view of the satellite. To point either of these 2.5° beams effectively, the attitude of the spacecraft must be determined and maintained to an accuracy of better than 0.1°.

Earth exploration satellites and meteorological satellites using imaging sensors must function as extremely stable platforms to prevent small satellite-motions from distorting or blurring the sensor images, while keeping the Earth-viewing side of the spacecraft pointed at the nadir. Thus, the attitude control system on an Earth-oriented spacecraft must rotate the Earth-pointing section of the spacecraft about its pitch axis (Fig. 1) precisely once each orbit and simultaneously remove the effects of any perturbing torques in pitch, roll or yaw.

Some spacecraft use the Earth as one of the principal reference bodies. The primary limitations of this type of system arise from the Earth's optically indistinct periphery which contributes to attitude-sensor error. Another effect is the Earth's oblateness or ellipticity which, if not allowed for, may induce errors in local vertical determination.

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* This Report is brought to the attention of Study Groups 4, 7, 8, 10 and 11.

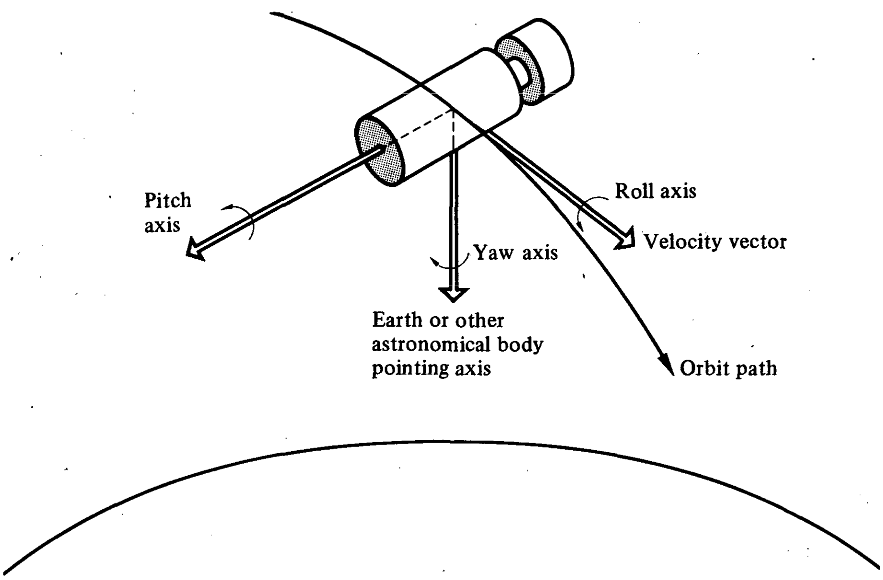

FIGURE 1 – *Attitude frame of reference*

Other space research missions require that the spacecraft attitude control reference be obtained from astronomical bodies other than the Earth. United States spacecraft, such as the Orbiting Astronomical Observatory (OAO), Orbiting Solar Observatory and the MARINER and VIKING planetary missions, use the Sun or other stars as references. Inertial reference systems such as that on the orbiting astronomical observatory, OAO-3, using gyros, four gimballed star trackers (providing data to control momentum wheels), and a fine star-sensor which operates through the experimental telescope, have reduced pointing errors with respect to the target bodies, to less than 1 arcsecond.

The intrinsic accuracy of an attitude control system is limited by the physical alignment of the sensors, the structural and thermal stability of the platforms and the resolvability of the reference point used. The haziness of the edge of the Earth and, to a lesser extent, the haziness of the apparent disc of the Sun, limits the accuracy of any attitude control system which uses either of these two bodies as a reference. The use of point sources, such as stars, for attitude reference permits more accurate attitude sensing. This is true to an even greater extent for a satellite for which the primary attitude reference system is an integral part of the experimental observation system (e.g., a star telescope).

3. Perturbing torques

The existence of perturbing torques on a spacecraft as a result of its interaction with the space environment, makes constant adjustment of the spacecraft attitude a necessity. Thus, detailed information concerning the perturbing torques is a basic prerequisite for the design of an attitude control system. The relative importance of the particular torque depends upon the configuration and orbit parameters of the specific spacecraft. The major sources of disturbance torques are the gravity gradient, the Earth's magnetic field, solar radiation pressure, aerodynamic pressure, meteoritic impacts, internal mass shifts and the flexibility of the spacecraft. Each of these is discussed briefly in the following paragraphs.

3.1 *Gravity gradient*

A body of finite size in orbit in a gravitation field will experience a gravity gradient torque. In a passive satellite this torque will cause the spacecraft to oscillate, which is usually undesirable, but through deliberate design the gravity gradient can be used to provide coarse passive attitude control.

3.2 *The Earth's magnetic field*

The torques due to the coupling of the magnetic field generated by a spacecraft, and the magnetic field due to external sources (primarily, the Earth's magnetic field) can also disturb spacecraft attitude. Proper shielding on the spacecraft can reduce these effects considerably; or, in some cases, the effect may be used as a counter-torque for the momentum wheel, or as a primary torque.

3.3 *Solar radiation pressure*

The torque caused by solar radiation and the solar ionic "wind" pressure can also perturb the spacecraft attitude. The magnitude of this torque, which is cyclic if the spacecraft is Earth oriented, will be a maximum for complete reflective surfaces and smaller in the case of an absorbent body.

In the case of a geostationary satellite, the solar radiation torque is dominant. Its magnitude depends on the shape and the surface material of the satellite and has seasonal variation due to the variations of Sun angle and the received solar radiation intensity.

By using measured solar radiation torque data, attitude prediction and correction planning of a spin-stabilized satellite are possible by calculation based on a simple model of the satellite attitude dynamics as shown in Annex II. Other perturbing torques of this nature also exist, for example, torques caused by cosmic rays, but the magnitude is usually small compared with that due to the Sun.

3.4 *Aerodynamic pressure*

Aerodynamic forces become significant or dominant for spacecraft in low-altitude circular orbits or in eccentric orbits with low perigees. The effect of aerodynamic pressure can usually be minimized through careful design of the configuration and shape of the spacecraft to minimize and equalize drag; and by the use of a higher nominal spacecraft orbital altitude.

3.5 *Impact by meteorites*

The angular momentum imparted by the impact of meteorites upon the spacecraft can usually be estimated statistically, that is to say, by determining the probability of meteorites of various masses striking a given satellite and the resulting magnitude of momentum transfer.

3.6 *Internal mass shift and structural flexibility*

The relative movement of antennas, cameras, solar panels, live occupants and fuel will result in torques on the main body of the spacecraft, and these torques are difficult to analyse. Because these moving parts must first be accelerated and then decelerated to obtain a new position, some of these torques are cyclic in nature. Structural flexibility may cause false attitude error signals and could resonate at the frequency of the attitude control system (ACS). Such problems are becoming more common with large solar array configurations. Outgassing and gas leaks can also cause disturbance torques.

4. Attitude sensing

The principles and devices which can be used to establish attitude reference systems (to sense the attitude or angular velocity of a vehicle) are of prime importance in today's high accuracy control systems. Since the accuracies of attitude control systems are bounded by the ability to sense attitude errors, much effort has been directed toward attitude sensing instrumentation. The following sections briefly describe some of the techniques which are employed in this fundamental and essential aspect of satellite attitude control.

4.1 *Sensing with reference to the Earth or the Sun*

It is a natural advantage to use as a reference target the celestial body of experimental interest. This is the case with most near-Earth satellites which use the Earth's line of maximum atmospheric gradient (tropopause) as a means of locating the centre of the Earth. The sensors may operate in response to the Earth's far infra-red radiation (> 8 µm) with such devices as thermistor bolometers, pyroelectric detectors, or thermopiles or the sensors may use the scattering of reflected sunlight (Earth's albedo) as an indicator (e.g. by means of silicon photocells, or photo transistors). The most widely used spectral band for defining the Earth's disc has been the 14.0 to 16.3 µm band which is associated with CO_2 absorption.

Basically, these sensor systems either bisect the angle between the opposite horizons or detect the instrument off-axis angle to the horizon, to sense local vertical error. Horizon sensors may be used in wide-angle systems which produce a conical scan of the reference body, in edge tracking systems which lock onto the maximum gradient line of the body, or in radiometric balance systems which compare the radiation received from opposite horizons of the reference body.

The factors which contribute the largest error in this determination of the local vertical with earth sensors are the resolution limit at the tropopause and the constantly changing oblateness effects of the Earth.

Infrared sensors detect the "centre" of the Earth's infrared image; this "centre" is virtually the same as the sub-satellite point, so that these sensors give no information on satellite movements around the yaw axis.

In the case of present satellites in the geostationary-satellite orbit which have sufficient kinetic moment, yaw is detected indirectly every six hours by the exchanges between the roll and yaw axis.

The irreducible bias introduced by the infrared sensors is 0.02°: this is the minimum intrinsic contribution of the infrared sensor to the total pointing error balance, which might be achieved in the 1980's. At present, the intrinsic infrared sensor error has a random component of between 0.01° and 0.05° at 3σ.

Solar reference sensing is conceptually similar to earth sensing with reference to the Earth. Although higher pointing accuracies with respect to the Sun may be achieved (a few seconds of arc); due to the Sun's more readily defined apparent disk, additional errors are introduced in co-ordinate transformation of this data to an Earth-pointing mode.

4.2 *Sensing with respect to celestial bodies*

The use of point sightings on distant stars such as Canopus or Polaris has indicated that stellar reference systems can offer more accurate attitude determination capabilities than earth sensors because of a star's low and predictable relative motion over long periods of time and its high angular resolvability.

If star sightings are used to establish an earth-centred local vertical, the computation of the reference system co-ordinate transformation involves knowledge of the "true" geographical location of the spacecraft which may be obtained only within the limits of present-day abilities in orbit determination.

Star sensors may operate on a tracking or mapping principle. Star trackers usually sense in two axes to enable versatile pointing. Either mechanical gimbals or electronic offset may be used. Servo-mechanisms mounted on each axis drive the trackers to acquisition, and the offset angles provide measurement data in a code suitable for use in the computer.

Sensors which operate on a star mapping principle have received attention recently because of their mechanical simplicity. They do not involve servo loops, encoders, or a gimbal axis. A computerized star catalogue and pattern recognition system identifies star fields and determines the relative position.

Considering the accuracies usually obtained with star mapping sensors, launch and orbit thermal stresses are a major design consideration and necessitate periodic tracker misalignment corrections. For example, the OAO-2A star tracker misalignment errors with respect to the spacecraft, were from two to five times larger than the desired pointing accuracy and were the results of both thermal distortions and misalignments arising from vibration during the powered phase of the launching. This necessitated calibration and compensation of the sensors after launching, to achieve the desired pointing accuracy.

OAO-3 uses gimballed star trackers to adjust momentum wheels for coarse stellar reference, to bring the star telescope into its field-of-view of four minutes of arc, and also uses a body-fixed star sensing system which operates through the experiment telescope. Since the sensor optical axis is that of the experiment, and is body-fixed, the system has enabled the OAO-3 spacecraft to point to its experimental target to within about 0.01 arc seconds of jitter. The variations in pointing error are primarily due to thermal stresses (day-night operation) and to orbital position.

4.3 *Inertial sensors*

Inertial systems use the gyroscope as the prime sensing device. The simplest, a set of three orthogonal body-mounted rate integrating gyros, is capable of high accuracy error sensing. Another application of the gyroscope is as a gyrocompass for the detection of yaw deviation out of the orbit plane, assuming that the direction of the local vertical has been independently established. Inertial sensing may also take on the form of a rate gyroscope which measures the velocity of the body and resolves it into body-fixed co-ordinates, and thus acts as an indicator of the damping required. The main drawback with body-mounted rate-integrating gyro sensors is that the motion of the reference frame, which is not a measure of attitude, must be taken into account. Gyro drift must be continually accounted for.

4.4 *Radio-frequency sensing*

An alternative to earth sensing is provided by radio-frequency (RF) sensing, where antennas and circuitry aboard a satellite determine the orientation of an RF signal arriving from a ground based beacon. This class of sensor seems a natural one for communications satellites since communications equipment will already be on board and many perturbations affecting the attitude signal will also modify the communications transmission in a like manner.

RF sensors include monopulse and interferometer types, both of which operate on the general principles of monopulse radar tracking systems, processing phase or amplitude information from either single or multiple antennas [Skolnik, 1970].

With RF sensors it is easier to determine the off-boresight angle of the signal, (i.e. azimuth and elevation, or in spacecraft co-ordinates, roll and pitch) while rotation about the boresight (the yaw angle) is more difficult to measure accurately. Yaw may be calculated by measuring rotation of a polarized signal from a single beacon, by processing roll and pitch from each of two beacons separated by the maximum baseline possible, or by processing additional information from Earth, Sun or star sensors. There are drawbacks to each of these yaw measuring options. The polarization orientation is affected by Faraday rotation and orbital parameters, as well as by differential rotation and phase shift caused by weather conditions. Yaw calculation from two earth stations suffers from the relatively narrow angle subtended at the spacecraft by the Earth, while yaw estimation from Earth, Sun or star sensor information entails the inclusion of an additional sensor aboard the spacecraft.

Despite these undesirable effects on yaw computation, RF attitude sensing is still a viable and promising approach, especially since for synchronous communications satellites, the yaw angle error affects beam pointing less than either roll or pitch errors. Indeed, RF attitude sensors have been flown and more are being selected for projected missions, having accuracies of the order of $\pm$ 0.05° for roll and pitch, and about $\pm$ 0.5° for yaw. The basic sensor is capable of considerably greater accuracy, but a disproportionate degree of compensation for the various perturbations becomes necessary. [Mamen, 1973; CCIR, 1974-78.]

4.5 *Attitude determination using a laser*

Some new methods using lasers are available for the orientation of antennas or detectors on spacecraft toward specific locations on the Earth. An Earth laser beacon sensor for Earth-oriented geosynchronous satellites has been proposed [Sepp, 1975], and in [Aruga and Igarashi, 1977] a new attitude-determination method has been proposed. The latter system consists of a transmitter of a linearly-polarized laser beam on the Earth, and receiving equipment on a satellite. The distinctive feature of this method is its complete attitude determination (the three elementary angles can be determined) using the laser and its polarization. The accuracies of determination are estimated to be 10^{-4} radian (0.006°) or better for the angles corresponding to roll and pitch, and about 10^{-2} radian (0.6°) for the angle corresponding to yaw. The ground-based laser beacon technique is applicable to absolute location calibration in earth observations from space as well as to spacecraft attitude determination and antenna orientation. This technique is especially useful for geostationary satellites since the ground laser station observed from the geostationary spacecraft stays fixed in the geocentric coordinates. The accuracy limitation of the earth laser beacon as a reference point is finally decided by the effect of the terrestrial atmosphere. A recent experiment [Aruga *et al.*, 1985] shows that the limitation is smaller than 30 µrad ($\approx$0.002°) for geostationary satellites.

4.6 *Other considerations (geostationary-satellite orbit)*

In normal mode, the kinetic moment of the satellite is high enough to maintain a quasi-inertial pitch axis and to provide adequate satellite rigidity in its movements around the yaw axis.

In positional corrections on orbit, torque effects are applied by the working jets. Since the pitch axis can no longer be considered as quasi-inertial, its movement has to be detected during these operations by measuring the yaw angle.

Several types of sensor are used for this purpose: solar sensors, integrating gyrometers or possibly, stellar sensors.

5. Attitude control elements

The achievement of the desired satellite attitude may be accomplished by the use of active or passive devices. The following two sections briefly describe these two categories of attitude control elements.

5.1 *Passive devices*

Of the perturbing torques described in § 3, the gravity gradient, magnetic field and solar pressure may be used constructively as primary or secondary attitude control elements. Although these may provide only coarse attitude control and are useful only at altitudes where their effects are large compared to other orbital perturbations, passive devices have the obvious advantage that they do not consume spacecraft resources.

5.2 *Active devices*

Active control devices, unlike passive devices, use spacecraft power for attitude control. The most common types are angular momentum-exchange devices (flywheels, control moment gyros) and momentum-elimination devices (reaction jets, magnetic coils).

Techniques which use fixed-axis variable-speed flywheels have long been considered more desirable than passive devices because of the higher degree of pointing accuracy attainable with their use. Their operation is based on the principle that an external torque applied to a spacecraft may be countered by an appropriate change in the rate of angular momentum of the vehicle (torque being the first derivative, with respect to time, of angular momentum). Essentially, perturbing torques on a spacecraft may be countered by varying the angular speed of the flywheel about its axis or through gyroscopic precession.

Control moment gyros (CMG's) operate on the same momentum exchange principle as the variable-speed flywheel. A CMG is a constant-speed flywheel which is gimballed about one or two axes in such a way as to allow the angular momentum axis to be skewed through an angle which may attain, theoretically, 90°.

In considering perturbation torques which are cyclic, for example, the oblateness effect of the Earth, or the gravitational cycle of the Sun, flywheels and CMG's may, in some cases, be designed to "absorb", (for example by limited control of their speed and/or orientation), these cyclic perturbations, the cumulative effects of which are essentially zero over one complete cycle. Otherwise, for the case of secular torque, such as solar pressure, these devices must be desaturated periodically so that wheel speed or gimbal angle limits are not exceeded. For this reason, flywheels and CMG's are usually best suited to inertially oriented payloads, rather than earth pointing satellites.

Mass expulsion control systems (reaction jets) differ from flywheel and CMG control in that momentum is disposed of rather than stored. Of the various techniques of mass expulsion the most common are cold gas systems, which employ the escaping stored gas to produce the restoring force, and monopropellant and hypergolic systems, in which momentum is produced by chemical reaction. Since reaction jet systems use expendable propellants, the momentum required to perform the various mission functions must be determined and provided for beforehand. This contrasts with on-board closed-loop null-seeking systems, such as momentum wheels and CMG's. This is an obvious disadvantage of the use of reaction jets as the primary attitude control subsystem. Another point of consideration is that regardless of the smallness of the impulse required to re-orient the spacecraft, a precisely equal and opposite impulse needs be provided to arrest the resultant angular motion of the spacecraft at the appropriate point.

6. Attitude control systems

6.1 *Passive systems*

When pointing accuracies are not stringent and when long satellite lifetimes are desired, passive attitude control systems may be employed. Some of the perturbation torques can be used for satellite attitude control, for example, gravity gradient, the Earth's magnetic field or the solar radiation pressure. A typical method of passive attitude control is the gravity gradient method. The Dodge satellite, for example, made use of a gravity-gradient effect by means of extendable booms.

The basic principle of attitude control by gravity gradient is that a satellite in a gravitational field, having a moment of inertia about one axis which is less than those about the other two axes, will experience a torque which will tend to align the axis of least inertia with the local gravity gradient vector. In this system, an undamped oscillation about the control axis would result from the action of external torque disturbances. A passive device is usually used to damp out these oscillations. The pointing accuracies which can be achieved by this means are generally no better than a few degrees.

6.2 *Spin stabilization*

Spin stabilization is an accepted means of maintaining spacecraft attitude because a spinning body has an inherent resistance to torques tending to disturb the spin axis. As a result of internal and external disturbances, the spin stabilized satellite will generally exhibit wobble or coning of its spin axis. A damper performs the function of dissipating the energy associated with this motion, eventually causing the spin axis to align itself in the desired attitude within preset limits. Generally, the spin axis is the axis of greatest moment of inertia (nutationally stable axis) and will become perpendicular to the orbit plane, because of the gravity gradient torques, which precesses the momentum vector to the normal.

6.3 *Dual-spin stabilization*

Dual-spin stabilization uses the same basic principle to achieve attitude control system; a part of the satellite rotates about its spin axis at a predetermined rate. The momentum caused by the spinning portion of the spacecraft tends to lend gyroscopic stability to the attitude of the vehicle. The remainder of the spacecraft is freely mounted about a shaft passing through the spin-axis of the spacecraft, and is rotated with a very low angular velocity, in the opposite direction to the spinning body. The velocity, typically one revolution per spacecraft orbit, is maintained by active control loops so that the de-spun platform points to the Earth or other reference within the limits of preset errors.

The alignment of the de-spun platform shaft and the main spin axis is critical to the performance of the dual-spin system. Any misalignment will tend to make the de-spun platform unstable and thus degrade the accuracy of the system. The coning motion caused by the misalignment is termed "wobble". Wobble can be eliminated by adjusting the position of two or three masses on a satellite spinning body [Nakatani and Izumisawa, 1977; Wright, 1974]. Also, as in passive-spin stabilization, damping of spacecraft nutation is necessary, especially if the spin axis is the axis of minimum moment of inertia.

An example of advances in the development of dual-spin technology is demonstrated by Intelsat-IV. Developments in bearing and power transfer assemblies, which form an interface between the spun and de-spun platforms, allow the realization of the advantages of mechanically de-spun antennas; as compared with electronically de-spun antennas having an equivalent number of elements and in which the ferrite phasing networks incur an insertion loss of 2 dB or more. The bearing and power transfer assembly incorporates a motor with permanent magnet armature and a field coil to produce the torque to counterbalance friction effects on the bearings and slip rings. A labyrinth seal, a polymer elastic reservoir, and an impregnated bearing retainer ensure a lubricant lifetime of an order of magnitude greater than anticipated mission life of seven years.

An important feature of Intelsat-IV's stabilization is the fact that rather than being spun about its axis of greatest moment of inertia, in which case energy dissipation within the rotor would not tend to destabilize the satellite, it was arranged to take as the spin axis, the axis about which the moment of inertia was the least (this depending on spacecraft volume and mass distribution design considerations). To counteract the destabilizing force associated with the choice of spin axis, an active nutation damper system was required on the non-spinning platform for dissipation of the energy.

6.4 *Three-axis stabilization*

Generally, three-axis orientation for an earth orbit is such that the spacecraft pitch axis is parallel to the normal to the orbit, the roll axis is parallel to the local horizontal, and the yaw axis is maintained parallel to the local vertical. This set of orthogonal co-ordinates makes one revolution about the pitch axis in one orbit period thus maintaining an Earth-pointing yaw axis. Three-axis stabilization may be desirable to point an experiment, or may be necessary when spacecraft power considerations necessitate a constant, or nearly constant, orientation of the solar panel to the Earth-Sun line; this cannot be achieved in a spin stabilized vehicle where effective solar array area is limited to the geometrical projection of the spacecraft surface area.

Three-axis stabilization may be achieved by mass expulsion techniques or, in appropriate instances, by passive environmental effects employed solely as the momentum-correction devices. Typically, however, these techniques are used in conjunction with reaction or momentum wheels which provide primary control in attitude. An external torque applied to the spacecraft may be countered by means of control loops which feed attitude-error signals from sensors to the momentum wheels to produce a time rate of change in the wheel momentum. Since momentum devices have limited momentum storage, this type of attitude control system must be augmented with reaction jets or with a magnetic torquing system so that the increasing wheel momentum may be reduced periodically.

Techniques of using flywheels and CMG's in conjunction with reaction jets or some passive means of reducing wheel momentum vary widely and their design depends primarily on mission requirements.

The medium-scale broadcasting satellite for experimental purposes (BSE) of Japan uses the zero-momentum three-axis method of stabilization as the attitude control system. The attitude errors are fed from the three types of sensors: the Earth sensor, the radio-frequency sensor (both fixed to the body) and the Sun sensor on the solar paddles. This system realized dynamic errors of the attitude control within ± 0.03° for pitch and roll by the use of an Earth sensor, and generally within ± 0.3° for yaw by the use of a combination of a radio-frequency sensor and an Earth sensor. It was noted that for short duration periods the errors exceeded these values due to the zero-crossing of angular velocity of the wheel and the interference of the Sun to the Earth sensor [Shimizu, 1980].

Through the multipurpose use of a single, speed-modulated, double-gimballed, control-moment gyroscope, the Molnya-I communication satellite, has achieved three-axis stabilization which alternates between solar orientation for solar panel efficiency and Earth orientation for communications. Speed modulation is needed to counter the effects of the satellite's highly eccentric orbit.

A dual-spin technique, known as "Stabilité", employs a single reaction wheel as the only moving part of the attitude control system to maintain pitch axis orientation. Roll and yaw control in this system is maintained by the stored momentum and precessed by torque produced by the Earth's magnetic field. If magnetic torque is not applicable because the altitude is high and therefore the magnetic field is weak (and variable), reaction jets may be necessary to supply roll and yaw control. Pointing accuracies of ± 0.1° may be attained about all three axes, and with more advanced attitude sensing instrumentation this accuracy may be improved.

The Communication Technology Satellite (also known as Hermes) used a system with a momentum wheel and offset thrusters for three-axis stabilization of a geostationary satellite. The primary components of the system were an Earth sensor, a momentum wheel with axis parallel to the pitch axis, offset thrusters having a torque vector in the roll-yaw plane and control electronics. The Earth sensor provided pitch and roll error signals to the control electronics. The gyroscopic properties of the wheel coupled the roll and yaw dynamics and eliminated the need to sense yaw error directly. Pitch control was obtained by accelerating or decelerating the wheel about its nominal speed in response to a control signal derived from the pitch error. Roll and yaw were stabilized by the gyroscopic stiffness of the momentum wheel. Small roll and yaw errors were corrected by automatic firing of the offset thrusters in response to a control signal derived from the roll errors. The performance and flight operations experience are outlined in [Vigneron and Millar, 1978]. The system successfully stabilized Hermes for the four-year duration of the mission. It performed as designed, except for occasional minor temporary malfunctions of an Earth sensor, and a minor occasional transient associated with the bearings of the momentum wheel. The pointing error of the communications antenna was deduced from flight measurements to be ± 0.09° in pitch, ± 0.1° in roll, and ± 0.5° in yaw during the normal operating mode. In the mode during which desaturation of the momentum wheel was occurring the pointing errors were within ± 0.6°, ± 0.11°, and ± 0.5° in pitch, roll and yaw respectively.

Skylab had primary (solar and Earth), as well as secondary, (celestial) space targets necessitating the use of three-axis stabilization provided by sensing rate gyroscopes, a Sun seeker, a star seeker and a control moment gyro-system which consisted of three mutually perpendicular CMG's for primary attitude control. Desaturation of the control moment gyroscopes was provided by reaction thrusters.

Spacecraft designed to view celestial objects will in general require three-axis stabilization for multi-target viewing. For example, the inertially-referenced OAO-3 is equipped with gimballed star-trackers for coarse attitude sensing and a fine error sensor operating integrally with the astronomical telescope. Error signals derived from equal outputs of the starlight passing through a diffraction slit are processed to drive fine adjustment inertia wheels on the appropriate axes. Continuous wheel desaturation is provided by magnetic torquing. This system has provided stellar pointing to the order of milliseconds of arc.

6.5 *Orbit position corrections*

In addition to the sensing of and reduction or elimination of attitude errors, it is necessary from time to time to correct the orbital position of a geostationary satellite. During these position corrections, the attitude stability of the satellite may be temporarily degraded.

In the case of a spin-stabilized satellite, pointing accuracy may be temporarily degraded due to the spin axis nutation which is induced when an axial thruster is fired for the purpose of corrections of the attitude or the orbital inclination.

In the case of a three-axis stabilized satellite, attitude control systems use servo devices with an error detector in normal mode in the form of either an infrared sensor or an RF sensor. During orbital position corrections, these sensors are backed up by a yaw sensor.

The actual orbital correction phase may last less than an hour with conventional high-thrust propellants (hydrazine) or several hours with very low-thrust propellants (ionic drive). It is followed by a residual oscillation phase, particularly on direct TV broadcasting satellites using large solar generators, which always have a degree of mechanical flexibility.

With the conventional hydrazine systems in current use (high-thrust), corrections have to be made at intervals of about two months; with low-thrust ionic propulsion, corrections will be carried out almost daily.

The time of day, or night, exactly twelve hours later, at which these manoeuvres have to be performed, varies throughout the year, since it is linked to the orbital precession, so that the inclination may be corrected either on the ascending or the descending node.

With regard to pointing accuracy during orbital corrections, Table I sums up the main factors involved for telecommunication satellites (solar generator power of less than 2.5 kW, satellite weight 700 kg).

7. Prospects and limitations

The importance of precise attitude control increases as the beamwidth of a satellite antenna decreases, with a corresponding decrease in the service area of the satellite on the Earth. The relationship between attitude control perturbations and displacement of the aiming point of a geostationary satellite antenna are discussed in Annex I, for the attitude frame of reference given in Fig. 1.

TABLE I – *Effect of thrust level on accuracy of attitude control loops during orbital position correction*

		Current systems (hydrazine)		Future systems (ionic propulsion) AOCS one degree of freedom
		AOCS without degree of freedom (1)	AOCS one degree of freedom (2)	
Correction time (hours)		0.45	0.45	2
Thrust (mN)		1500	1500	20
Control accuracy	Roll and pitch	0.08°	0.06°	0.05°
	Yaw	0.35°	0.25°	0.12°
Correction time margin (3)		minimum 30 minutes	minimum 30 minutes	

AOCS: Attitude and Orbital Control System.

(1) The direction of the kinetic moment is fixed in a trihedral system tied to the spacecraft.

(2) The direction of the kinetic moment is variable in a plane containing the pitch axis of the spacecraft.

(3) The normal correction time varies with time. A time of day or night may be selected depending on whether correction is made on the ascending or descending node of the orbit.

Since the ultimate accuracy of any attitude control system is a function of attitude-error determination, both the sensors and the sensed targets chosen as references are important. Systems design must be based upon basic mission requirements, weight, cost and reliability.

Earth-oriented systems employing the Earth as the prime attitude reference body are orientation-limited to about 0.1°. Removal of atmospheric and oblateness effects by the use of an on-board computer will allow the pointing accuracy to be improved to about 0.05° in the near future.

The likelihood of improving low Earth-oriented, Earth-sensing systems to better than 0.05° is small. If higher Earth-pointing accuracies are required, the use of Sun or star sensors is indicated. In Earth-oriented stellar tracking systems, transformation of stellar-reference co-ordinates is limited by the present-day abilities of orbit determination with respect to the Earth. The first National Aeronautics and Space Administration attitude control system of this type will be used on the Earth Observation Satellite (EOS). The EOS is expected to be capable of providing a 0.001° pointing accuracy with respect to the Earth, by means of both a gimballed star-tracking system and an on-board computer system, which will provide orbit determination errors of less than about five metres.

Inertially referenced spacecraft such as OAO have shown that extremely accurate pointing with respect to astronomical bodies may be achieved (within milliseconds of arc). Such accuracies are possible through the use of experiment sensors and attitude sensors operating in co-ordination.

With angular pointing requirements of a few seconds of arc, design control of structural and thermal deformation of the spacecraft is extremely important. Very slight deformation in the spacecraft, especially if in the neighbourhood of an attitude sensor, may result in relatively large errors in the spacecraft's attitude-keeping capability. Also, when considering attitude control errors of the order of 0.001°, the overall ability of a satellite to point to a particular location on the surface of the Earth is no longer primarily a function of the attitude control system. Rather, an equivalent contribution of pointing error can be caused by uncertainties in ephemeris data. For example, a pointing uncertainty of 0.001° will produce a pointing error of about ± 9 m from a 500 km orbit. This is of the same magnitude as the orbit determination accuracy expected in the near future.

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ANNEX I

IMPACT OF ATTITUDE CONTROL ERROR ON THE COVERAGE AREA OF A GEOSTATIONARY SATELLITE

1. Introduction

The purpose of this Annex is to describe the impact of errors in a geostationary-satellite attitude control system on the service area of the satellite. Although the importance of this effect is highly mission dependent, this Annex presents a simplified description of the impact of rotational errors in geostationary-satellite pitch, roll and yaw axes.

2. Attitude frame of reference

Figure 2 presents the orientation of the pitch, roll and yaw axes, described in Cartesian co-ordinates, of a typical geostationary-satellite. The figure also shows the desired boresight of the satellite antenna (point P) and the sub-satellite point S. The displacement of point P for small rotational errors about each of the three orthogonal spacecraft axes are described in the following sections.

2.1 *Pitch axis*

Figure 3 presents the effect of rotation about the satellite pitch or Y axis. Such a rotation would cause the satellite Z axis to be displaced east or west on the equator.

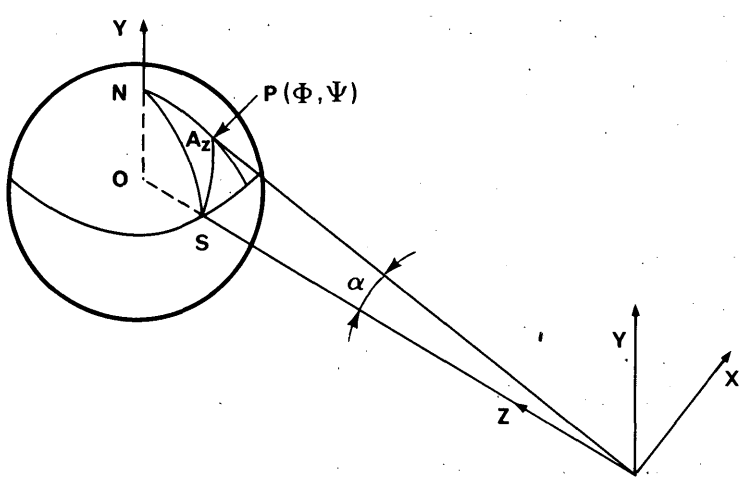

FIGURE 2 – *Satellite coordinate system*

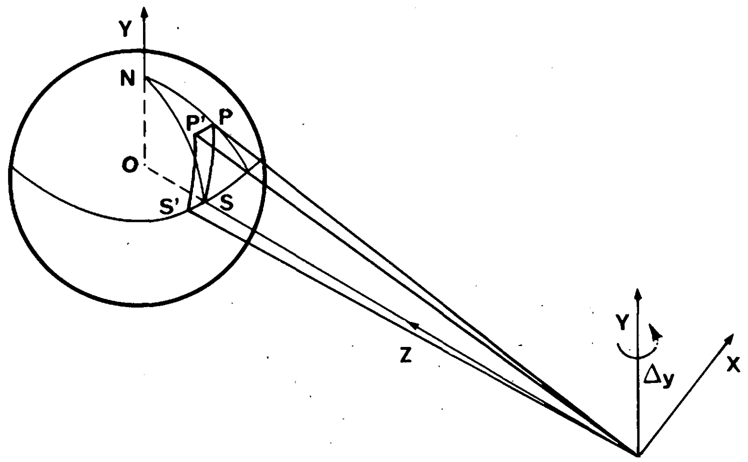

FIGURE 3 – *Pointing error due to pitch axis error*

The displacement of point P in km is a function of the pointing angles measured at the spacecraft. For pointing locations near the equator (or satellite pointing azimuth of 90° measured from North) the boresight displacement is approximately:

$$d_y = R_e [\sin^{-1} \{k \sin (\alpha + \Delta y)\} - \Delta y - \sin^{-1} (k \sin \alpha)] \frac{\pi}{180} \qquad \text{km} \qquad (1)$$

where:

R_e : equatorial radius of Earth (km)

$k = (R_e + h)/R_e$

h : geostationary altitude (km)

α : elevation angle from satellite to point P (measured from nadir in degrees), and

Δy: rotational error about pitch or Y axis in degrees.

Figure 4 presents the sensitivity of antenna boresight point displacement as a function of pitch error (Δy) and elevation angle (α) for pointing locations on or near the equator.

For Earth pointing locations on or near the satellite meridian (satellite pointing azimuth of 0° measured from North), the elevation angle α does not significantly impact the displacement error, and the boresight displacement is given by:

$$d_y \approx h \cdot \Delta y \cdot \frac{\pi}{180} \qquad \text{km} \qquad (2)$$

Figure 5 presents the sensitivity of antenna boresight displacement error to pitch errors for Earth pointing locations on or near the satellite meridian.

Figure 6 is presented as an example of the sensitivity of boresight displacement error to pitch or roll errors at 45° pointing azimuth (in any quadrant).

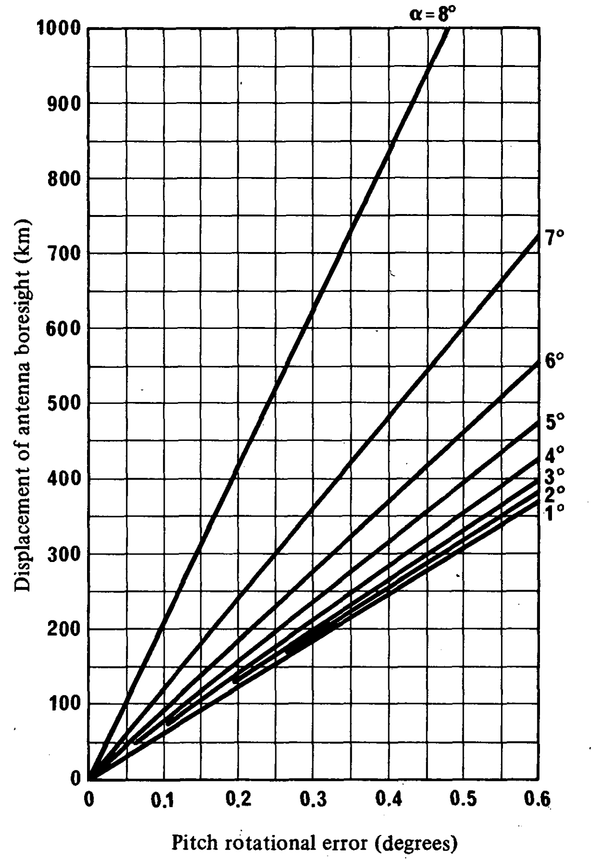

FIGURE 4 – *Pointing error as a function of pitch rotational error; azimuth = 90°*

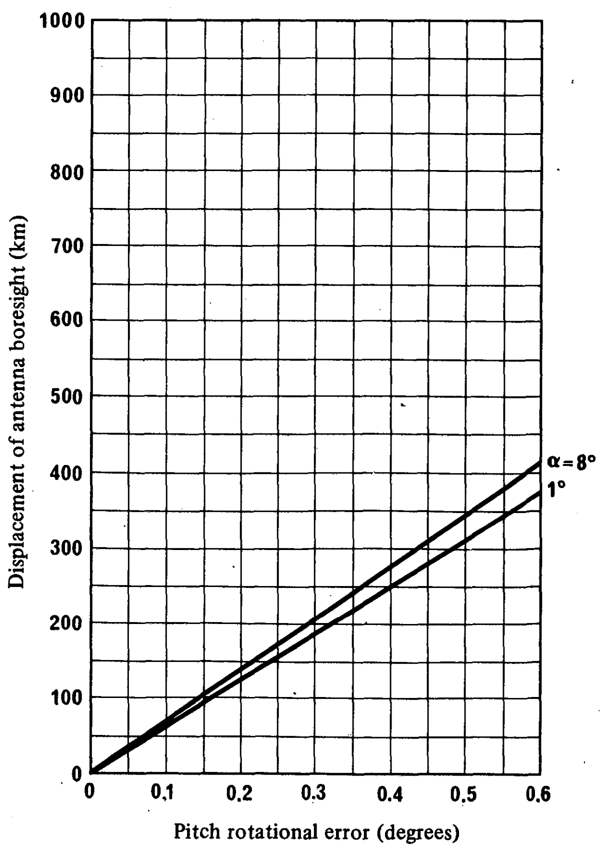

FIGURE 5 – *Pointing error as a function of pitch rotational error; azimuth = 0°*

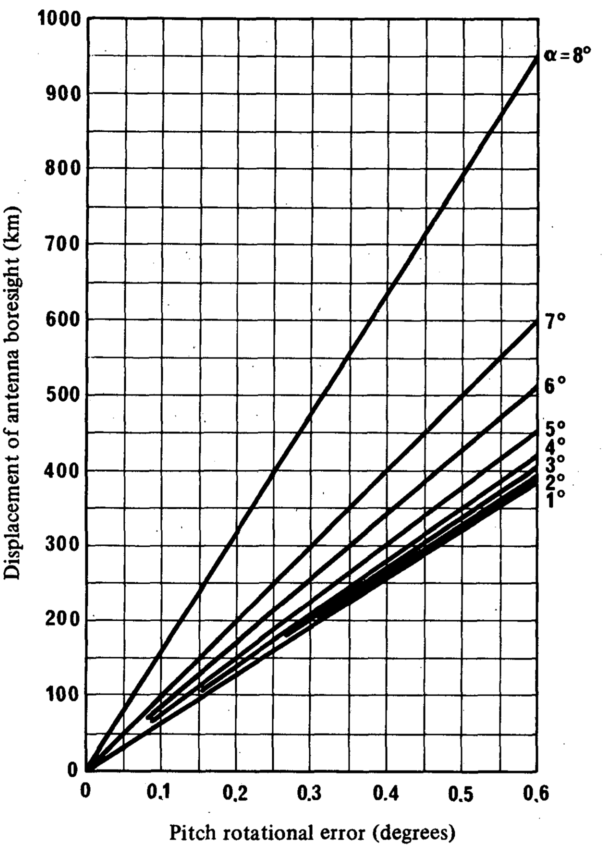

FIGURE 6 – *Pointing error as a function of pitch rotational error; azimuth = 45°*

2.2 *Roll axis*

Figure 7 presents the effect of rotation about the satellite roll axis. The distance that the boresight of the antenna would shift is derived similarly to that in § 2.1 of this Annex. The figures in § 2.1 presenting the results of pitch error (Figs. 4, 5 and 6) apply also to roll errors in the following manner. Figure 4, which shows displacement due to *pitch* errors for a pointing azimuth of 90°, also shows the displacement due to *roll* errors for a pointing azimuth of 0°. Likewise Fig. 5, showing boresight displacement due to *pitch* errors for a pointing azimuth of 0°, also shows the displacement due to *roll* errors for a satellite pointing azimuth of 90°.

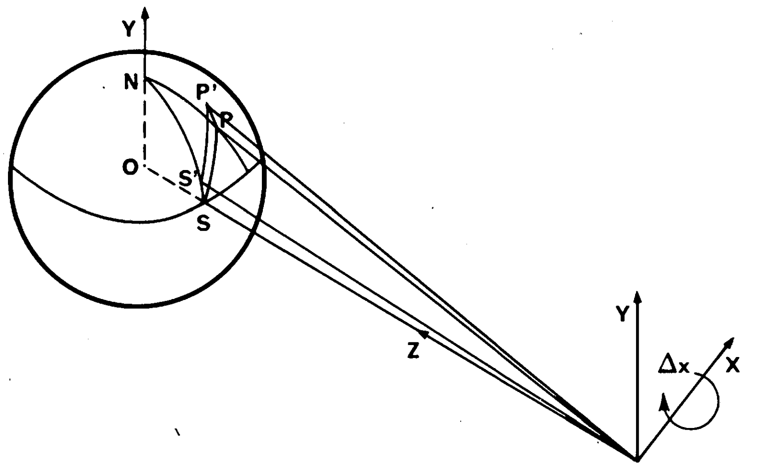

FIGURE 7 – *Pointing error due to roll axis error*

2.3 *Yaw axis*

Figure 8 presents the effect of rotational errors of the satellite about the yaw, or Z axis. As can be seen, point P would be displaced both in latitude and longitude.

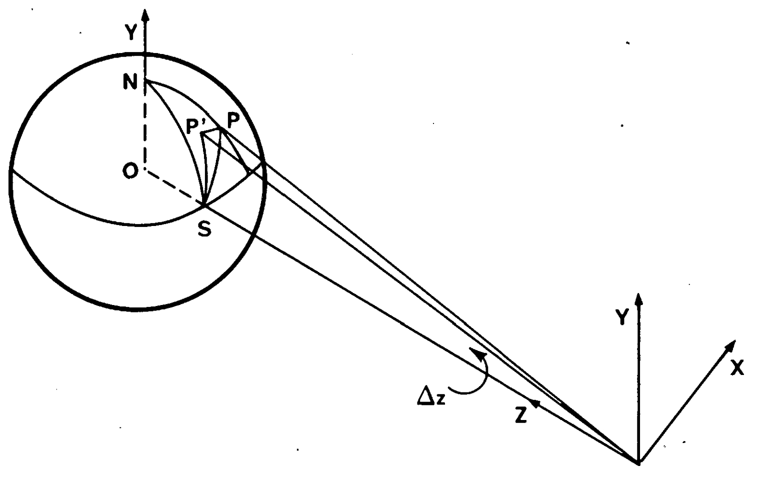

FIGURE 8 – *Pointing error due to yaw axis error*

Errors in the satellite yaw axis produce corresponding one to one errors in the azimuth pointing direction of the satellite. Therefore, in order to determine the location of point P′ as a function of yaw errors, it is necessary to determine the changes in latitude and longitude of P as a function of changes in pointing azimuth. The latitude of point P (Φ) is related to the azimuth and elevation pointing angles of the satellite as follows:

$$\Phi = \sin^{-1} [\cos (A_z) \sin \{\sin^{-1} (k \sin (\alpha)) - \alpha\}] \tag{3}$$

where:

A_z : pointing azimuth of the satellite (degrees measured from North)

The change longitude (Ψ) of point P (from the sub-satellite point S) is given by:

$$\Psi = \tan^{-1} [\sin (A_z) \tan \{\sin^{-1} (k \sin (\alpha)) - \alpha\}] \tag{4}$$

The sensitivities of Φ and Ψ to small changes in azimuth are given by:

$$\frac{d\Phi}{dA_z} = \frac{-a \sin (A_z)}{\sqrt{1-\{a \cos (A_z)\}^2}} \tag{5}$$

where:

$$a = \sin [\sin^{-1} \{k \sin (\alpha)\} - \alpha]$$

and,

$$\frac{d\Psi}{dA_z} = \frac{b \cos (A_z)}{1 - \{b \sin (A_z)\}^2} \tag{6}$$

where:

$$b = \tan [\sin^{-1} \{k \sin (\alpha)\} - \alpha]$$

For a given elevation angle, a and b are constant.

Figure 9 presents the distance from P to P′ based on the above changes in latitude and longitude of the antenna boresight. The distances are presented as a function of the error in yaw (Z axis) and parametrically for various satellite antenna elevation angles (measured from nadir). As can be seen, at high elevation angles (i.e., especially approaching the Earth's limb at 8.5°), the maximum error induced by a 1° error in yaw control is of the order of 90 km.

An approximation of the allowable error in yaw rotation (Δz), such that the displacement of point P does not exceed that induced by errors of Δy or Δx in pitch or roll respectively, is derived below:

$$d_z = R_e \Delta z \{\sin^{-1} (k \sin \alpha) - \alpha\} \frac{\pi}{180} \quad \text{km} \tag{7}$$

and,

$$d_x \text{ or } d_y = R_e [\sin^{-1} \{k \sin (\alpha + \Delta y)\} - \Delta y - \sin^{-1} (k \sin \alpha)] \frac{\pi}{180} \quad \text{km} \tag{8}$$

where:

d_z : distance traversed by point P due to a rotation about the yaw axis of Δy

d_x or d_y : distance traversed by point P due to a rotation about pitch or roll axis of Δx or Δy.

Equating d_z and d_x or d_y and solving for Δz yields:

$$\Delta z = \left[\frac{\sin^{-1}\{k \sin (\alpha + \Delta y)\} - \Delta y - \sin^{-1} (k \sin \alpha)}{\sin \{\sin^{-1} (k \sin \alpha) - \alpha\}}\right] \tag{9}$$

For small values of α and Δy, the expression can be simplified to:

$$\Delta z \approx \frac{\Delta y \text{ or } \Delta x}{\sin \alpha} \tag{10}$$

where Δy, Δx, Δz and α are expressed in degrees.

It should be noted that this expression is an approximation, valid only for small angles ($\alpha = 2°$, Δx or $\Delta y = 0.1°$ results in 3% error). For larger angles, the unsimplified relationship should be used.

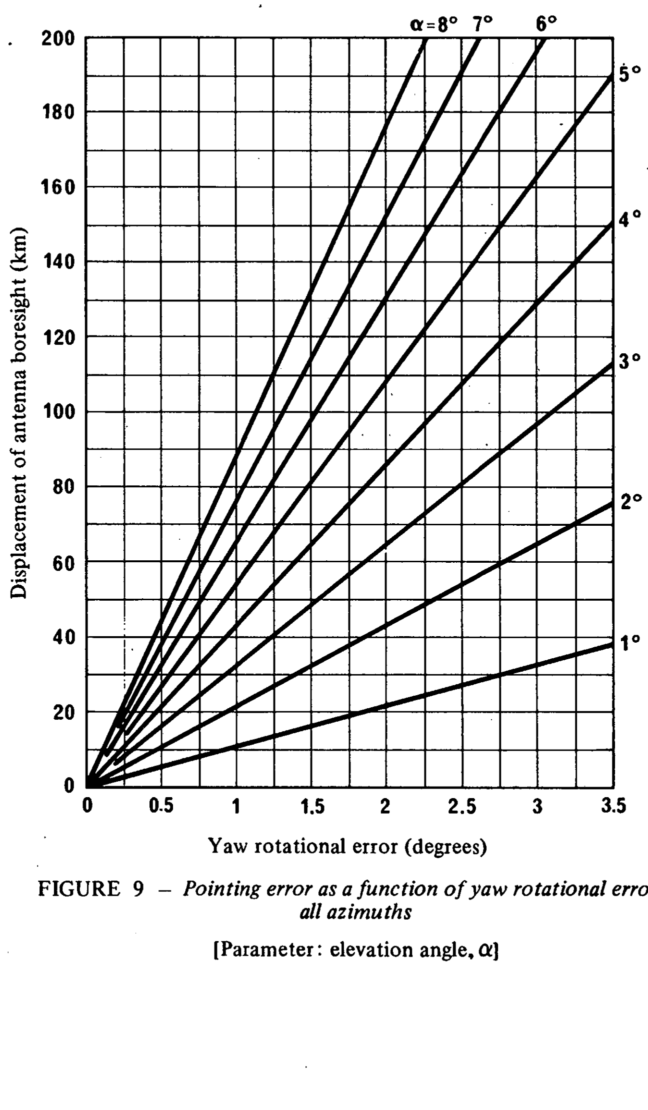

FIGURE 9 – *Pointing error as a function of yaw rotational errors – all azimuths*

[Parameter: elevation angle, α]

2.4 *Conclusions*

To sum up, displacements due to a given pitch error are relatively insensitive to pointing direction on or near the satellite's meridian (see Fig. 5) and are proportional to offset on or near the equator (see Fig. 4). Conversely, displacements due to a given roll error are relatively insensitive to pointing direction on or near the equator, and are proportional to offset on or near the satellite's meridian. For the worst case, small errors ($\approx 0.1°$) in pitch or roll cause displacements equal to or greater than yaw errors of the order of 2°.

ANNEX II

SPIN AXIS DRIFT DUE TO SOLAR RADIATION TORQUE

Many geostationary communication satellites have axis-symmetrical bodies and de-spun antennas. The spin axis of such a satellite is drifted mainly by the solar radiation torque. The magnitude of the torque depends on the shape and the surface material of the satellite and has seasonal variation due to the variations of the sun angle and the receiving intensity of the solar radiation.

The drift rate of the spin axis is in proportion to the solar radiation torque. Figure 10 shows the actual drift rate data of Japan's experimental satellite CS (the medium-capacity communication satellite for experimental purpose).

The variation of attitude due to disturbing torques can be theoretically calculated, but the process is rather complicated. On the other hand, by using actual data of the drift rate of spin axis it is possible to predict the attitude by solving the equation:

$$\frac{d\vec{r}}{dt} = D(\vec{s} \times \vec{r}) \tag{11}$$

where:

$\vec{r}$: unit vector along the spin axis,

$\vec{s}$: unit vector toward the Sun,

D : drift rate of the spin axis.

These vectors and the coordinate system are shown in Fig. 11.

Using the drift rate data in Fig. 10, equation (11) is solved and the attitude predictions of the CS are obtained. An example of the predictions is shown in Fig. 12. They are found to agree well with the actual attitude calculated from the telemetry data.

In order to keep the attitude of a satellite within a given allowable error, periodic corrections are necessary. The period is in proportion to the magnitude of the allowable error and in inverse proportion to the attitude drift rate. As regards a satellite which has the same drift rate as that shown in Fig. 10, the correction periods are shown in Fig. 13 for three different allowable errors 0.2, 0.1 and 0.05°.

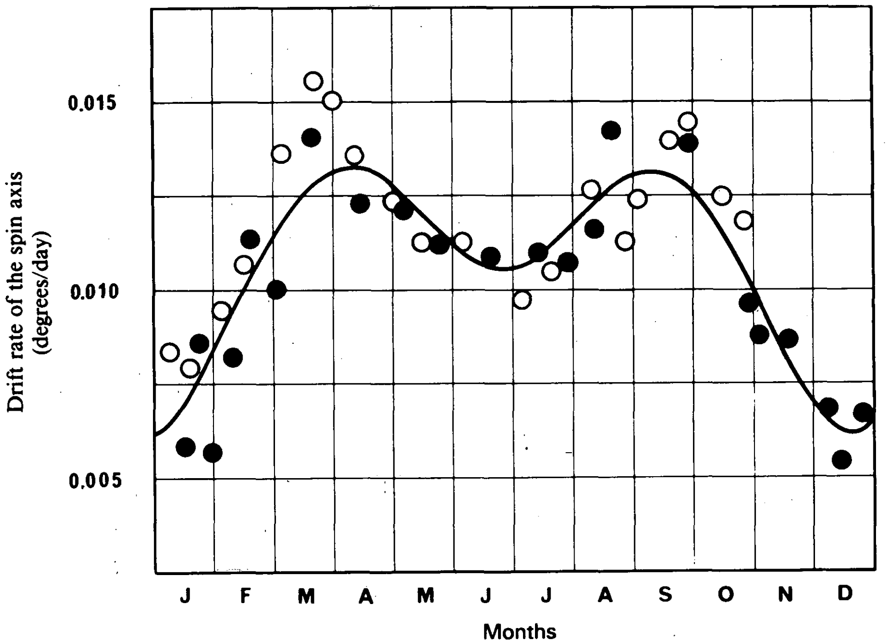

FIGURE 10 — *Drift rate of the spin axis of the CS satellite*

● 1978

○ 1979

——— Fitting curve for 1978

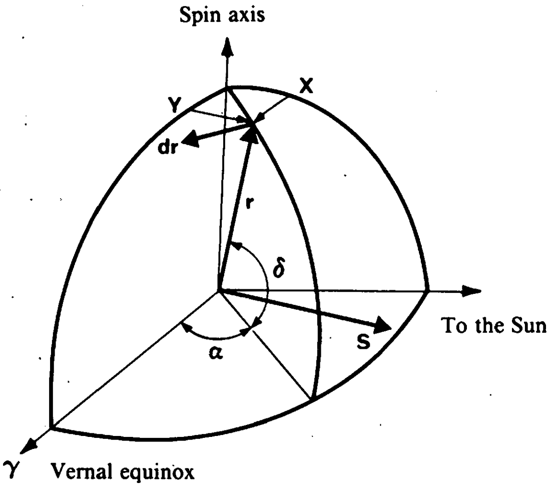

FIGURE 11 — *Coordinates for the equation of spin axis drift*

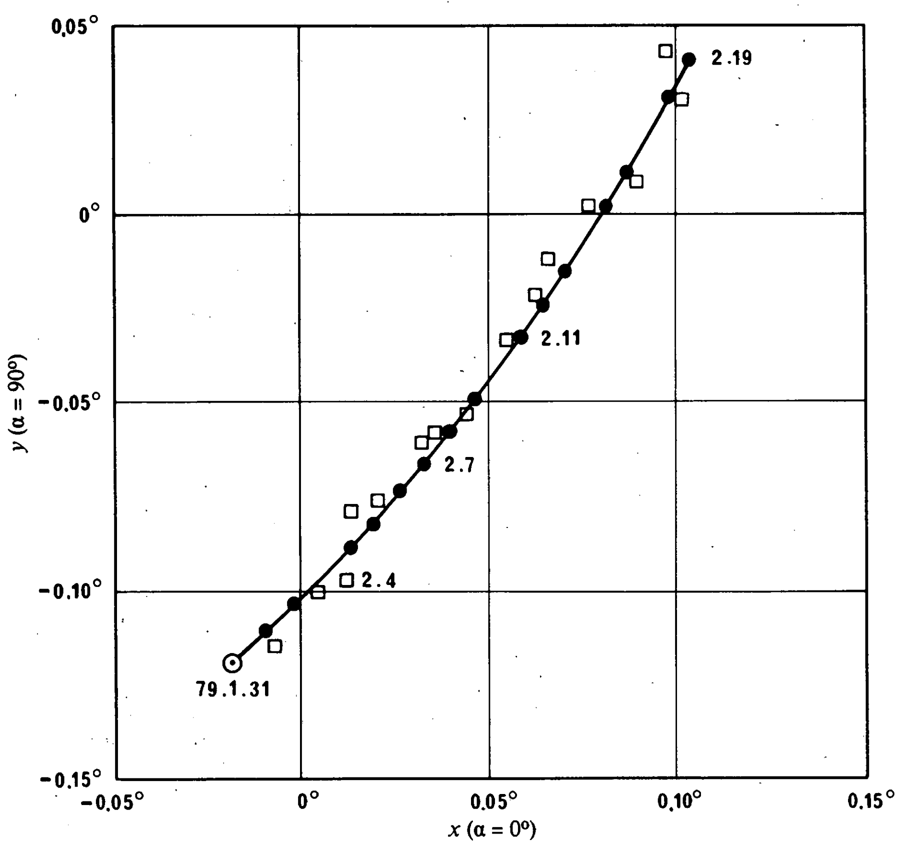

FIGURE 12 — *Attitude predictions of the CS*

□ Attitude obtained by telemetry data

● Prediction

⊙ Initial attitude

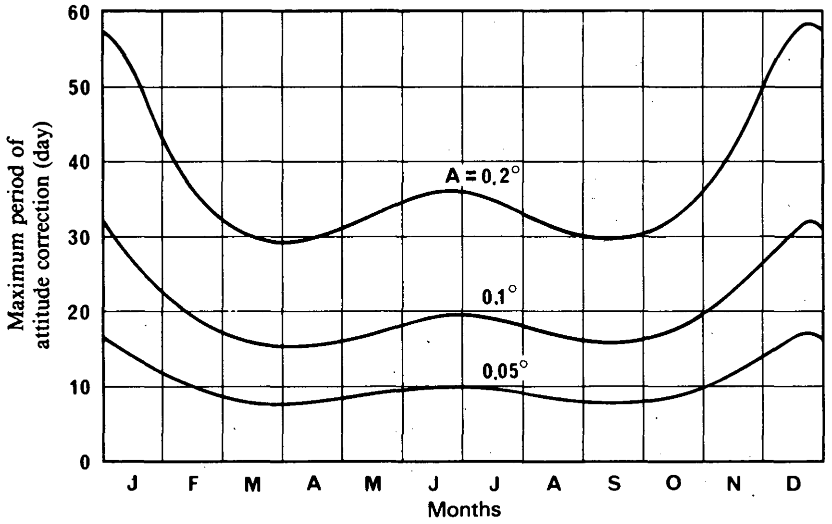

FIGURE 13 — *Attitude correction period of a satellite with the drift rate shown in Fig. 10*

A: allowable attitude error

REPORT 673-2

ELECTRICAL POWER SYSTEMS FOR SPACECRAFT

(Question 15/2)

(1978-1982-1986)

1. Introduction

The purpose of this Report is to provide information on past, current, and future (to 1990) satellite electrical power systems. The Report is confined to those systems which have received extensive study and which are considered feasible for application in space during the time frame to 1990.

2. Background

In general, the requirements for on-board electrical power have increased in the past, and are expected to continue to increase in the future.

Present requirements have reached 1 to 2 kW_e* for large capacity communication satellites and are increasing to 6 to 10 kW_e during non-eclipse period for direct television broadcasting satellites. Power at this level is or will be delivered by photovoltaic conversion systems in combination with chemical storage battery systems which supply power when the satellites are eclipsed by the Earth. In the case of broadcasting satellites, a large storage battery capacity will allow more freedom in selecting orbit positions instead of the current practice of placing them west of the service area.

Space flights to the outer parts of the solar system, where solar electrical conversion becomes impractical, and certain other space missions, have necessitated the development and implementation of nuclear power systems in the range of several hundred watts. The application and development of nuclear power systems will only be possible in so far as safety problems have been thoroughly understood.

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* W_e refers to electrical Watt and W_t to thermal Watt; W_e equals W_t times the conversion efficiency.

3. Current technology

The following sections discuss the current technology of satellite prime power generation.

3.1 *Solar array/chemical battery systems*

Body mounted solar arrays on spin stabilized vehicles such as the Intelsats, early Applications Technology Satellites and certain US and Canadian domestic satellites have been limited to an upper power level of about 1 kW_e, due to limitations imposed by the dimensions of shrouds enclosing payloads on launch vehicles. The shuttle as a launch vehicle will provide a considerably larger launch volume and will allow increases in the power level of body mounted arrays to about 2 kW_e.

Arrays mounted on paddles deployed from the spacecraft after launch can increase the power level of photovoltaic systems to multi-kilowatts. These arrays usually track the Sun continuously in order to optimize their efficiency. Large, deployable rigid, Sun-oriented arrays having a power capability as high as 16 kW_e have been built and successfully used in space (Skylab). A major disadvantage of rigid solar panels is the relatively large stowage volume needed in the shroud of the launch vehicle. Deployable flexible solar arrays (cells mounted on flexible substrates) allow a higher packing density during launch when the flexible solar array blankets are folded or rolled-up. An experimental roll-up solar array was flown in 1971 [Wolff and Wittman, 1972]. A flexible fold-up array of 1.2 kW_e was incorporated in the Canadian communication technology satellite [Harrison *et al.*, 1976].

Research in solar array power systems is aimed at increasing the power-to-mass ratio of solar arrays in space and decreasing the stowage volume during launch. A major part of the research is still directed toward further improvements of solar cells and cover glasses. Following the development of silicon solar cells with a higher sensitivity in the blue and violet part of the spectrum and of cells with a reduced reflection loss in the mid-seventies, further improvements have been achieved [Scott-Monck, 1978] by the development of cells with a back surface field and back surface reflector. The back surface field cell has a built-in electrical field near the rear contact which reduces the electrical losses at the rear contact. A combination of the back surface field technology with new etching methods for silicon has led to the development of experimental ultra-thin cells with a thickness as low as 50 μm (compared to the presently-used thickness of 200-250 μm) and a correspondingly low mass without a significant reduction of the electrical performance after several years of operation in space. Back surface reflector layers in silicon cells lead to a lower operating temperature in space and to a further improvement of the effective conversion efficiency since it increases with decreasing cell temperature. In total, the beginning of life efficiency of space silicon solar cells has increased from 10% to about 14% during the last decade.

So far, all operational solar arrays on spacecraft have used silicon solar cells. Other solar cell materials have been extensively studied but in the near future only gallium-aluminium-arsenide solar cells appear to be a potential alternative for certain applications. Laboratory cells [Knechtli *et al.*, 1980] of this type have shown a very high efficiency (18%) and lower sensitivity to space radiation. None of the other solar cell types presently investigated, e.g. cadmium sulphide, amorphous silicon or multi-band-gap cells, have so far reached the efficiency and reliability of present space silicon solar cells. It can be expected, however, that in the future, the results of the current large effort in terrestrial photovoltaic power research will have a strong impact on the evolution of space solar cells.

In conjunction with the continuing improvement in solar cell efficiency, much effort has also been directed toward the development of new structural concepts in order to reduce the weight and increase the allowable size of deployable solar arrays [Reinhartz, 1978; Mullin *et al.*, 1979]. A 4 kW roll-up array specifically designed for Shuttle operation is presently under construction. Flexible fold-up solar arrays for power levels up to 10 kW specifically designed for high power television broadcasting satellites are already under development, as well as flexible fold-up arrays for Shuttle operation with power levels up to 50 kW.

It is further expected that, around 1990, Shuttle-based orbital construction techniques might allow the assembly of solar arrays with power levels of several hundred kilowatts, covering an area of several thousand square metres.

The technological advancements both in solar cells and in structures have led to significant improvements of the power-to-weight ratio of solar arrays during the last decade (the following data refers to the initial performance in space and the weight includes both the solar cells and the supporting structure). Body-mounted solar arrays have provided up to 7-8 W_e/kg at a specific mass of 4 to 5 kg/m^2. The performance of deployable arrays with a power level of 0.5-2 kw has increased from 10 to 30 W_e/kg, with the specific mass decreasing from 7 to 3.6 kg/m^2. Solar arrays presently under development promise a further increase of the power-to-weight ratio of 60-120 W_e/kg at power levels of 25 kW.

The reliability and the total weight of a solar array/battery system are strongly affected by the characteristics of the chemical storage batteries. Battery systems are of particular importance for high power geostationary communication and broadcasting satellites if continuous operation is needed during the semi-annual 45-day periods of daily eclipse. At present, battery life time appears to be the most critical factor in the design of long-life power systems.

So far, nickel-cadmium batteries have been used in most space missions. Since the mass of nickel-cadmium batteries in high power communication satellites may represent 10-20% of the satellite dry mass, metal-hydrogen – in particular, nickel-hydrogen and silver-hydrogen cells [Young, 1979] – are being developed as a lighter alternative. Experimental nickel-hydrogen batteries have been successfully flown on the NTS-2 spacecraft [Dunlop and Stokel, 1978] and will be used on several of the Intelsat-V type spacecraft. It is expected that the change from nickel-cadmium to metal-hydrogen batteries will raise the usable specific energy from 15 Wh/kg to 25 Wh/kg or more. Nickel-hydrogen batteries in particular are also expected to have a considerably higher life expectancy than nickel-cadmium batteries.

3.2 *Solar collectors*

Solar collectors or concentrators have been proposed as energy sources, with a variety of power conversion methods, for electric power generation or cooling in space. Although the amount of study effort has been rather extensive, in-flight hardware has not been produced. One of the inherent problems appears to be the very stringent pointing requirements of these devices.

3.3 *Nuclear systems*

The application of nuclear technology to the generation of electrical power in space has shown distinct potential in terms of power levels, long lifetimes and high reliability. However, a great deal of effort [Stadter and Weiss, 1975] has been required to assure safety in the implementation of these systems. The following sections discuss some of the power source and energy conversion techniques which have been the subject of extensive study to date.

3.3.1 *Radioisotopes*

The use of radioisotopes as energy sources for space electrical power has been recognized since the early 1960s, and the systems derived therefrom have been described in many published references.

Nuclear electric power for space application was first achieved in 1961 when a 2.7 W plutonium-238 fueled generator was orbited by the United States. More recent missions using radioisotope thermoelectric generators (RTGs) in five Apollo Lunar Surface Experiment Packages (ALSEP) on the lunar surface, and four RTGs aboard each of the Pioneer 10 and 11 interplanetary satellites (exploration past Jupiter and Saturn), attest to their inherent reliability.

Radioisotope thermoelectric generator technology growth has reached the point where kilowatt levels of electric power for spacecraft can be considered as practical. Through extensive research, efficiencies can now be doubled by application of new selenide thermoelectric materials. Specific powers of these systems are expected to increase to 9 to 11 W_e per kilogram. These improvements, coupled with the projections of a 50% reduction in the cost of long-lived plutonium-238, indicate that, for some specific missions, RTG space power systems could be nearly competitive with solar technology in the 1 kW range, at a price of approximately 4000 dollars per W_e in the late 1970's.

Additional study has continued into means other than thermoelectric materials for conversion of radioisotope thermal energy to electrical. Perhaps the most significant are the Brayton, Rankine, and Stirling dynamic cycles. These conversion cycles are thermodynamic engines typically consisting of the nuclear heat source which transfers energy to a working fluid which in turn drives a turbine, electrical generator and compressor. Typically, these conversion systems deliver 2 to 3 times the energy conversion efficiency of thermoelectric materials. However, present-day cost and weight factors are also higher.

3.3.2 *Fission reactors*

Several generic types of nuclear fission reactors have undergone study for space applications. An operational system might be developed in the next ten years under the United States SP-100 research programme [Truscello and Davis, 1984]. Such a system will possibly employ uranium dioxide fuel clad in molybdenum with heat removal by sodium heat pipes.

A number of power conversion options are under study including SiGe thermo-electric conversion, yielding efficiencies of up to 9%, and Stirling, Rankine and Brayton dynamic cycles yielding efficiencies of up to 30%.

4. Prospects and limitations

Table I presents estimated performance parameters of the three prime systems for electrical power generation for spacecraft. Although many other power generation and conversion technologies exist and have been studied, the three generic systems listed in Table I are considered the most likely to be realized in space qualified hardware within the foreseeable future.

The immediate future space power generation systems will probably continue to be comprised of advanced solar cell/chemical battery systems due to recent technological advancements and their proven space qualified performance in the low multi-kilowatt range. Deep space and interplanetary missions at distances of several AUs from the Sun will continue to require advanced RTG technology as well as possible advanced Brayton or Rankine energy conversion systems. Very high power (5 to 20 kW_e) Earth-oriented communications or broadcasting-satellites may realize the advantages of utilizing nuclear power systems (continuous power independent of sunlight) once the inherent safety and weight/cost restrictions are overcome. The critical safety factors associated with spaceborne nuclear power systems which must be studied are fairly numerous compared to those associated with today's terrestrial commercial reactor systems. In addition to special handling and disposal requirements of long-lived nuclear reactor by-products, spaceborne nuclear power systems have associated critical accident potentials such as launch booster failure and detonation, shrapnel dispersion, fire immersion, aerodynamic heating during re-entry, high velocity terrestrial impact and potential post-impact burial and oxidation. Each of these failure modes require extensive materials research and development to ensure that the radioactive heat source (some of whose half-lives may be of the order of 100 years or more) does not contaminate the Earth's atmosphere or water resources.

5. Summary

The selection of a power system for space applications depends on a number of factors, in addition to the amount of on-board electrical power that is required. The estimated performance and cost parameters for the most likely systems are listed in Table I.

Solar array/battery subsystem characteristics are mission dependent, and the number of integrated subsystem elements such as the arrays orientation mechanisms, sensors, storage units and power conditioning circuitry must all be included in an overall power system evaluation.

Nuclear radioisotope and reactor system performance capabilities have not yet been fully explored in a mission operations context, and safety and cost considerations require further evaluation.

The continuing evolution in the performance and in the achievable power level of solar array/battery systems will probably ensure that this system will continue to remain the dominant power source for space missions, at least in the 1980-1990 period. Nuclear systems may replace solar array/chemical battery systems in some applications at a later stage, provided the potential safety problems can be solved.

TABLE I — *Estimated power system performance parameters of some US power units*

System	Technology status	Year of availability	Performance and cost parameters (1)	
			kg/W_e	US dollar/W_e
Photovoltaic cells				
< 2 kW units (2)	In use	—	3×10^{-2}	5×10^{2}
2 to 100 kW units (lightweight)	In use	1980–1985	2×10^{-2}	2×10^{2}
> 100 kW units (low cost)	Future development	1985–1990	5×10^{-3}	5×10^{3}
Radioisotopes				
Thermoelectric conversion 0.1 to 1kW_e unit	In use	—	3×10^{-1}	1.5×10^{4}
Brayton conversion 0.5 to 5 kW_e units	In development	1985	1.5×10^{-1}	2×10^{4}
Reactors				
Thermoelectric conversion 100 kW_e units	In development	—	2.5×10^{-1}	1.5×10^{2}

(1) Estimated performance parameter uncertainty, ± 20 to 100%.
(2) In special applications such as Skylab this number has been exceeded.

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REPORT 674-1

SPACECRAFT CHARGING

(Question 15/2)

(1978–1982)

1. Introduction

The electrostatic charging, to large negative potentials, of the external surfaces of spacecraft in synchronous orbits was discovered in 1972. This phenomenon of charging and the subsequent discharge was probably responsible for the destruction of the US Defense Satellite Communications System (DSCS) Flight 9431 spacecraft, and for numerous serious operational anomalies on other synchronous orbit spacecraft. In addition to the operational anomalies the charging compromises measurements such as low energy particles' flux and spectra, electric fields, antenna impedances, and surface contamination on scientific spacecraft in the magnetosphere, and outside the plasmapause.

The anomalies occurred predominantly in the 0000 to 0600 h (local spacecraft time) sector of the orbits, and there appears to be a correlation between the anomalies and polar substorms. The ATS-5 and ATS-6 electron and proton spectrometers have been used to determine the potential of the spacecraft "ground". Potentials as large as -15 kV have been observed in eclipse and as large as -200 V in sunlight. The ATS instruments have also shown that large fluxes of electrons are being injected into the environment at the same time as the large potentials are observed.

The problem is now widely recognized and it is of immediate and vital concern to all space agencies. Many large aerospace companies and space agencies have programmes for the study of the causes and effects of the charging and of methods for protection of spacecraft against these effects. The United States of America has built the Spacecraft Charging At High Altitude (SCATHA) spacecraft for the sole purpose of investigating spacecraft charging and its effects on spacecraft systems and materials. The SCATHA satellite was successfully launched in January, 1979. At the Communications Research Center (CRC) Ottawa, a laboratory simulation experiment has recently been completed.

Investigations now underway can be grouped into five categories: environment, mathematical models, laboratory simulation experiments, material research and SCATHA experiments. These efforts will lead to a set of specifications and guidelines for the design, construction and testing of subsystems and the integrated spacecraft. In this Report is presented an overview of the phenomenon, and of the work being carried out in the various agencies. It is concluded with a set of recommendations for construction of spacecraft, based mainly on Canadian experience with the Hermes spacecraft.

2. The charging mechanism and consequences

The equilibrium potential of a surface in the space environment is established when the net current to the surface is zero. The sources of current are: charged particles from the environment, electrons and positive ions, predominantly protons, secondary electrons and photoelectrons emitted from the surface, and in the case of a dielectric surface the current through the surface material from the underlying substrate. The secondary ions and photoelectrons balance the electron current; the bulk current will depend on the difference in potential between the surface and the substrate and this current is not always negligible even for relatively good insulators. All these currents are complex functions of the surface potentials. For a spacecraft in near-Earth orbit, within the plasmapause the potential of surfaces in shadow or sunlight is only a few volts negative or positive respectively, because of the flux of low energy (a few eV) ions and electrons is far larger than the flux of higher energy particles. However, in a near synchronous orbit, particularly in the 2100 to 0900 hours local time sector, the flux of low energy ions is so low that the flux of electrons of a few keV to a few tens of keV, injected during a substorm will be larger and the spacecraft will then tend to charge highly negatively. Surfaces can charge to the order of -15 kV when shadowed, whereas in sunlight the photoelectron current balances the incident electrons and surface potentials are limited to a few tens of volts.

Analysis of data gathered to date by the SCATHA satellite has verified and quantified the spacecraft charging mechanism [Koons *et al.*, 1980]. Charging levels and rates are a function of location on the spacecraft in relation to the incident flow of charged particles. Parts of the spacecraft in shadow can charge to high levels even though the vehicle is in sunlight.

So far only isolated surfaces have been considered. For a complete spacecraft, the potential of the "ground" depends on not only those factors described above but also on the distribution of exposed metal, on grounded surfaces in sunlight and in shadow, and on the currents through the external dielectric surfaces to the grounded substrates.

The danger to a spacecraft is not that the whole body is charged to several kilovolts in eclipse but that in sunlight there will be large differences in potentials, between dielectric surfaces in shadow and ground, between isolated metal surfaces in shadow and ground, etc. It has been demonstrated in several realistic laboratory simulation experiments that high current discharges, similar in appearance to lightning strikes, occur along charged dielectrics, the discharge current flowing to a nearby ground plane or through a plasma to the chamber structure. These discharges are sufficiently powerful to destroy electronic components and to seriously damage the reflective coating on thermal control mirrors and on thermal blankets. The discharge currents from isolated, charged metal surfaces to ground are much larger and therefore potentially more dangerous. This situation may be avoided by securely grounding exposed metal surfaces wherever possible.

The determination of potentials of exposed surfaces, the discharges off these surfaces, the effects on measurements of the environment, and spacecraft responses are very complex and investigations must be pursued by theoretical, experimental and engineering methods.

3. Work currently in progress

There are several groups working on various aspects of the problem. A brief description of the main activities follows:

3.1 *Environment*

The most pertinent data on the environment have been obtained from ATS-5 and ATS-6. At the present time there is not enough data on the environment to provide a unique model for the conditions that will or may cause operational anomalies. It is expected that the SCATHA experimental data will help resolve this problem.

3.2 *Mathematical models*

It is fairly easy to calculate the potential of conducting bodies with simple shapes, or of more complex bodies using idealized assumptions with regard to the functional form of the currents from the environment. However, it is extremely difficult to calculate potentials for realistic spacecraft. The most sophisticated models employ iterative solutions of the Poisson and Vlasov equations.

The sophisticated models are necessary but the simple model is useful for obtaining fast although approximate results to guide further more detailed calculations and to make engineering decisions.

3.3 *Laboratory experiments*

The laboratory experiments are being carried out at several places. The original work done at Thompson Ramo Wooldridge Inc. (TRW) on the failure of one particular satellite used a laboratory experiment to demonstrate to the aerospace industry the danger in spacecraft charging. The group at NASA Lewis Research Center have an experiment with good theoretical and hardware support, and they are able to test new ideas and materials quickly. The European Space Technology Centre is testing large samples of flexible solar arrays. The experiment at the Communications Research Centre (CRC) will be used to determine the energy in the discharges off dielectric surfaces, and the energy and spectrum of the electromagnetic radiation.

3.4 *Materials*

The effort on material research is concentrated mainly in finding a conductive dielectric that will meet the requirements of a surface with the thermal characteristics of low absorptivity and high emissivity. An estimate has been made at the US Air Force Materials Laboratory, Wright Patterson Air Force Base, that at least two years would be required for significant progress on space qualified materials.

3.5 *SCATHA*

SCATHA is the acronym of a space measurements program entitled Spacecraft Charging At High Altitudes which has been formulated to define the environment, to measure charging and discharging characteristics of materials, to provide data for calibration of analytical models, to measure satellite contamination, and to evaluate the utility of various corrective techniques which can minimize differential charging on board satellites.

The SCATHA satellite was launched in early 1979 into an elliptic, low inclined (approximately 8°) orbit. The orbit, with an apogee of 7.7 Earth radii and perigee of 5.5 Earth radii, was chosen in order to investigate the geostationary orbit "area". The satellite drifts eastwards about 6° per day resulting in data sampling at approximately all local times.

The SCATHA mission supports thirteen experimental payloads. They are:

SC1 – Satellite Surface Potential Monitors and Spacecraft Electrical Analyzers.

SC2 – Spacecraft Sheath Electric Fields and Energetic Proton-Detector.

SC3 – High Energy Particle Spectrometer.

SC4 – Particle Beam System.

SC5 – Rapid Scan Particle Detectors.

SC6 – Thermal Electron Monitors.

SC7 – Light Ion Mass Spectrometer.

SC8 – Energetic Ion Spectrometer.

SC9 – Charged Particle Detectors.

SC10 – Electric Fields Detector.

SC11 – Magnetic Field Monitor.

ML12 – Thermal Control/Contamination Monitors.

TPM – Transient Pulse Monitor.

At the time of this writing, detailed analyses of SCATHA data are not available. However, some data from the SC5 (Rapid Scan Particle Detector) and the SC9 (Charged Particle Detector) have been statistically analyzed and used to produce a preliminary description of the SCATHA plasma environment.

Measurements of electron density in these preliminary data show expected pronounced variation with local (sub-satellite) time. Maximum density levels occur between 0000 h and 0600 h local time with values of about 1.5 electrons/cm^3. Corresponding electron current density maximum measurements are about 0.020 nA/cm^2 and show approximately the same level of variance as does the electron density.

4. Conclusions and recommendations

The spacecraft charging problem is not completely understood. The correlation between the anomalies experienced by some spacecraft and polar substorms appears well established, but not every substorm produces an anomaly and some anomalies are not coincident with substorms. Some spacecraft appear to be immune to the effects for long periods of time, such as Intelsat-IV, then experience several anomalous events. Other spacecraft like ATS-5 and ATS-6 have experienced no anomalies attributable to spacecraft charging.

The Hermes spacecraft is a very light weight design and, during its operational lifetime from January 1976 to November 1979, only two anomalies were seen that may have been related to charging. The following recommendations are based on the experience with the Hermes spacecraft.

4.1 Use command and data line interface circuits which provide protection against short high level transients.

4.2 Bond all second surface mirrors (SSM) with conductive adhesive.

4.3 Ground all metal parts.

4.4 Ground all layers of all thermal blankets.

4.5 Carry out spacecraft level electromagnetic interference (EMI) tests on the engineering model spacecraft using a very fast spark source, to establish the electrical signature on the wiring lines. These data should be used to specify electromagnetic interference (EMI) protection on flight model units.

4.6 EMI specifications should include limits on emission and susceptibility on command and telemetry lines.

A further recommendation is that where possible synchronous orbit spacecraft should carry a small package of instruments to monitor EMI signatures, the potential of some small isolated surfaces and, if weight restrictions permit, the particle environment.

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REPORT 843-1 *

STATION-KEEPING TECHNIQUES FOR GEOSTATIONARY SATELLITES

(Question 15/2)

(1982–1986)

1. Introduction and background

Report 556 discusses the factors affecting station-keeping of geostationary satellites, and provides some information on both the magnitudes of these factors as well as on station-keeping accuracies of some spacecraft. The purpose of this Report is to provide general information on current technologies available or projected for use in geostationary-satellite station-keeping systems.

Current and future geostationary spacecraft with multiple narrow antenna beams directed at specific locations on the surface of the Earth may require orbital determination and maintenance to within ± 0.1°. This level of station-keeping will allow the use of earth-station antennas with fixed pointing. Additionally, the maintaining of close tolerance on spacecraft position will enhance geostationary orbit and spectrum utilization. The station-keeping systems described in this Report are capable of providing accuracies of location within the orbit of the order of ± 0.1° for 7 to 10 year satellite lifetimes.

The factors affecting the orbital elements of a geostationary satellite (see Report 556) are:

– the gravitational effect of the Sun and Moon: the primary effects of these bodies is to change the inclination of the satellite orbital plane, causing the satellite to follow a figure-of-eight path relative to the surface of the Earth;

– the non-uniformity of the Earth's gravitational field: this non-uniformity causes an increase or decrease in a geostationary satellite velocity and, hence, orbital period. Consequently, the satellite tends to drift east or west at a rate proportional to the magnitude of the local gravitational acceleration. Figure 1 illustrates spacecraft drift directions as a result of the non-uniformity of the Earth's gravitational field along various longitudes;

– solar radiation pressure: this secondary effect can change the eccentricity of the satellite orbit, and hence cause a cyclic east or westward motion of a satellite.

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* This Report should be brought to the attention of Study Group 4.

Early communication-satellite station-keeping systems, such as those of Intelsat-I and II and Syncom, employed pulsed jet systems on spin-stabilized platforms. The primary choice of propulsion fluid was hydrogen peroxide, due to its relatively high specific impulse (I_{sp} = 155 s)* and its acceptable performance over limited periods (≈ 1 year).

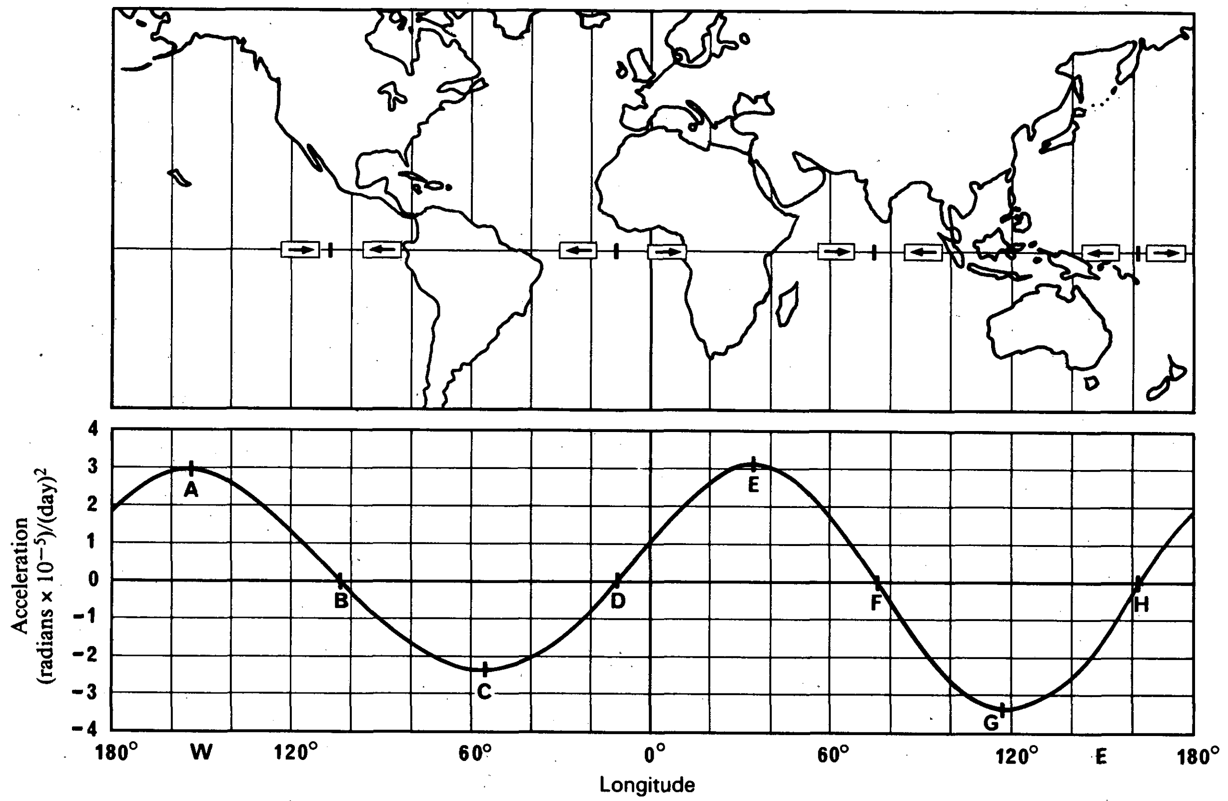

FIGURE 1 – *Easterly component of gravitational acceleration*

Spacecraft drift direction under the influence of the Earth's gravitational field

A: 155° west longitude
1.64×10^{-3} degrees/day²
2.86×10^{-5} rad/day²

B: 105.5° west longitude
Stable equilibrium point
(gravity valley)

C: 56° west longitude
-1.42×10^{-3} degrees/day²
-2.47×10^{-5} rad/day²

D: 11.5° west longitude
Unstable equilibrium point
(gravity peak)

E: 34° east longitude
1.80×10^{-3} degrees/day²
3.14×10^{-5} rad/day²

F: 75° east longitude
Stable equilibrium point
(gravity valley)

G: 117° east longitude
-1.98×10^{-3} degrees/day²
-3.45×10^{-5} rad/day²

H: 161.8° east longitude
Unstable equilibrium point
(gravity peak)

* A performance measure of a rocket propellant, expressed in seconds, equal to the thrust F divided by the propellant mass flow rate w: ($I_{sp} = F/w$).

2. Current systems technologies

Current communications satellite systems require lifetimes of about 7 years, and future satellites will be designed for lifetimes up to 10 years. Additionally, the mass of a communications satellite is continually increasing. For instance, Intelsat-V weighs more than 900 kg. Consequently, greater station-keeping energy requirements are being placed upon communications and other types of satellites in order to maintain a given orbital position within the necessary limits. As a general rule, north-south station-keeping requires an average of 50 m/s per year velocity increment capability, while east-west station-keeping requires about 2 to 5 m/s per year. (The exact value for E-W station-keeping depends on the longitude of the satellite.)

Much effort has been directed toward light weight, efficient* station-keeping control systems. Basically, all of these systems involve the expulsion of mass at a desired velocity and direction relative to the satellite centre of mass. Spin-stabilized, as well as three-axis stabilized satellites, employ axial (along the spin axis or north-south) thrusters and radial (in the plane normal to north-south axis) thrusters. The axial thrusters control the orientation of the north-south axis, as well as latitude excursions of the spacecraft. The radial thrusters control the east-west satellite position.

Ideally, station-keeping manoeuvres are accomplished by applying an impulse each time the spacecraft crosses the line-of-nodes between the actual orbit and the geostationary orbit. Since "impulse" or zero time interval thrusting is, in general not possible, thrusters must fire for a finite period of time in order to impart the necessary velocity increment. In this connection, it is noted that the quantity of propellant required to maintain the position of a satellite (of given mass) is essentially independent of the "duty cycle" employed, except in those cases where the efficiency of the propellant varies with the duration of valving or pulsing, or when thrusting has to be carried out for hours around the nodes.

The bulk of current and expected future technology for station-keeping systems is confined to chemical and electric engines. Additionally, these systems are often used for initial orbit insertion, as well as to "dump" momentum stored in attitude control devices such as momentum wheels. The following sections discuss the chemical and electrical propulsion systems.

2.1 *Chemical engines*

A great deal of effort has been directed toward development of improved propulsion systems employing a variety of propellants. Intelsat-III introduced the first United States-built production spacecraft for which station-keeping was accomplished through the use of hydrazine thrusters [Meredith, 1972]. The flight history provided by five Intelsat-III spacecraft indicated the inherent high reliability and performance characteristics of these systems. Since that time, nearly all geostationary satellites have employed thruster jets using hydrazine fuel. Hydrazine typically has a specific impulse of 220 s and supplies thrust in the range of a newton.

Perhaps the greatest amount of experience in the use of mono-propellant** systems has been gained by Intelsat [Owens, 1976]. Intelsat-I through IV-A have all used a mono-propellant of either hydrogen peroxide (for Intelsat-I and II) or hydrazine (for Intelsat-III, IV, and IV-A). Tables I and II list the technical and performance specifications of the onboard propulsion systems of these five satellites. As can be seen from Table I, each propulsion sub-system total weight equals approximately 1/5 of the total initial in-orbit satellite weight. The sum (175 kg) of propellant weight and dry weight, for instance, of Intelsat-IV-A is the satellite's heaviest sub-system (9 kg heavier than the total communications sub-system). Table III lists the velocity requirements (ΔV) budget for Intelsat IV-A.

TABLE I — *Intelsat satellite on-board propulsion system hardware*

Satellite	Dry weight (kg) (1)	Propellant weight (kg)	Number of tanks	Number of thrusters	Initial orbit satellite weight (kg)
Intelsat-I	3.7	5.0	4	4	39.5
Intelsat-II	7.0	9.6	4	4	86.3
Intelsat-III	5.6	21.8	4	4	133.0
Intelsat-IV	16.8	136.4	4	6	732.0
Intelsat-IV-A	16.8	158.2	4	6	828.0

(1) Tanks, thrusters, valves and associated piping.

* That is, high specific impulse.

** Single propellant systems not requiring an oxidizer.

TABLE II — *Intelsat satellite on-board propulsion system performance*

Satellite	Propellant	ΔV (m/s)	Design life (years)	Thrust level (N)
Intelsat-I	Hydrogen peroxide	190	1.5	14–5.5
Intelsat-II	Hydrogen peroxide	200	3	14–5.5
Intelsat-III	Hydrazine	320	5	16–7
Intelsat-IV	Hydrazine	432	7	26–13
Intelsat-IV-A	Hydrazine	432	7	26–9

TABLE III — ΔV *budget for Intelsat-IV and IV-A*

Manoeuvre	ΔV (m/s)
Attitude correction	0.305
Spin-up	0.61
Spin speed control	4.17
E-W and station repositioning	14.6
Initial orbit correction	54.9
N-S station-keeping	358.4

Due to the weight requirements associated with the use of hydrazine, efforts have been directed toward other liquid propellants which may provide higher overall performance characteristics. These studies have included different blends of hydrazine azide and hydrazine which resulted in an increase in the specific impulse. However, due to a higher combustion temperature, problems have been encountered with thruster lifetimes.

Two other candidate systems are considered feasible for future communication satellite station-keeping systems. These are bipropellants, and electrically-augmented hydrazine. Both of these systems offer advantages in weight and specific impulse.

An advanced bipropellant system has been designed and successfully flown by Germany (Federal Republic of) in the Symphonie programme [Pfeiffer and Viellard, 1970]. This bipropellant system used mono-methyl hydrazine for the fuel and nitrogen tetroxide for the oxidizer. This type of system offers a substantial weight saving to station-keeping systems.

The electrically-augmented hydrazine systems [Free, 1978] add electrical energy to the hydrazine flow, thus increasing the system gas temperature and specific impulse (up to 300 s). Pursuit of this technology has resulted in selection of the augmented hydrazine thruster for north-south station-keeping on Intelsat-V. To perform N-S station-keeping of a 1000 kg satellite for 10 years, two high performance hydrazine thrusters (HIPEHT) could be fired simultaneously for about 0.5 h once each week. Hydrazine can be stored for years, if sealed properly and kept in a cool, dark place. Table IV lists HIPEHT specifications for the Intelsat-V configurations.

2.2 *Electric propulsion*

In an electric propulsion system, an ionized or electrically charged propellant is acceleratd to a high velocity by an electrostatic field or by the interaction of a discharge-current with a magnetic field. With two exceptions, all devices require the propellant to be in a gaseous form, and therefore liquids are usually vapourized and solids ablated via electric discharges prior to ionization and acceleration. The exceptions are colloid and field emission thrusters; in the former, charged liquid droplets are accelerated, and in the latter, a film of propellant covering a sharp point or edge emits ions under the influence of a strong electric field.

TABLE IV — *High performance hydrazine thruster (HIPEHT) specifications, Intelsat-V configuration*

Description, thruster assembly	
Solenoid propellant valve	Series redundant seats Redundant coils Redundant valve heaters
Thermal decomposition chamber	Redundant heaters
Vortex heat exchanger with nozzle	
Temperature sensors	Valve thermistor Thermal barrier thermistors
Propellant	Low-carbon hydrazine
Performance	
Inlet pressure range	1725–830 kPa
Extended range	1860–760 kPa
Thrust	0.45–0.18 N
Total impulse (qualification)	240 000 Ns
Specific impulse	> 285–305 s
Cyclic life	> 450 starts
Aggregate thrusting life	> 214 h
Thermal	Similar to 1.3-N catalytic hydrazine thruster interfaces
Environments	Typical of Atlas-Centaur and shuttle-launched geosynchronous spacecraft
Weight (without mounting bracket)	0.4 kg

Although thrust levels from these devices are usually low, being in the one to several hundred mN range, exhaust velocities are very high, since they are limited only by the available electrical energy. Consequently, large values of specific impulse are readily attainable, currently reaching to nearly 10 000 s, while 20 000 s should be feasible in the near future. Thus the propellant masses required for a given mission can be reduced very considerably by the use of electric propulsion systems.

Over the past 25 years or so, many different electric propulsion systems have been developed. The characteristics of some of the more significant of these are summarized in Table V [Fearn, 1982], in which the values quoted are from typical experimental data. It will be noted that only the ion thrusters and pulsed plasma rail gun have so far achieved flight status in the West. Very little has been published regarding the extensive Soviet flight experience, so the table does not take that into account [Zhurin *et al.*, 1983].

In Table V, the first three main columns refer to ion thrusters. In these, a propellant in gaseous form is ionized in a discharge chamber. The positive ions are then extracted and accelerated by high electric fields between sets of perforated grids at one end of the discharge chamber, thus forming an ion beam which produces thrust. In the Kaufman thruster, also known as the electron bombardment thruster, a d.c. discharge is employed to produce the required ionization. The magnetic field used to assist in this process has a modified form in the magneto-electrostatic containment (MESC) thruster. A radio-frequency discharge is utilized in an RF thruster, which has been developed in the Federal Republic of Germany.

TABLE V – *Comparison of typical parameters of ion and plasma thrusters*

Type	Kaufman ion		RF ion		MESC	Colloid	Field emission	Contact ionization	Rail gun	MDP arc
Acceleration mechanism	ES SS		ES SS		ES SS	ES SS	ES SS	ES SS	EM Pulsed	EM Pulsed
Usual propellants Alternative	Hg Argon, Xenon		Hg Argon, Xenon		Cs Hg, Argon	Glycerol (1)	Cs	Cs	Teflon	Argon N_2
Spacecraft acceptability	Good		Good		Poor (Cs) Good	Fair	Poor	Poor	Good	Good
Exhaust exit dimensions (cm)	8 dia	30 dia	10 dia	35 dia	12 dia	3 dia annulus	3 cm linear	5 × 0.6 rectangle	7.5 × 3.4 rectangular	10 dia
Potential: – accelerating (A) – discharge (D)	1.2 kV (A)	1.1 to 5.0 kV (A)	1.5 kV (A)	~ 3.7 kV (A)	760 V (A)	10-16 kV (A)	2-4 kV (A)	4 kV (A)	2.5 kV (D)	100-400 V (D)
Power (kW)	0.13	2.6 to 10.4	0.3	3.6	0.34	~ 0.01	~ 0.16	~ 0.12	0.15	6000
SI (s)	2800	2000 to 6300	3100	3400	3300 to 4000	1000 to 2000	9000	6700	1800	2400
Electrical efficiency	0.69	0.84 to 0.96	0.64	0.79	0.81	0.7	~ 0.9	~ 0.4	0.32	0.31
Mass efficiency	0.84	0.89 to 0.95	0.80	0.88	0.97	0.2 to 0.8	~ 0.7	0.99		
Thrust (mN)	5 to 18	130 to 290	10	160	17 to 64	0.5 (2)	~ 2.5 (2)	1.5	4.5	140×10^3
Life test (h)	15 000	10 000	8000	None	600 (3)	475 (4)	Few 100	None (5)	2×10^6 pulses	None
Development status	Flight ready	Flight ready	Flight ready	Medium	Medium	Good	Fair	Fair	Flight operational	Fair

(1) Doped with NaI.
(2) Easily stacked to give increase by a factor of 10 to 100.
(3) But 2600 h on smaller device.
(4) But 6500 h on multiple needle thruster.
(5) Components up to 5000 h.

ES: electrostatic
EM: electromagnetic
SS: steady state
SI: specific impulse
MESC: magneto-electrostatic containment
MDP: magnetoplasma-dynamic

The principles of operation of the colloid and field-emission thrusters have already been mentioned; both rely on electrostatic phenomena. The contact ionization device incorporates a heated porous tungsten emitter, through which gaseous caesium is passed. The caesium becomes ionized upon emerging from the tungsten emitter, and the ions are then accelerated by high voltages applied to a multi-element electrode system.

Many different types of pulsed plasma thruster have been studied, but most have not reached an advanced state of development. In these devices, the propellant is often vapourized from the solid or liquid storage phase by an auxiliary discharge, but gaseous propellants are frequently chosen, especially in larger, high thrust variants. A high voltage, high current discharge then ionizes the propellant, and the interaction between this current and a magnetic field expels the plasma at the desired velocity, giving a very large specific impulse. The magnetic field can be that induced by the discharge current itself, or it can be provided by some other means.

In the rail gun, the discharge occurs between a pair of rail electrodes, and the resulting plasma is accelerated along these rails until it emerges from the muzzle of the thruster. Power is provided from a high voltage capacitor, and frequent operation can give a quasi steady-state thrust.

The much larger and more powerful magnetoplasma-dynamic (MPD) arc thruster requires instantaneous power levels in the MW regime to achieve acceptable efficiencies. This device is coaxial or conical in form, with a stud-shaped or rod cathode and a tubular or ring anode. Gaseous propellants are usually employed, and thrust levels can be high, although there are very serious problems with limited lifetimes. Operation can be pulsed or in a quasi-d.c. mode.

Only the rail gun has been used operationally in space, but several ion thrusters of various types have been flown experimentally. These include the very successful SERT II thrusters, placed into orbit by NASA in 1970 and operated at intervals for the next 11 years. These two 15 cm diameter Kaufman thrusters were run for an aggregate time of over 6000 h, including a total of nearly 400 starts. The ion thrusters mounted on ATS-6 were not so successful, the use of caesium causing the electrical breakdown of high voltage insulators and leading to total system failure. More recently, there has been a flight test of a Japanese ion thruster, and several other similar experiments are planned. In addition, a great deal of ground testing has been carried out, particularly on Kaufman and RF thrusters, which has provided most of the information needed for spacecraft integration purposes and has given a high level of confidence of mission success, particularly for North-South station-keeping.

Early work in the United States of America [Free and Huson, 1972] suggested that the weight of a mercury ion thruster system would be equivalent to only 27% of the weight of a comparable hydrazine system for 7 years of North-South station-keeping. This study assumed thrust levels of the order of 5 mN, with the thrusters fired for many hours on a daily basis around the equatorial crossing nodes. To reduce both operating times and the number of starts, higher thrust levels are attractive, a possibility made more feasible by the advent of the lightweight nickel-hydrogen battery [Hyman and Dulgeroff, 1978].

Several mercury ion thruster systems are now available for the North-South station-keeping mission [Bassner and Klein, 1979; Fearn and Hughes, 1978; Murakami *et al.*, 1984; Power, 1984]. These are suitable for medium to large geostationary satellites (over 500 kg) having lifetimes of 7 to 10 years, provided that adequate electrical power can be made available. The low overall mass resulting from the use of such a system will increase considerably payload capability within a given mass budget, and thrust vectoring will also allow some attitude control functions to be undertaken. Very extensive ground testing suggests that there should be no spacecraft-thruster compatibility problems, and that proven thruster lifetime is fully adequate for these missions [Fearn, 1982].

3. Conclusion

The Radio Regulations (1982) require the following station-keeping accuracies for geostationary spacecraft.

"Satellites in the fixed-satellite service or broadcasting-satellite service shall maintain their positions within $\pm$ 0.1° of longitude, but experimental stations on geostationary satellites and space stations on geostationary satellites which do not use any frequency band allocated to the fixed-satellite service or the broadcasting-satellite service shall maintain their position within $\pm$ 0.5° longitude."

However, space stations need not comply with the above limitations as long as the satellite network to which the space station belongs does not cause unacceptable interference to any other satellite network which does comply with the above limitations.

Several operational satellites have demonstrated for extended periods of time the capability to maintain orbit location within the limits of ± 0.1°. For satellites having narrow antenna beamwidths, precise station-keeping could reduce the spacing between adjacent satellites servicing different, non-contiguous service areas.

Conventional hydrazine thrusters have proven high reliability and performance characteristics for long lifetime (7 years) operations. However, a hydrazine system comprises about 20% of total spacecraft weight. Advanced technologies, using propellants of a higher specific impulse, may offer weight savings. Electric engines, already used in space, offer a substantial weight saving, and it is expected that their use will increase in the future.

These weight savings are achieved at the expense of added complexity, which may affect reliability and lifetime. Consequently, the value of such weight saving technology, after the advent of the Space Transportation System (Shuttle-tug), will require further study.

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REPORT 675*

RADIATION DIAGRAMS OF ANTENNAE AT SPACE RESEARCH EARTH STATIONS FOR USE IN INTERFERENCE STUDIES

(Question 15/2; Study Programme 15A/2)

(1978)

1. Introduction

Interference coordination procedures between systems operating in the same or adjacent frequency bands depends on knowledge of specific operational characteristics of the systems involved. Most of the required information for the formulation of sharing criteria is available. In a great majority of cases, however, there is a lack of information as to the specific levels of antenna side lobe response in the far field. Since the antenna gain of an interfered-with or interfering source in the direction of the unwanted signal is of prime importance in determining the levels of interference, there exists a need for a generalized earth station antenna pattern which could be used in situations where adequate measured data do not exist.

2. Representation of measured data by a reference radiation diagram

Values of side lobe radiation from a number of earth station antennae in the Fixed Satellite Service are plotted in Fig. 1 of Report 391. These data may be represented for antennae of diameter greater than 100 wavelengths and in the frequency range 2 GHz to 10 GHz by:

$$G \text{ (gain relative to isotropic antenna)} = 32 - 25 \log \varphi \qquad \text{dB}$$

where

φ is the angle in degrees between the main beam axis and the direction in question and is limited to $\varphi \geqslant 1°$. The equation is valid for $G \geqslant -10$ dBi. At larger angles G is constant at -10 dBi.

However, it should be noted that the pattern in Fig. 1 may not apply to a prime-focus (focal-feed) antenna system.

Measurements of patterns of earth station antennae used in the Space Research Service have been made using collimation towers and in one case (64 m antenna), using a Surveyor spacecraft transmitting from the Moon [Levy *et al.*, 1967]. The difference between these measured data and the accepted reference radiation diagram for the Fixed Satellite Service is small. In most cases the space research antenna side lobe levels are lower. This is to be expected since there has been an emphasis on minimizing antenna temperature in the design of the large antennae used in space research.

A more recent set of measurements at 11.5 and 34.5 GHz obtained with a 10 m Cassegrain antenna used in the Japanese space programme is shown in Fig. 1, in comparison with the reference radiation pattern. Further details are given in [CCIR, 1974-78]. Statistical distributions of the side lobe peaks show that only 10 percent lie above the values given in Fig. 1.

3. Conclusions

The reference radiation diagram employed in the Fixed Satellite Service (see Recommendation 465) is representative of the side lobe patterns of a number of earth station antennae used in the space research service. It is therefore considered that in situations which require interference calculations, and for which actual antenna patterns for earth stations do not exist, the reference radiation diagram of G (dBi) $= 32 - 25 \log \varphi$ may be used as a representation of the peak envelope of the side lobes of these antennae. Administrations are invited to submit measured antenna radiation patterns concerning various types of antenna systems which may be used to add to the statistical data of Fig. 1.

* This Report is brought to the attention of Study Groups 1, 4, 8, 10 and 11.

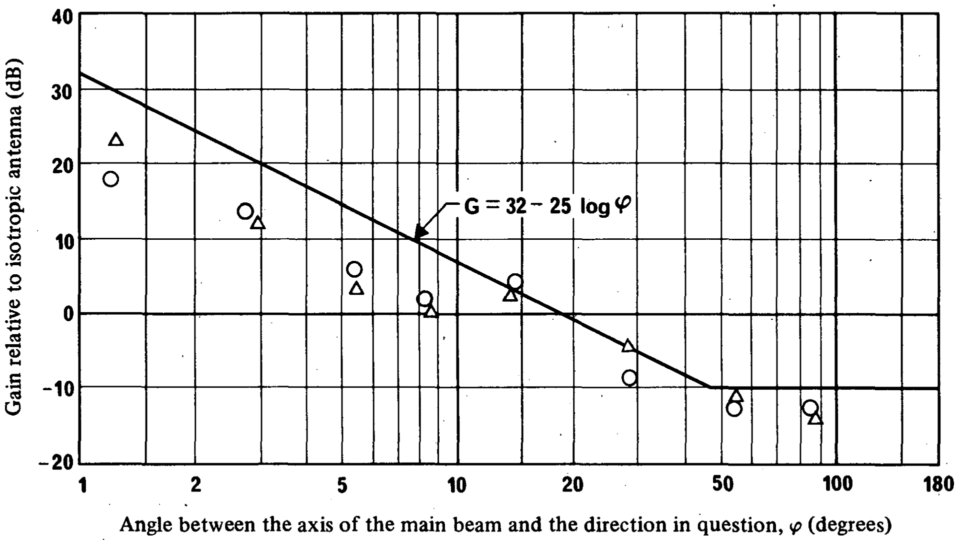

FIGURE 1 – *Statistical data from earth-station antenna diagrams*

(Levels exceeded by 10% of the side-lobe peaks)

Δ : 11.5 GHz, $D/\lambda \approx 380$

O : 34.5 GHz, $D/\lambda \approx 1150$

Antenna type: Cassegrain; polarization, right-hand circular

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CCIR Documents

[1974-78]: 2/210 (Japan).

RECOMMENDATION 509

GENERALIZED SPACE RESEARCH EARTH STATION ANTENNA RADIATION PATTERN FOR USE IN INTERFERENCE CALCULATIONS, INCLUDING COORDINATION PROCEDURES

(Question 15/2 and Study Programme 15A/2)

(1978)

The CCIR,

CONSIDERING

(a) that the application of coordination procedures between space research earth stations and stations of other services is dependent upon specific antenna radiation patterns;

(b) that where this information does not exist, it may be desirable to use a reference antenna radiation diagram which closely represents the majority of antennae used in the service;

(c) that measured data from some large ($D/\lambda \geqslant 100$) parabolic Cassegrainian antennae used in the Space Research Service indicate an off-axis discrimination that is as good as, or better than, that of antennae in the Fixed Satellite Service (see Report 675),

UNANIMOUSLY RECOMMENDS

1. that in the absence of measured data on the levels of side-lobe response of a space research earth-station antenna which is subject to interference coordination procedures, a reference radiation pattern recommended for use in the Fixed Satellite Service (Fig. 1, reproduced below, from Recommendation 465) be used to represent provisionally the space research earth station side-lobe response;

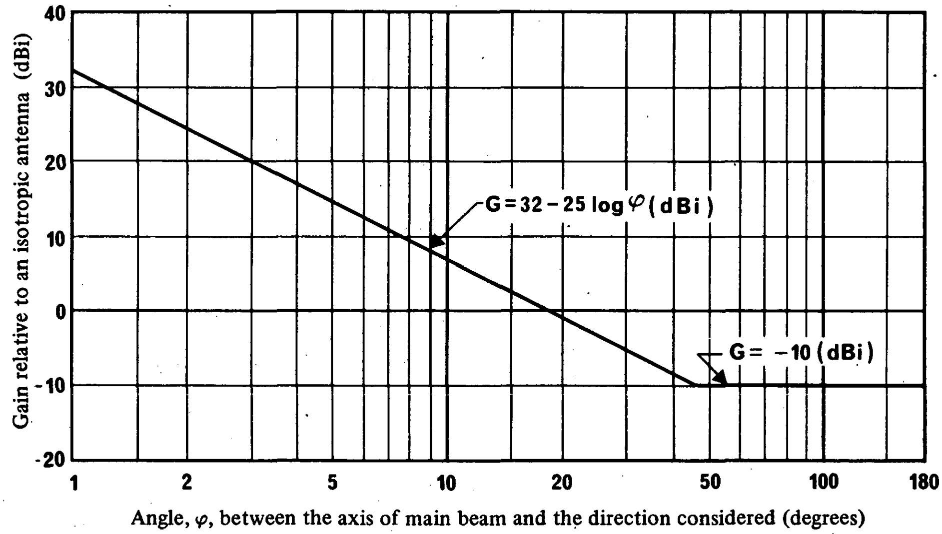

FIGURE 1 – *Provisional reference radiation diagram*

2. that this reference radiation pattern be used only for antennae the diameters of which are greater than 100 wavelengths, for angles greater than 1° from the main beam axis and for frequencies between 2 GHz and 10 GHz;

3. that administrations be invited to submit measured antenna radiation patterns which may be used to improve the accuracy of the provisional reference radiation diagram in Fig. 1.

REPORT 676*

SHAPED BEAM ANTENNAS

(Question 15/2, Study Programme 15A/2)

(1978)

1. Introduction

The increasing tempo of satellite applications to telecommunication requirements, and the necessity for frequency sharing between space services and terrestrial services, is causing more emphasis to be placed on factors which enhance orbit/spectrum utilization, and sharing. One of the most important factors is the directivity of both spacecraft and earth station antennae.

One aspect of this matter which has already received considerable attention is the technology for minimizing the side lobe response of antennas.

Another factor which is not so well defined is the generation of asymmetrically shaped beams for spacecraft antennas. Asymmetrically shaped beams are designed to optimize coverage of particular geographical areas while minimizing power flux-density in adjacent areas. This coverage can be obtained by the use of a single shaped beam or by combining multiple beams to obtain the desired pattern.

* This Report is brought to the attention of Study Groups 4, 10 and 11.

2. Beam shaping techniques

The following sections discuss beam shaping techniques as applied to reflector, lens and array antennas. Recent advances in mathematical synthesis procedures are also described.

2.1 *Reflectors*

The parabolic antenna is the most widely used for beam shaping. A combination of two techniques is usually involved, the shaping of the illumination pattern of the parabolic reflectors, and the shaping of the parabolic reflectors themselves.

The first technique, illumination tapering, is a process by which the amplitude and phase of the illumination across the aperture is varied in order to match the pattern required. Due to the fact that curvature of the phase front reduces the total effective aperture available thus leading to a reduction of contribution in the direction of maximum gain, tapering can be accomplished only at the expense of a broadening of the main lobe, and so reducing the directivity of the antenna [Radio Spectrum Utilization, 1965; Silver, 1949].

Practical means by which illumination tapering can be achieved include the use of single feeds designed with limited beam patterns to produce under illumination, offsetting of feeds from focus, and the employment of array type feed structures.

The second technique used in the control of side lobes and the shaping of the beam involves a direct modification of the reflector, and is usually supplementary to the tapering of the illumination. Reflector modifications for symmetrically shaped beams can include squaring the edges of the antenna for a square-ended sector beam, cutting the paraboloid so that the centre is elevated relative to the periphery for a normal sector shaped beam; flaring the edge of the reflector for a flared beam and so on. Modified reflector designs have also been used successfully to obtain asymmetrically shaped beams. These are usually accomplished by the use of an extended feed in conjunction with reflector modifications [Silver, 1949].

A basic problem common to reflector systems is aperture blockage. Many designs and techniques have been evolved with regard to this problem. One particularly satisfactory technique is to offset the feed. This technique is increasingly effective with increasing offset and there is a consequent decrease of directly reflected energy into the feed. However, where the asymmetry of the offset configuration creates unacceptable electrical performance or problems of a mechanical nature in some applications, the use of a Cassegrain antenna is preferred. In Cassegrain antennas the feed is located behind the main paraboloid reflector, and radiates the energy through a small aperture in the main reflector, to a secondary sub-reflector which reflects the energy to the main reflector from which the final collimated beam is radiated. Other techniques include active compensation for the blockage by use of a single radiator at the feed, as discussed in Report 558, and zone suppression techniques which can involve either stepping of the reflector or the installation of a ring of radiating elements around the periphery.

Several antennas utilizing a combination of shaped reflector structure and tapered illumination have been built or are currently under development. These include the Japanese Experimental Broadcast Satellite (BSE) described in Report 810. The pattern produced by the antenna is designed to cover the Japanese home islands with side lobe coverage of the Bonin and Volcano Islands. Another example of a shaped coverage parabolic reflector antenna, operating at present, is the Atlantic coverage INTELSAT-IV A, as described in Report 558.

2.2 *Lenses*

Lenses, like reflectors, enable a satellite to serve a number of separate regions on the Earth simultaneously through a single antenna aperture and a common band of radio frequencies. Desirable properties of lenses for production of shaped beams include the ease of shaping the lens surfaces and the ability to maintain precise surface tolerances [Collins and Zucker, 1969]. Certain techniques such as zoning of the lens elements contribute to reduction in chromatic aberration and therefore side lobe levels as described in Report 810. At present, lenses are a promising alternative for providing multibeams [Ricardi, 1977]. They have an advantage over reflectors as the feed is located behind the aperture, thus eliminating aperture blockage. One multibeam lens is being constructed [Elson, 1975] with potential applications to an INTELSAT 6 class of satellites, for use primarily in the 11 and 14 GHz bands. The lens is capable of generating a large number of pencil beams simultaneously which can be combined to produce larger shaped beams. This particular design takes advantage of dual polarization (right and left circular) and spatial separation techniques for frequency re-use and isolated shaped coverage. Side lobes from a 5 feet (1.53 m) test lens are at least 30 dB below on-axis peaks scanned across an 18° field of view (Earth coverage).

2.3 *Arrays*

Satellite borne multi-element arrays have been determined in many studies to be well suited for multiple beam and shaped beam operations. This is discussed in further detail in Report 810. There are limitations to the use of arrays based on weight, but their performance with respect to weight and cost, improves considerably at higher frequencies.

Side lobe control for array antennas can consist of null-placing techniques in which the directly radiating elements of the array are properly excited to form a multiple beam system, with beam peaks and nulls in specified angular positions. This technique is applicable to spacecraft antennas operating in higher frequency bands where the size and mass of the array is reduced to reasonable values [Atia and DiFonzo, 1975].

Recent developments [Phelan, 1976] such as "Spiraphase" are leading to lower cost, lower loss, and lighter weight phased arrays. "Spiraphase" involves a different technique for obtaining phase shift control in an array aperture. It is based on the fact that as a circularly polarized antenna is rotated, the phase shift of the radiated field from the antenna changes proportionally to the rotation of the antenna. Utilizing a completely symmetrical radiation pattern, the phase shift of the "Spiraphase" is frequency independent and limited in bandwidth only by the bandwidth of the antenna used. To obtain the phase shift, it would be necessary to rotate the circularly polarized antenna mechanically. This method would not apply to linear polarization.

3. Synthesis procedures

The far-field pattern of an aperture source can be computed from a knowledge of the Fourier components of the illumination function over the plane subtended by the aperture [Jasik, 1961]. For simple geometric shapes, determination of the aperture distribution for a given pattern is relatively simple. One of the more familiar of the earlier analytical developments is the Taylor aperture distribution [Taylor, 1955] which is designed to produce a minimum antenna beamwidth, together with a specified side lobe level, out to a point beyond which the side lobe amplitude level decreases.

For complex patterns, however, the mathematical relationships involved become difficult, and computerized numerical methods are needed to solve the requisite integrations. In recent years, considerable effort has been devoted to the exploration of various analytical techniques based on physical optics, diffraction theory, etc., with a view to developing a general procedure for the synthesis of shaped beam antenna designs with a minimum of computational complexity.

Parallel with the theoretical effort, prototype antenna designs based on synthesis techniques have been constructed and tested. Of particular importance are studies leading to the development of antennas having multiple beams, each having irregular beam shape and sharp skirts, in order to permit frequency re-use with a minimum of interference.

Several recent studies [Erickson, 1972; Byrnes, 1972] have led to the development of multiple shaped beam antennas designed to cover the United States on a time-zone basis. A summary of recent progress in this area is given in Annex I to this Report.

4. Conclusions

It is possible to develop shaped beams by the use of reflector, lens and array type antennas. Each of the three antenna types offer particular advantages for certain applications. Recent advances in synthesis techniques are useful for analytic design of shaped beam antennas.

Many applications require highly irregular beam shapes which are beyond what can be achieved by using passive reflectors and multiple feeds. More complex structures using a combination of several techniques to provide the desired amplitude and phase distribution across an aperture are needed. Optimization studies concerned with efficiency, cost, performance and weight of such antenna designs should be performed.

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ANNEX I

CONTOUR PATTERN SHAPING

1. Introduction

The purpose of this Annex is to describe a computerized method of antenna beam synthesis that permits the design of contoured-beam antennas to meet specified far-field pattern characteristics such as pattern contour, null positions, and side lobe level.

Contour-beam antennas are important for various applications such as the broadcasting and fixed-satellite services. Additionally, properly designed contoured beam antennas may be important in other applications, such as:

– high beam efficiency (low sidelobe) antennas for radiometric land/sea observations,
– shaped beam antennas for reducing pointing loss of spacecraft antennas,
– fixed beamwidth (within a reasonable bandwidth) antennas for radio frequency interference (RFI) detection.

2. General

The design of a contoured beam antenna to meet prescribed far-field pattern characteristics is a very complex problem, particularly if the required geographical coverage is irregular in shape. Careful consideration must be given to uniformity of power level and polarization (for dual polarized antenna systems) within the area of coverage, spillover radiation into other areas, and sidelobe response. In terms of far-field pattern characteristics, the following parameters are therefore of major importance in a contoured beam synthesis problem:

– pattern contour (to match the geographical boundary),
– pattern ripple (within the coverage area),
– rate of drop or slope (at the boundary of the coverage area),
– sidelobe level,
– polarizations of dual patterns are approximately orthogonal over contour.

The design method, upon which this Annex is based, takes these factors into account. These techniques have been the subject of continuing study in the United States for several years.

2.1 *The Spherical Wave Expansion method*

The Spherical Wave Expansion (SWE) method is an earlier synthesis procedure. It consists of the following basic steps:

2.1.1 Obtain a realistic contoured antenna pattern to meet the prescribed requirements.

2.1.2 Expand the pattern into spherical waves.

2.1.3 Perform physical optics scattering calculations of the spherical waves to determine the far-field pattern of the antenna feed necessary to produce the contoured antenna pattern of § 2.1.1.

2.1.4 Determine the aperture illumination of a physically realizable feed array that will approximate the feed far-field pattern as determined in § 2.1.3.

The SWE method has the ability of determining the aperture illumination of the feed array for any prescribed contoured antenna pattern. This enables a designer to synthesize a universal antenna (within a reasonable frequency band) for any chosen far-field characteristics. However, the SWE method requires a large amount of computer time for calculations involving symmetrical and particularly non-symmetrical antenna systems such as offset paraboloids. The SWE method is not new [Erickson, 1972; Byrnes, 1972].

2.2 *More recent advances*

More recent approaches during the past two years include the following major advances:

2.2.1 A rapid integration technique for calculating the secondary spot beams is used to reduce computer time.

2.2.2 The far-field phase and amplitude distributions of spot beams are optimized for best fit to the prescribed pattern contour under the prescribed constraints on side lobe level, rate of drop, and pattern ripple.

2.2.3 A new overall synthesis procedure is used to determine the minimum reflector size and minimum number of feed elements needed, leading to a minimum cost antenna design.

2.2.4 The technique has been extended to include offset parabolic and shaped reflectors [Galindo-Israel and Mittra, 1977].

2.2.5 Further synthesis design techniques for circularly symmetric and offset geometries have been developed and are considered as major break-throughs in reflector synthesis [Galindo-Israel *et al.*, 1977].

2.2.6 Further optimization of the synthesis methods to include diffraction synthesis have been made [Lee *et al.*, 1977].

The method in § 2.2.5 above, does provide a new method for synthesizing fixed contour patterns from simple feeds. However, work is continuing in the study of the application of shaped reflectors and dual polarization in the synthesis procedure.

When fully developed, it is anticipated that the optimization methods will provide:

- best fit for prescribed requirements,
- rapid computing time,
- physically realizable feed,
- minimum cost antenna design.

3. Antenna beam design example

In order to show the usefulness of the method, this Annex concentrates on several possible antenna beam designs capable of providing coverage to the Eastern Time Zone (ETZ) of the United States (Fig. 1) from a space station located at 112° W longitude. The following examples are concerned with the design of the feed structure parameters of a parabolic antenna which is intended to provide coverage to the ETZ with a minimum of spillover into adjacent geographical areas. The feed structures consist of feed antenna arrays each element of which emits a cosine illumination pattern. The optimized beam is generated by controlling the phase and amplitude of each feed antenna.

Figure 2 shows the resulting far-field pattern which can be obtained by using a 7 × 9 feed element array structure, overlaid on the ETZ as it would appear in the space station antenna co-ordinates. The agreement between the ETZ and the antenna pattern is quite good. The array element spacing for this example is 0.71 wavelengths (λ) along the 9-element side and 0.91λ along the 7-element side; and the array has been rotated about its boresight axis by 26° so that it lines up to advantage for generating the feed pattern. A very encouraging result is the retention of the extremely low side lobe level. Note that a −20 dB level is obtained about the ETZ contour and beyond this region, all side lobes are kept below −30 dB.

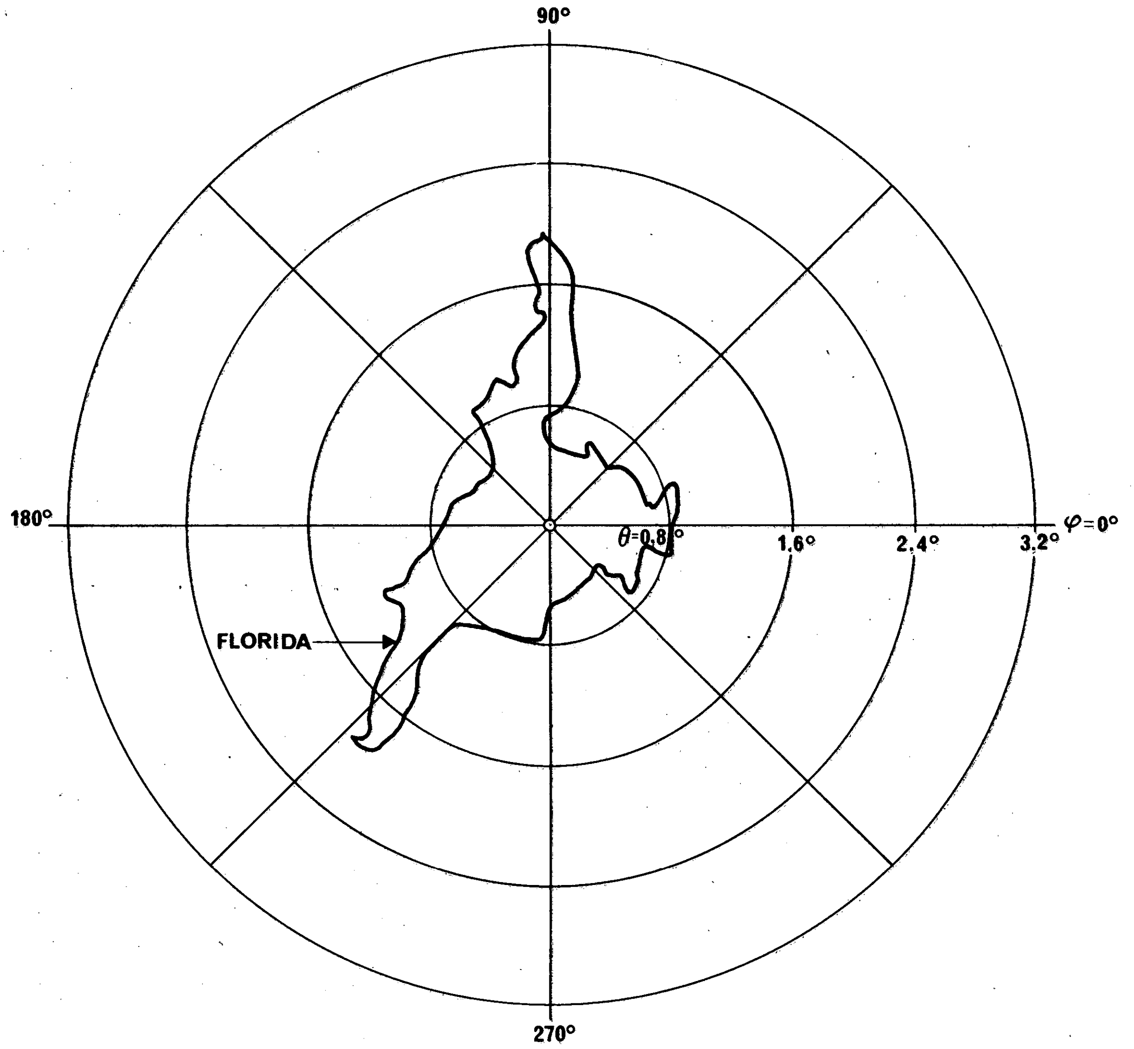

FIGURE 1 – *Eastern Time Zone (ETZ) of USA in Antenna Co-ordinates*

Boresight, 79°W long., 39°N lat.
Satellite location, 112°W long. Geostationary

Figure 3 presents the far-field solution for a 12 × 12 element array.

When compared to Fig. 2, the following characteristics are noted:

- additional ripple occurs within the contour region, probably about an extra 1 dB, from ± 0.75 dB to ± 1.25 dB of ripple;
- the region of coverage is somewhat reduced. The region formerly included above the −1 dB level is only above the −3 dB level;
- the side-lobe level remains very low, more than 30 dB below peak with few exceptions.

4. Discussion

The study of methods for synthesizing contour patterns is continuing. The results to date are very encouraging and they should promote continued interest in pursuing these design techniques to a logical conclusion.

The new approaches, besides using much faster computer techniques, do optimize the desired pattern to obtain pattern "fit" in the secondary pattern region.

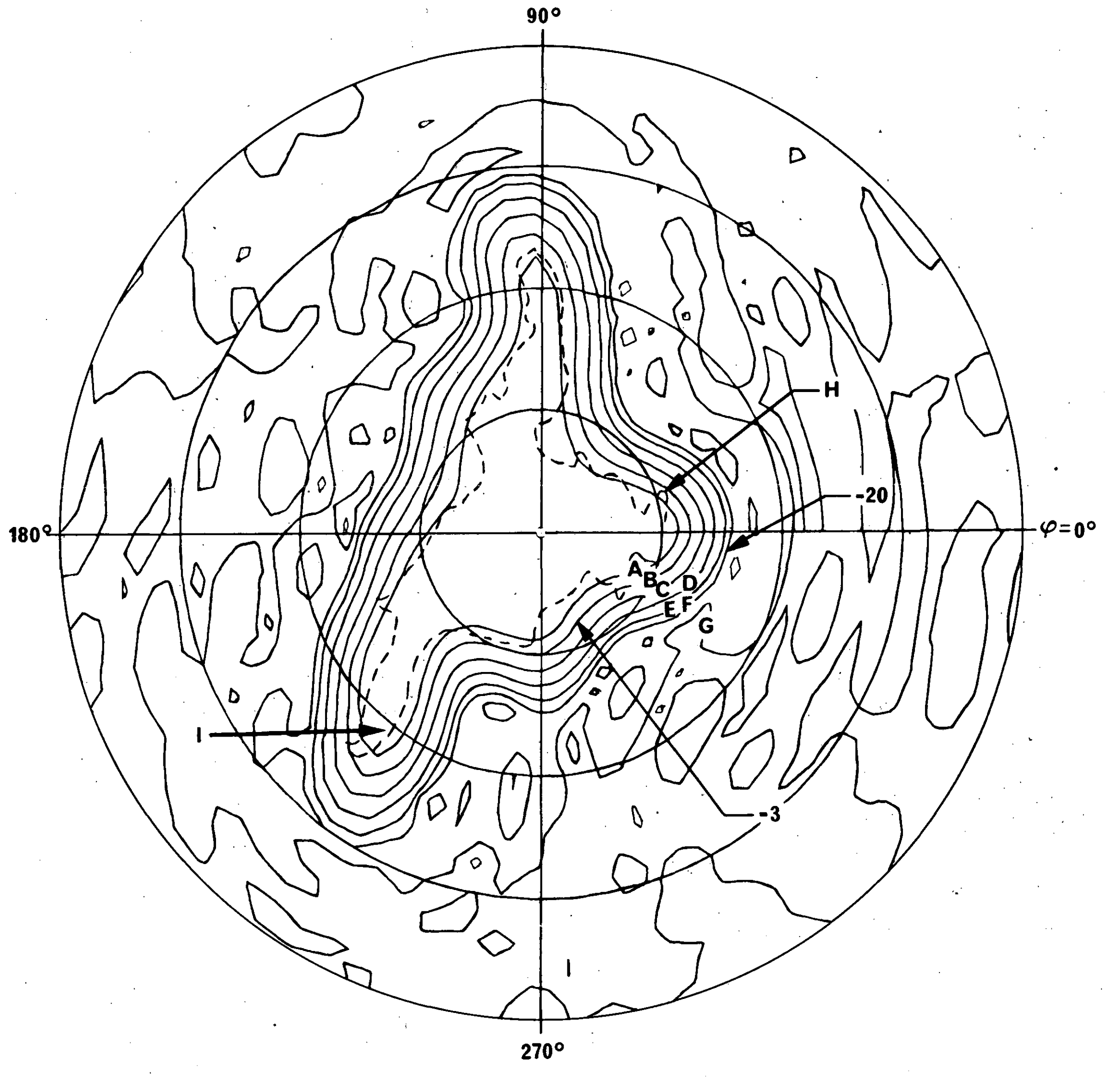

FIGURE 2 – *Far-field antenna pattern utilizing a 7 × 9 element feed structure*

A	: – 1 dB	F	: –20 dB
B	: – 3 dB	G	: –30 dB
C	: – 6 dB	H	: State of Maine
D	: –10 dB	I	: State of Florida
E	: –15 dB	– – – – –	: Eastern time zone of USA

5. Conclusions

It has been shown that an accurate determination of an antenna reflector and feed system is possible for complex contour beams. The optimization techniques will give any degree of accuracy desired depending only upon allowable reflector size. The success of the work to date indicates that indeed an array fed reflector can be designed and that by commanding particular array distributions, it will generate contour beams of any desired shape.

A major difference becomes apparent when the region to be contoured represents many beamwidths for the chosen antenna size, i.e., the larger and higher-gain antennas. The design methods will permit sharper skirts on the side of the beam so that low radiation levels are reached nearer the contour edge. This is extremely important when the purpose of contouring is to permit the sharing of frequencies.

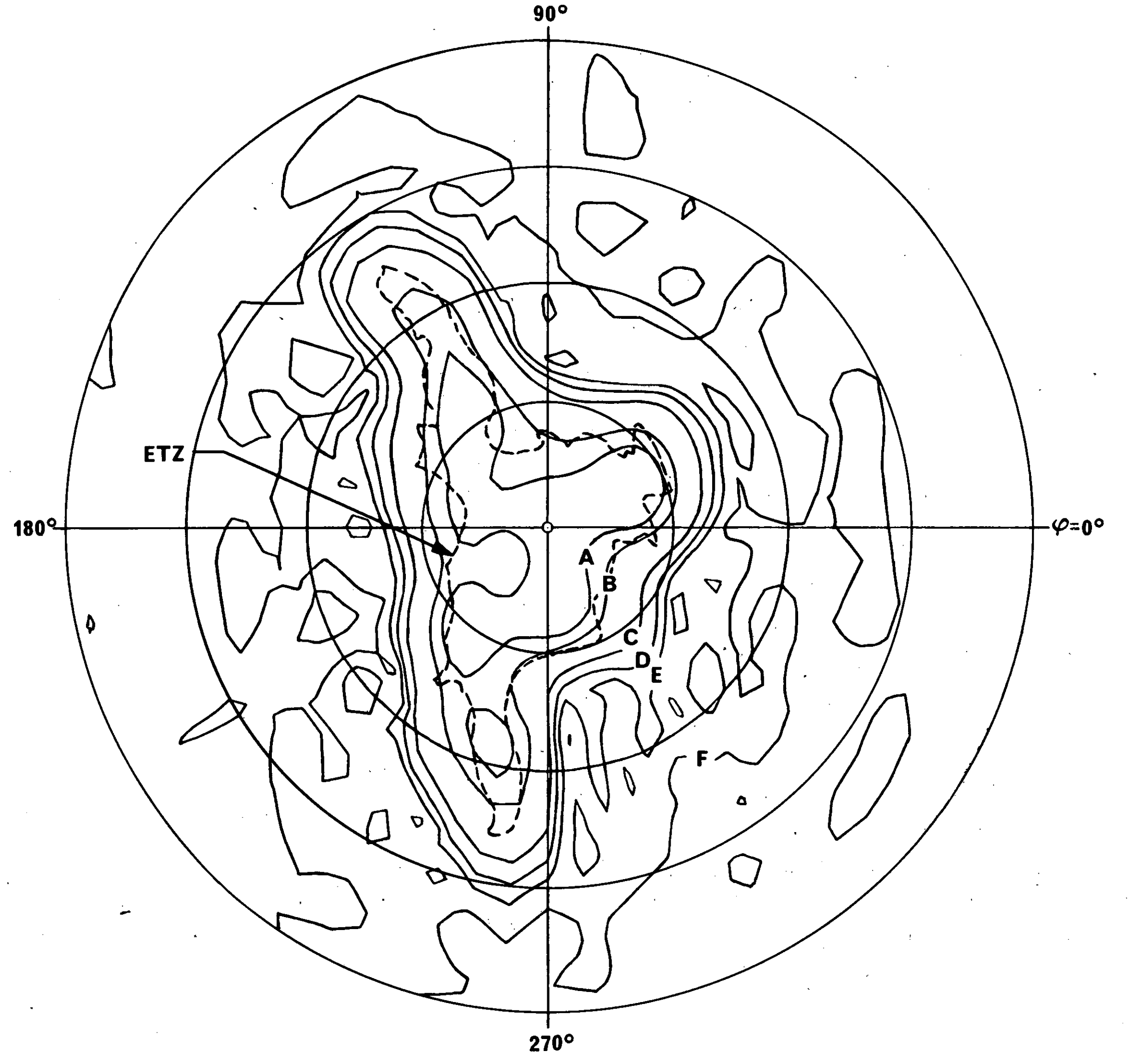

FIGURE 3 – *ETZ, using feed pattern of 12 × 12 array*

A : – 1 dB	D : –15 dB
B : – 3 dB	E : –20 dB
C : –10 dB	F : –30 dB

Note. – The apparent rotation of this figure when compared to Figs. 1 and 2, is only due to the use of a rotated coordinate system for convenience in the computer generation of the antenna pattern.

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REPORT 677-1

LOW SIDE-LOBE ANTENNAS FOR SPACE RESEARCH EARTH STATIONS

(Question 15/2; Study Programme 15A/2)

(1978-1982)

1. Introduction

This Report describes the performance characteristics of offset reflector antennas with very low side lobes, which may be suitable for space research earth station antennas.

2. Causes of side lobes and their reduction

The causes of side lobes of reflector antennas are mainly:
- spill-over power from the sub-reflector and the main reflector;
- blockage by the sub-reflector and supports;
- diffracted power from the main reflector edge depending on the field distribution;
- scattered power from the sub-reflector edge and its supports;
- profile errors in the reflector surfaces.

Various techniques have been developed to reduce side lobes. Side-lobe levels due to edge diffraction of the main reflector can be reduced by increasing the taper of the feed pattern across the aperture of the reflector, involving a penalty of reduced gain. The use of an offset reflector configuration is very effective, because it is free from aperture blockage and scattered power due to the sub-reflector edge and supports. In addition to this, microwave absorbers attached around the outer edges of reflectors and primary radiator suppress side lobes to extremely low levels.

3. Side-lobe characteristics of offset reflector antennas

Offset reflector antennas may be classified as:
- offset single reflector antennas such as the offset paraboloidal antenna and the horn reflector antenna; and
- offset multiple reflector antennas such as the offset Cassegrain antenna and the offset Gregorian antenna.

These configurations are shown in Fig. 1.

Side-lobe levels of the horn reflector antenna are lower than those of the offset paraboloidal antenna because of the shielding structure of the feed horn. However, the horn reflector antenna has disadvantages in size and weight compared to the offset paraboloidal antenna. The offset paraboloidal antenna has side lobes due to spill-over in the side and backward regions. Side lobes of offset multiple reflector antenna can be reduced by controlling the aperture distribution over the main reflector, since these antennas have high freedom in choosing the antenna parameters. In order to achieve an optimum amplitude and phase distribution of the aperture of the main reflector, the sub-reflector and main reflector surfaces can be modified.

Figure 2 shows an offset Cassegrain antenna fed by three beam-waveguide reflectors which works with Japan's CS (medium-capacity communications satellite for experimental purpose) [Ogawa *et al.*, 1978]. In this antenna, the wind load on the antenna base is reduced by the use of a flat and nearly horizontal main reflector. The antenna can be constructed on top of a building. It also offers an adjustable elevation angle capability. The antenna can be applied to earth stations not only for geostationary satellites but also for various space research satellites. Figure 3 shows the measured side-lobe characteristics (peak value) of an offset Gregorian antenna [Mizugutch *et al.*, 1976], the offset Cassegrain antenna and a symmetrical Cassegrain antenna compared with the reference radiation diagram (Recommendation 509). The side-lobe levels of the offset reflector antennas are much lower than those of the conventional Cassegrain antenna.

4. Side-lobe reduction by microwave absorbers and effect on antenna noise temperature

Though offset Gregorian antennas have very low side lobes as explained above, much lower side lobes may be required in an interference-sensitive space research system. It is very effective to attach microwave absorbers around the outer edge of reflectors for suppressing the spill-over rays. Figure 4 shows an antenna with microwave absorbers attached. Figure 5 shows the comparison of the measured side-lobe patterns with and without microwave absorbers. The measured efficiency of this antenna was about 70%.

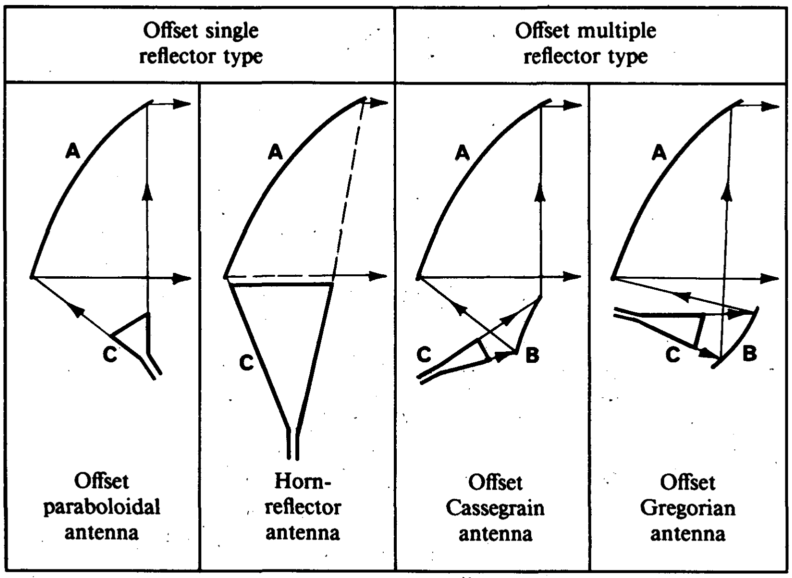

FIGURE 1 — *Various offset reflector antennas*

A: main reflector
B: sub-reflector
C: primary horn

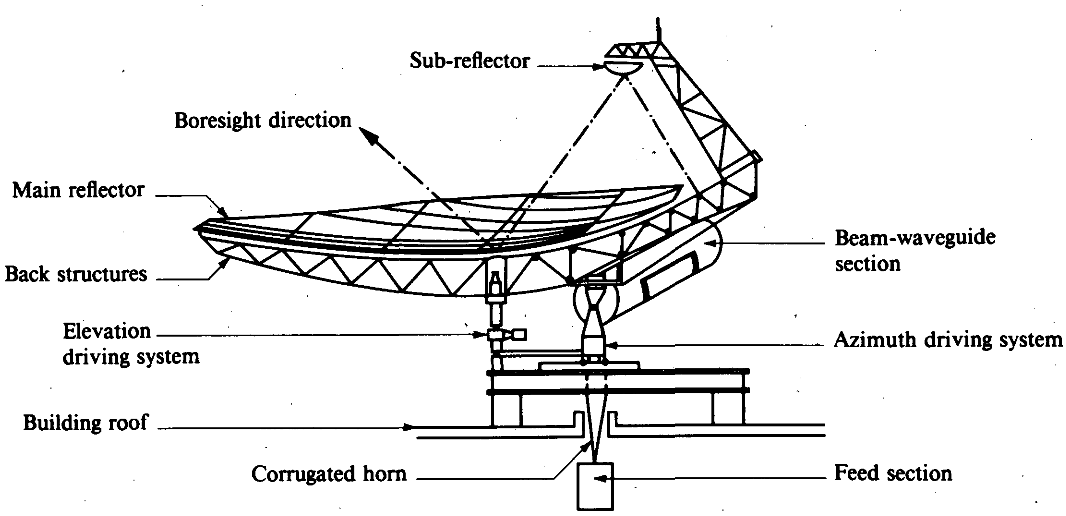

FIGURE 2 — *Detailed antenna configuration*

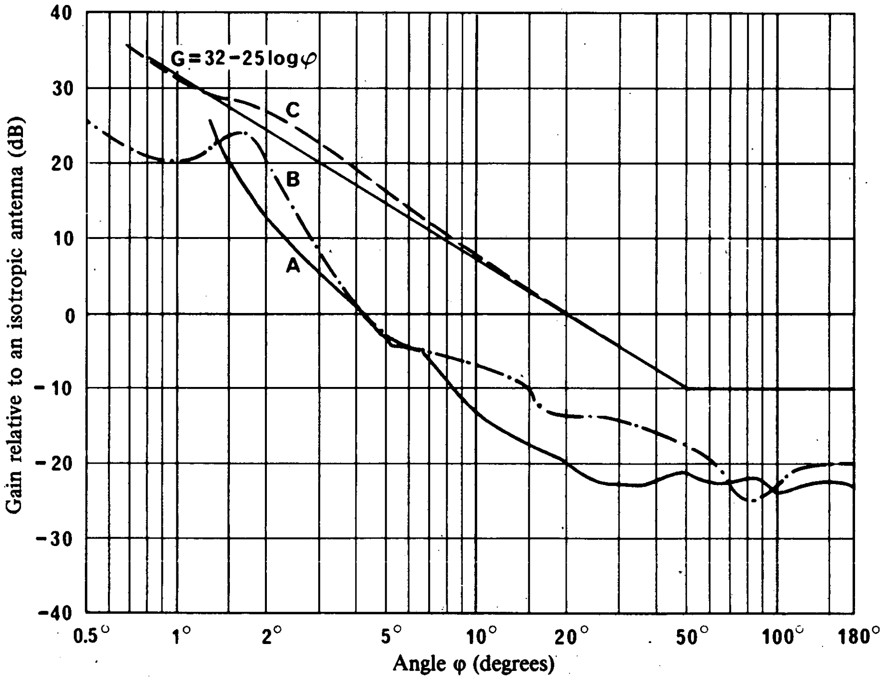

FIGURE 3 — *Measured side-lobe patterns (peak value)*

A: offset Gregorian antenna (D/λ = 66, 25 GHz, D = 0.8 m)
B: offset Cassegrain antenna (D/λ = 750, 19.5 GHz, D = 11.5 m)
C: symmetrical Cassegrain antenna (D/λ = 600)

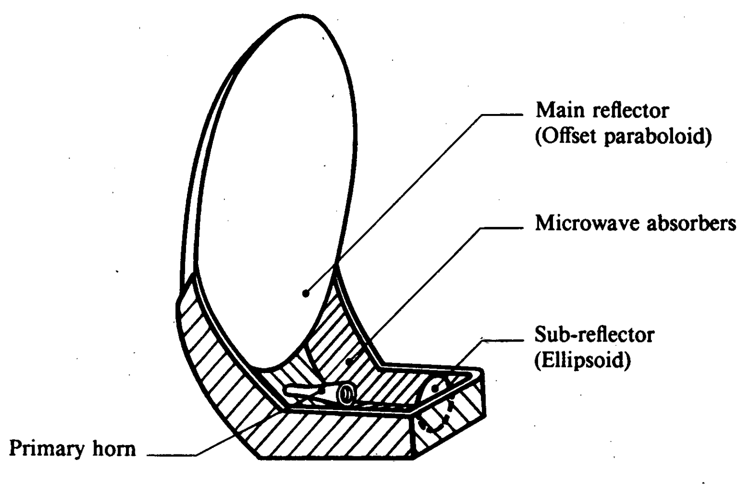

FIGURE 4 — *Offset Gregorian antenna with microwave absorbers*

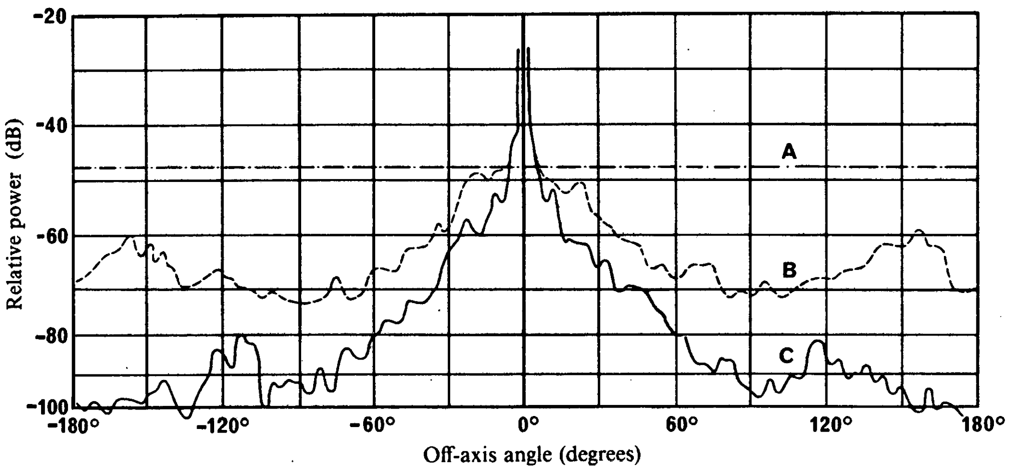

FIGURE 5 — *Measured side-lobe patterns of offset Gregorian antenna with and without microwave absorbers*

A: isotropic level
B: without microwave absorbers
C: with microwave absorbers
D/λ = 91
D = 0.8 m
f = 34 GHz

As shown in the figure, the high side lobes at about 20° and 150° caused by the spill-over rays around the sub and main reflectors respectively, are greatly reduced by attaching the absorbers. The resultant wide-angle side lobes are as low as −30 to −35 dBi.

Almost no effect is anticipated in the on-axis gain due to the microwave absorbers, since these are attached to the area where illumination level is very low.

The antenna noise temperature increase ΔT due to the microwave absorbers is considered to give its maximum at the zenith. The value ΔT can be given by:

$$\Delta T = T'_A - T_A \approx \Sigma_j(\gamma_a - \gamma'_a)T_0 \tag{1}$$

where,

T'_A, T_A : antenna noise temperature with or without microwave absorbers,

γ'_a, γ_a : antenna beam efficiency with or without microwave absorbers in the j-th region,

T_0: temperature of microwave absorbers ($\approx$290 K).

The noise temperature increase ΔT is evaluated to be 4.4 K by using the equation above.

Measurements of antenna noise temperature at 11.7 GHz were carried out under clear sky conditions by use of 3.3 m offset Gregorian antenna with microwave absorbers. Introduction of the microwave absorbers generates an overall noise temperature increase of about 5 K. This result agrees with the estimation and is equivalent to a loss of about 0.07 dB at room temperature.

5. Conclusion

This Report shows the measured radiation patterns of typical offset reflector antennas as possible candidates for space research earth station antennas. It has been shown that the offset antenna configuration is very effective for reducing the side-lobe levels, since it has no obstacle in the aperture plane. It is also important to use a low side-lobe horn antenna as the primary radiator to suppress the spill-over rays.

The side-lobes are further reduced by attaching microwave absorbers around the primary feed system including the sub-reflector, and also around the outer edge of main reflector. The antenna noise temperature increase due to the microwave absorbers was estimated and found to be fairly small.

Such techniques as described in this Report can reduce the wide-angle side lobes by as much as 15 dB, and the back lobes behind the reflector could diminish to -30 dB relative to the isotropic level. It may be worthwhile to pay attention to such techniques for reducing interference in the space research service.

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REPORT 543-1 *

SAFETY ASPECTS OF RADIO-FREQUENCY RADIATION FROM SPACE RESEARCH EARTH STATIONS

Comparison between predicted and measured field strengths at 2 GHz

(Study Programme 15B/2)

(1974-1986)

1. Introduction

This Report provides a summary of a study in which calculated and measured power flux-densities in the vicinity of a large (64 m) diameter reflector were analyzed and compared. It is an abbreviated version of the previous Report 543 published in Volume II, Geneva, 1982. Reference should be made to that Report for the full details of the studies made, and of the system characteristics. Power flux-densities greater than 10 mW/cm^2 were examined in the greatest detail since they may be considered as being potentially dangerous to human beings exposed to the radiation [USA Standard, 1986]. Intermediate densities, from 1 to 10 mW/cm^2, were covered in lesser detail, since this category is considered safe for occasional exposure. Densities less than 1 mW/cm^2 were examined, although radiation in this category is considered safe for indefinite exposure. The origin of the material discussed here is a report published in the United States of America [Bathker, 1971].

High power radio-frequency radiation constitutes a biological hazard and also a hazard to volatile fuels and electro-explosive devices. This Report is concerned primarily with the levels of radiation which are considered biologically hazardous; applicability to fuels and electro-explosive devices is not discussed. Radio-frequency radiation effects in these areas are discussed elsewhere [Constant and Martin, 1963; IME, 1968, Wood, 1969].

The system discussed is the United States NASA, 64 m diameter, Cassegrain-fed, parabolic reflector antenna at Goldstone, California, operating at 2.12 GHz with 400 kW CW transmitter power input to the antenna. This system is a very carefully optimized transmit/receive arrangement wherein high beam efficiency (percentage of total radiated power delivered to the main beam) and low spillover and scatter (the percentage of the total energy that is wasted in the form of stray radiation) were sought after in design and achieved. This point is important; a poor selection of a feed system could invalidate the results of this study.

* This Report is brought to the attention of Study Group 1 with respect to Question 52/1.

2. Comparison, predicted and measured power densities

A number of radiation surveys have been made in the station area around the 64 m Goldstone reflector. Radiation surveys are typically taken with probes having a rather large (500 cm^2) effective area and using a radio frequency thermal detector with a usable sensitivity in the 10^{-2} mW class. Such an arrangement responds to the average power flux-density over a few square wavelengths or several spot maxima and minima, if any exist. The minimum detectable average power density is 10^{-5} mW/cm^2, and larger fields are accurately managed by use of attenuators. Experience has shown one characteristic of the stray radiation is strong elliptical polarization, i.e., the polarization tends towards linear for each sample.

Selected results from the various surveys are given in Table I (the entries in Table I indicating the points at which measurements were made; see Fig. 1). The primary purpose of Table I is to show the measured high fields on the 64 m aperture, and in the tubular beam. The moderate fields expected on the ground in front of the reflector at 6° elevation are also shown. The back radiation is seen to be very small.

TABLE I – *Selected power flux-densities, 64 m/400 kW Goldstone system (see Fig. 1)*

Measurement point	Power flux-density		Remarks
	Measured values (mW/cm²)	Calculated values (mW/cm²)	
On 64 m reflector	43·5	29·5	Radius: 5 m
On 64 m reflector	22·0	19·0	Radius: 15 m
On tubular beam centre	28·0	30·0	Range: 700 m
Below beam, on ground (1)	0·02 to 2·0	4·0	Range: 100–300 m
Reflector edge, on ground (1)	0·32 to 0·8	2·5	Height: 1·7 m
Directly behind reflector	0·11	—	Leak near opening
Directly behind reflector	< 0·02	0·001	Continuous panel
Behind reflector, on ground	0·002	≈ 0·000032	Angle of elevation: ≈15°
Back lobe search, on ground (1)	< 0·001	≈ 0·000032	Plunge tests
Under hyperboloid, on ground	0·11	—	Height: 1·7 m

(1) At 6° elevation.

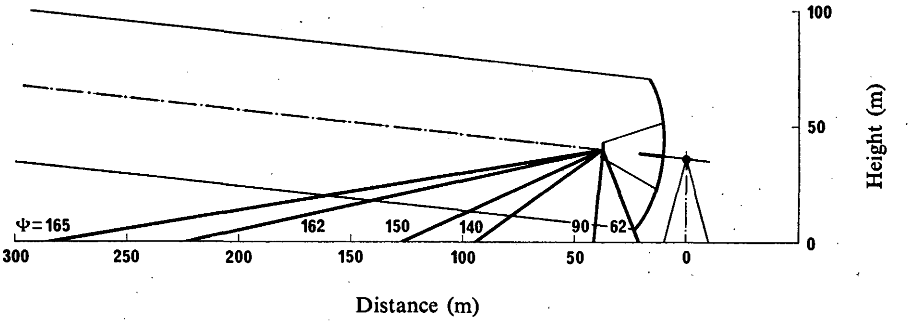

FIGURE 1 – *64 m antenna system power flux-density study (see Table I)*

Elevation angle: 6.0°

It is considered that the 64 m/400 kW system is very adequately described for power flux-densities greater than 10 mW/cm^2. Totally independent studies of apertures with tapered illumination show a ratio of power flux-density at the aperture to the density at $2D^2/\lambda$ of 14.2 dB [Bickmore and Hansen, 1959]. The results obtained here yield 14.3 dB. The calculated tabular beam maximum agrees with the measurement at 700 m to within 0.3 dB. The limitations in handling the multiple and reflected fields near the ground both analytically and during the field surveys should be borne in mind, i.e., the spot maxima and minima phenomenon (standing waves) and the averaging provided by the measuring process are important in interpreting the results *.

The first order tubular beam approach taken above is considered totally valid in the context of this study. A survey party using the hand-held equipment would observe a received power of about 25 W at 7 km while a 2 m diameter dish would receive nearly 1 kW **. Higher power flux-densities are possible in a mis-focused condition. An approximate density increase of 6 dB is available at 14.5 km although the reflector power flux should always remain focused at infinity when transmitting.

In the intermediate (1 to 10 mW/cm^2) zone, which, necessarily, is likely to be more loosely controlled, mention of unlikely, but possible, effects should be made. Resonant or focusing devices, perhaps key-rings, metal eyeglass frames or wrenches are capable of exhibiting a reasonable absorption area at 2 GHz. For example, a half-wave dipole (7.0 cm) in a 1 mW/cm^2 field will deliver 25 mW to a matched load.

Effects of this kind have been reported, but are considered little more than an improbable irritation. Normal tracking motion of the antenna will impose a time limit on the intermediate zone to some extent. In this intermediate zone, spot power flux-densities have been calculated but the measured average power flux-densities (the average over the aperture of the test horn) appear lower as might be expected. It is considered that the average value is important in terms of personnel exposure, while the spots are important in the event of resonant phenomena, if any. In either case, this zone, on the ground, is considered safe for incidental or occasional exposure, even at 6.0° elevation angle.

The greatest hazard is the tubular beam itself because acceptable siting of large microwave ground antennas generally places such installations in depressions, the primary restriction is to avoid interception of the tubular beam with the surrounding terrain. Surrounding terrain includes man-made objects such as towers, other antennas, power lines and possibly roofs of buildings near to the antenna. Generally, the NASA 64 m station sites are such that the transmitter will be inoperative at 6° elevation angles, due to the above primary restriction. This further helps to alleviate the power flux-density in the intermediate zone, as may be seen by inspection of Fig. 1.

3. Conclusions

As a result of the adopted standards, the following restrictions on the movement of personnel when operating the described system are required:

- access to the reflection surfaces must be avoided;
- access to the tubular beam must be avoided;
- the time during which access into the zone described as intermediate is allowable must be limited (to 1 hour in 24 hours).

All operating personnel should be made well aware of the tubular beam characteristics (range and power density) and the unlikely, but possible, effects in the zone where time-limited access is applicable.

The following environmental restrictions are also important:

- restrictions are necessary as regards the masking of the site by obstacles;
- restrictions are necessary as regards the height of the station buildings;
- collimation and other towers are potentially dangerous.

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* More recent information based upon the use of a small aperture polarization-independent probe confirms that, in a complex field, measurements taken with such a probe are generally 6 to 10 dB greater than with a large aperture.

** A 2 m dish, 1.5 km from a 25 m/400 kW system operated at 2.39 GHz, has been inadvertently swept, during normal tracking, by the tubular beam. The power flux-density and range of the tubular beam in this case is 186 mW/cm^2 and 2.7 km, respectively. Further, the 2 dB increase at half range as predicted by the second order tubular beam theory was evident here; the dish collected approximately 5 kW with resultant loss of feed and cabling due to thermal damage.

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REPORT 682-1 *

PROBABILITY OF HAZARDS TO PERSONNEL WITHIN AIRCRAFT DUE TO RADIATION FROM DEEP-SPACE EARTH STATIONS

(Study Programme 15B/2)

(1978-1986)

1. Introduction

This Report is an abbreviated edition of that published in Volume II, Geneva, 1982. Reference should be made to Annex I to that Report for the main analysis. The subject matter relates to Question 15/2 and to Study Programme 15B/2; historically, it also refers to § 1 and 2 of Question 52/1 (former Question 21/4) and § 8.2 of Report 385. An analysis has been made of the potential hazard to which personnel in aircraft (especially light aircraft) may be exposed when flying in the vicinity of an earth station of the deep-space space research service. This situation is independent of the type of aircraft fuselage construction material used.

2. General

A deep-space earth station utilizes very high gain parabolic antennas in conjunction with high power transmitters and sensitive receivers. The primary function of such a facility is communications with deep-space space stations. The possibility exists that overflights by aircraft may occur in the vicinity of a transmitting earth station.

The possibility of a hazardous situation being created by high powered antennae beams to aircraft is dependent on several factors, such as:

- the types of aircraft flying in the area surrounding the space station,
- the effectiveness of the safeguards and controls imposed by regulatory agencies over the routes traversed by aircraft flying near a potentially hazardous area,
- the probability of an aircraft actually traversing the high power density region of the transmitting station.

3. Probability of a hazardous situation occurring

In the following discussion it is assumed that the regions surrounding a deep-space earth station such as Goldstone Lake, California, are restricted zones in which the flight paths of military and large civilian aircraft are controlled by the administrations in co-ordination with the deep-space operations, so that the major remaining radiation hazard potential problem, arises due to small non-instrumented aircraft deliberately or accidentally traversing the restricted or controlled region.

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* The attention of Study Group 1 is drawn to this Report.

The fortuitous circumstances under which an aircraft might encounter a high-power beam emitted from a deep-space facility may be calculated from the following conditional probabilities:

– The probability of an aircraft wandering into a restricted zone inadvertently. (This probability that a general aviation aircraft will enter into a restricted zone contiguous to a deep-space complex is a function of the number of aircraft flights in proximity to such a zone).

– The probability that an aircraft, moving at random, once having entered the restricted area, will enter the antenna butterfly *. (This in its simplest form is the ratio of the area of the butterfly to the area of the available flying space within the restricted zone.)

– The probability that once an aircraft is in the butterfly region, it will intercept the beam of the antenna. (This probability may be determined by assuming that the butterfly region at a given altitude is divided into a number of area segments, each being the same size as the hazardous region of the beam at the given altitude. Since only one of the regions is, in fact, the hazardous region in each case, the probability that the aircraft will intercept that one region is roughly a function of both the size of the hazardous region and the aircraft's longest path length through the butterfly.)

The overall probability of a small aircraft entering the transmitting antenna beam of the deep-space earth station is the product of the conditional probabilities described above. Since these probabilities are, in general, altitude-dependent, the expected altitude distribution of the general aviation aircraft should be applied as a weighting function to determine the overall probability of an aircraft entering the hazardous region of a deep-space space research station.

4. Conclusions

The principal conclusion, drawn from the numerical values derived for one specific example based upon air traffic taking off or landing in the general area of Southern California, United States of America (see Annex I to Report 682, Geneva, 1982), is that the probability of a light plane accidentally traversing the high power density region of a transmitting deep-space earth station is about one flight in a million.

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* The butterfly outline pattern results from the intersection of the minimum antenna elevation (10°) contour and two constant declination contours (± 30°) projected on to the surface of the altitude sphere from the location of the earth station antenna.

SECTION 2B: TOPICS OF GENERAL INTEREST

Recommendations and Reports

REPORT 980

FACTORS RELATIVE TO ESTABLISHMENT OF SPURIOUS EMISSION LIMITS FOR SPACE SERVICES

(Question 19/2)

(1986)

1. Introduction

Limits for spurious emissions from transmitters of the space services operating on frequencies above 960 MHz do not currently exist. As the space services continue to expand, the potential for harmful interference due to such emissions may grow to intolerable levels unless definite limits are established. Spurious emission limits are especially important for spaceborne emitters, because transmitter adjustment or modification is normally impossible after launch. If a space station is found to cause unforeseen interference after launch due to spurious emissions, curtailment or modification of operations may be necessary, possibly at great expense.

Setting limits to spurious emissions for all space services is a complex problem, owing to the multiplicity of possible emission frequencies and the number and variety of possible victims of the emissions. No comprehensive analysis has yet been made, but particular systems and services have been examined. Report 713 derives examples, for illustration only, of spurious e.i.r.p. spectral densities for fixed-satellite service earth and space stations, based on permissible interference levels for fixed, radioastronomy, space research, and fixed-satellite service stations and using several assumptions for the sake of simplicity. Report 844 analyzes the possible interference due to harmonics between deep-space research stations and stations of the fixed- and broadcasting-satellite services. Report 697 looks at potential interference to the radioastronomy service caused by spurious emissions of all other services.

This Report describes the general characteristics of spurious emissions from the types of transmitters and modulation methods commonly used in the space services. Techniques for controlling the levels of spurious emissions are reviewed. Finally, based on these findings, the kinds of levels that could be considered in establishing limits for spurious emissions are discussed, with the unique characteristics of the space services in mind.

2. Sources and nature of spurious emissions

2.1 *Spurious sources*

Spurious emissions are generated primarily through the action of non-linearities in the elements of the transmitter chain such as up-converter mixers, power amplifiers, and surfaces of the antenna structure. The spurious emission components include:

- mixing products, occurring at linear combinations of the frequencies used in the up-conversion process;
- harmonics, occurring at integral multiples of the carrier frequencies of the intentional emissions;
- intermodulation products (IMPs), occurring at linear combinations of the carrier frequencies of the intentional emissions; and
- local oscillator leakage through the transmitter.

Another component of spurious emissions is parasitic oscillation, occurring mainly in power-amplifying tubes. Parasitic oscillations are not harmonically related to the desired emissions.

Causes of spurious emissions for the space services operating above 960 MHz are substantially the same as those present in the lower frequency bands, with one exception. Transmitter intermodulation is a phenomenon that is well known in MF, HF, VHF, and lower UHF bands when multiple transmitters feed the same antenna or multiple antennas are in close proximity. It is due to emissions from one transmitter entering the output circuit of another transmitter and mixing with the intended output signal(s). This is not a significant problem in transmitters operating at frequencies above 1 GHz because their transmitter output circuits generally contain isolators which prevent power entering the antenna from reaching the output circuit of the transmitter and generating IMPs.

2.2 *Nature of harmonics and intermodulation products*

The transformation of an input voltage $v_i(t)$ by a memory-less non-linear device, generates an output voltage $v_o(t)$ which may be described as follows:

$$v_o(t) = \sum_{m=1}^{\infty} a_m \cdot v_i^m(t)$$

The coefficients a_m characterize the non-linearity of the device. For example, in mixers, a_2 dominates. In linear amplifiers, $a_m = 0$ for $m > 1$, but in most physically realizable amplifiers, the a_m for odd m have appreciable values. Coefficients with even m are present in devices with an asymmetrical response, i.e. $v_o(v_i) \neq -v_o(-v_i)$. The output voltage of such non-linear devices will contain harmonics and intermodulation products. The spectra and magnitudes of these are determined by the input signal and the coefficients a_m.

The effect of non-linearity on a single, constant amplitude, phase-modulated input signal is the production of harmonics which are located at integer multiples of the carrier frequency. The harmonic signals have the form:

$$A_n \cos\left[n\omega_0 t + n\theta(t)\right]$$

where:

A_n : amplitude coefficient;

n : order of harmonic;

ω_0 : fundamental carrier frequency;

$\theta(t)$: phase modulation of the fundamental.

When the phase modulation is an analogue waveform, the harmonic of order n will have the same modulating waveform, but with its deviation increased by a factor n. The spectrum of the n^{th} harmonic of a wideband FM or PM signal, therefore, will have approximately n times the bandwidth of the fundamental signal's spectrum.

The phase modulation of an unfiltered digital waveform of order m is given by:

$$\theta(t) = 2\pi i/m \qquad kT < t \leqslant (k+1)T$$

where $i = 0, 1, \ldots$ or $m - 1$, t is time, and T is the symbol period. The harmonic signals will mostly have spectra that are similar to that of the fundamental, with identical bandwidth. The exceptions are harmonics with order equal to an integral multiple of m. These harmonics have very narrow spectra.

Signals consisting of multiple independent spectral components, when passed through a non-linear device, acquire intermodulation products (IMPs) as well as harmonics. For N narrowband signals, having carrier frequencies f_i ($i = 1, 2, \ldots N$), the intermodulation products appear at frequencies:

$$k_1 f_1 + k_2 f_2 + \ldots + k_N f_N$$

where each k_i is a positive or negative integer, or zero. The order of an IMP is given by:

$$n = \sum_i |k_i|$$

Note that harmonics are included in the above expression. If the frequencies f_i are relatively close to one another, the IMPs are grouped about the original signals and their harmonics. For example, with two signals at frequencies f_1 and f_2, some of the IMPs occur at these frequencies:

2nd order:	$f_1 + f_2$ $2f_1$ $2f_2$	2nd harmonic group
3rd order:	$2f_1 - f_2$ $2f_2 - f_1$	fundamental group
	$2f_1 + f_2$ $2f_2 + f_1$ $3f_1$ $3f_2$	3rd harmonic group

The fundamental group of IMPs are those with associated frequency coefficients satisfying:

$$\sum_i k_i = 1$$

These IMPs are most troublesome because they are difficult to filter and produce self-interference. While much of the IMP power would often fall within the assigned band, substantial parts of it would also lie on either side of the assigned band and may interfere with adjacent band services depending on the frequency difference(s) $f_2 - f_1$. The extent of the spreading of IMP power beyond the band edges depends on the order of the product, n. IMPs of order n fall within a band n times the bandwidth occupied by the transmitted carriers. This spreading is illustrated in Fig. 1.

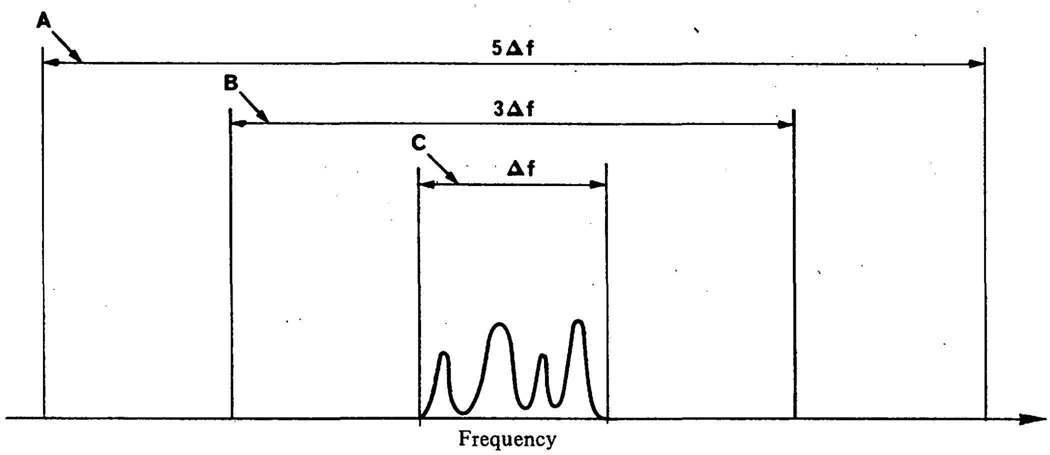

FIGURE 1 – *Spectral extent of intermodulation products*

Δf: bandwidth occupied by fundamentals
A: band occupied by fifth order IMPs
B: band occupied by third order IMPs
C: band occupied by carriers (assigned band)

The spectrum of an IMP is a scaled version of the convolution of the spectra of the signals that contribute to it. The scaling factor is a function of the coefficients describing the non-linearity. With input $e_i(t)$ consisting of N narrow-band bandpass signals:

$$e_i(t) = Re \left\{ \sum_{p=1}^{N} A_p \exp \left[j2\pi f_p t + j\varphi_p(t) \right] \right\}$$

the output of a non-linear device has the spectrum [Fuenzalida *et al.*, 1973]:

$$S_o(f) = \sum_K M_K \Omega \left(K, f \right) - \sum_{p=1}^{N} k_p f_p$$

where:

$K = (k_1, k_2, \ldots k_N)$

$\Omega(K, f) = S(k_1 \varphi_1)^* S(k_2 \varphi_2)^* \ldots S(k_N \varphi_N)^*$

$S(k_p \varphi_p)$: low-pass equivalent power spectrum, normalized to unit power, of a carrier phase modulated by $k_p \varphi_p(t)$

M_K : magnitude of spectral component, depending on non-linearity.

Because of the convolution process, the spectrum of an IMP has a bandwidth equal to the sum of the bandwidths of the contributing signals. The self-interference effects of fundamental zone IMPs have been mitigated in some multi-carrier systems by judicious assignment of carrier frequencies. Carriers are assigned frequencies so that IMPs fall primarily in unoccupied slots or out of the assigned band. This practice has the potential for increasing the probability of generating significant spurious emissions via IMPs, while decreasing self-interference.

2.3 *Interference effects of spurious emissions*

As shown in the previous section, an IMP or harmonic signal produced from phase-modulated carriers is itself a phase-modulated carrier which generally has a greater deviation than any of the carriers. A notable exception to this general situation is the case of the second harmonic of a 2-PSK modulated carrier, and IMPs involving it. The harmonic in that case has a narrow spectrum, and the IMP is likewise narrower. (This applies as well to the fourth harmonic of 2-PSK and 4-PSK, and other higher-order situations.)

IMPs, harmonics, and other spurious emissions of angle-modulated carriers, because they are not substantially different from the signals that produced them, should have an interference effect very similar to that of the fundamental undistorted carriers. This means that the analysis techniques developed to estimate interference effects apply to interfering spurious emissions with validity equal to that when applied to intentional emissions. Further, limits on levels of intentional emissions devised to protect services from intolerable interference can be applied to spurious emissions as well. In cases where an IMP is produced by multiple types of carriers (e.g., FM-FDM and digital 4-PSK), the interfering effects might best be allowed for by assuming that the IMPs were of the carrier type that caused the greater degree of disruption.

3. Spurious emission control techniques

3.1 *Power amplifier harmonics and IMPs*

Two general methods are available for controlling the level of spurious emissions generated by power amplifiers as described below.

3.1.1 *Improvement of linearity*

The levels of harmonics and intermodulation products, relative to the desired signal, are reduced by operating the amplifier at a reduced output level. When the output is significantly below the saturation (or significant compression) level, the portion of the amplifier's input-output characteristic that is used is nearly linear. As power is reduced from such a level, the rate of change of the power of an n^{th} order harmonic or IMP approaches n times the rate of change of the fundamental power, measured logarithmically [Westcott, 1967]. For example, third order IMPs are reduced by up to 3 dB for each 1 dB reduction in input (or output) power. This rate-order equality is approached only when output back-off is more than about 7 dB.

Various linearizing techniques have been applied to reduce IMPs and thus allow use of more of the power available from high-power amplifiers. These consist of predistorting the input to the power amplifier, or of adding oppositely-phased distortion products at the output. Annex II to Report 708 describes the performance of predistortion linearizers for travelling wave tube amplifiers.

3.1.2 *Filtering*

Harmonics from power amplifiers are normally suppressed by means of filters placed in the output transmission line. Characteristics of some typical harmonic filters for earth-station transmitters are given in Table I [Varian Associates, 1976].

TABLE I – *Examples of harmonic filter characteristics*

Passband (GHz)	Rated power (kW)	Insertion loss (dB)	Harmonic rejection (dB)			
			2nd	3rd	4th	5th
5.925- 6.425	8	0.25	50	50	40	25
5.925- 6.425	10	0.25	30	25	20	20
7.9 - 8.4	5	0.30	50	40	30	30
7.9 - 8.4	10	0.20	35	20	20	NS
14.0 -14.5	2.5	0.25	20	NS	NS	

NS: not specified

In order to attain a specific uniform level of harmonic emission suppression, the required harmonic filter rejection becomes less for each successive harmonic order. This is consistent with the characteristics of high power amplifying tubes, which typically have about 10 dB less harmonic output power for each successive order. The first filter described in Table I, placed at the output of a travelling wave tube, would ensure that all harmonics would be at least 60 dB below the fundamental. Harmonic output of a klystron is typically 15 to 20 dB less than that of a TWT, and would require less harmonic filtering to meet the same specification.

Bandpass filters may be used to attenuate out-of-band and spurious emissions in the vicinity of the passband. Table II gives characteristics of typical bandpass filters [Varian Associates, 1976]. The effectiveness of such filters in controlling emissions falling outside the band is limited by the rate of increase of attenuation with frequency from the band edge. Note that the frequency interval between the band edge and the point where full attenuation is achieved varies from 30% to 100% of the bandwidth for the filters listed. This interval can be made less, but at the expense of more passband loss and phase variation. Because of the finite slope of the filter response, IMPs falling immediately outside the band may be insufficiently rejected and could cause interference in the adjacent band. When transmitting multiple carriers extending up to the band edge, one would expect the out-of-band IMP power density to be high in the vicinity of the band edge.

3.2 *Other spurious emission sources*

Passive intermodulation products and harmonics are generated by layers of oxide and other surface corrosion products that are exposed to the high RF fields in the vicinity of a transmitting antenna. Metal-to-metal contacts are common IMP sources, especially when between dissimilar metals and when exposed to the atmosphere. Careful design, construction, and maintenance in transmit antennas will reduce the possibility of passive spurious generation of IMPs. Attention must also be paid to metal structures in the antenna's vicinity, which can likewise produce passive spurious emissions.

TABLE II – *Examples of bandpass filter characteristics*

Passband (GHz)	Rated power (kW)	Insertion loss (dB)	Stopband (GHz)	Rejection (dB)
2.7-2.9	10	0.25	d.c.- 2.59	50
			2.59- 2.64	25
			3.04- 3.84	25
			3.15- 3.70	50
5.925-6.425	3	0.25	d.c.- 5.5	80
			6.9 - 7.2	50
			7.2 - 8.2	60
7.9-8.4	12	0.5	d.c.- 7.75	80
			8.6 -10.0	80

Local oscillator mixing products, or even leakage of the local oscillator signal itself, at frequencies located in the power amplifier passband, are transmitted as spurious emissions. This can be minimized in the design process. Effective filtering of unwanted products at their sources and judicious selection of local oscillator frequencies are necessary.

Parasitic oscillations are abnormal and call for maintenance action. They may be eliminated by adjustment of operating voltages of active elements of the transmitter chain, or by reducing RF leakage at connectors, but replacement of the offending component is usually necessary.

4. Considerations for setting emission limits

4.1 *Form of the spurious emission limits*

Three general forms of space service spurious emission limits would be useful:

- a required level of spurious emission suppression relative to the power of the fundamental (or carrier) emission;
- a maximum permissible level of spurious emission power expressed as a spectral power density, a radiated spectral power flux-density, or a received spectral power flux-density;
- a receiving power.

The suppression type of limit would perhaps be a convenience to system designers since the specifications for many components are given in the same form (e.g. attenuation of filters). However, conformance with interference criteria can be assured only where limits on the spurious emissions power levels at the victim receiver are applied. The following equation relates these two types of limits:

$$S(f) = P_t + G_t(f) + G_r(f) - L(f) - I(f)$$

where:

$S(f)$: required suppression level (dB) of the spurious emission at the frequency f;

P_t : interfering carrier power spectral density level (dB(W/B)), where B is the reference bandwidth established by the interference criteria;

$G_t(f)$, $G_r(f)$: transmitter and receiver antenna gains (dBi) at the frequency f in the appropriate direction;

$L(f)$: basic transmission loss (dB) exceeded for all but p% of the time at the frequency f, where p is established by the interference criteria;

$I(f)$: permissible level of interference (dB(W/B)), to be exceeded in the reference bandwidth B for no more than p% of the time.

It can be seen from the above equation that many differing supression levels could be obtained for a given source of interference as the various spurious emissions are considered. Many assumptions must be made with regard to the antenna gains and the basic transmission losses in order to determine the required supressions in a general analysis.

Table III lists some of the protection criteria that have been developed for many of the services in Study Group 2. The Recommendations should be consulted for further details. In all cases, the total interference power within the indicated reference bandwidth is considered, which necessarily includes the contributions from all sources of out-of-band and spurious emissions. The maximum permissible level of interference from spurious emissions must be less than the thresholds indicated in Table III; however, further analysis is needed to determine appropriate limits.

TABLE III – *Compilation of Study Group 2 protection criteria*

Victim service	Reference	Station location	Frequency range (¹)	Type of criteria	Threshold	Maximum exceedance probability
Space operations	Recommendation 363	Earth	1-8 GHz	Power	–184 dB(W/kHz)	1%/day
		Spacecraft	Any	*S/I*	20 dB(1 kHz)	1%/day
Space research (near-Earth, unmanned)	Recommendation 609	Earth	1-20 GHz	Power	–216 dB(W/Hz)	0.1% of time
		(Low orbit) Spacecraft	0.1-30 GHz	Power	–177 dB(W/kHz)	0.1% of time
Space research (near-Earth, manned)		Earth	1-20 GHz	Power	–216 dB(W/Hz)	0.001% of time
		(Low orbit) Spacecraft	0.1-30 GHz	Power	–177 dB(W/kHz)	0.1% of time
Deep-space research	Recommendation 578	Earth	near 8 and 13 GHz	Power	–220 dB(W/Hz)	0.001% of time
		Spacecraft	near 7 GHz	Power	–189 dB(W/20 Hz)	0.001% of time
Earth exploration satellite (telecommunications links)	Recommendation 514	Earth	1-10 GHz	Power	–154 dB(W/MHz)	1% of time
		(Near-Earth) Spacecraft	0.3-10 GHz	Power	–161 dB(W/kHz)	0.1% of time
Earth exploration satellite (passive sensors)	Report 694	Spacecraft	(See Table I, Report 694)			
Radioastronomy	Recommendations 314 and 611	Earth	(See Tables I and II as well as § 4, Report 224)			

(¹) The referenced Recommendation should be consulted for criteris pertaining to other frequency ranges.

4.2 *Discussion of relevant material*

Report 844 presents information concerning potential interference to earth and space station receivers used for deep-space research, as a result of harmonic emissions of other services in harmonically related bands. The Report also considers potential interference to other services, as may be caused by harmonic emissions of earth and space station transmitters used for deep-space research. The analysis presented in Report 844 is based, in part, on protection criteria for deep-space research, as given in Recommendation 578 and Appendix 28 to the Radio Regulations. It is concluded in Report 844 that significant interference to the various systems included in the analysis would be avoided if the power spectral density of harmonic emissions was suppressed at least 50 dB below the fundamental power spectral density.

For the radioastronomy service, the harmful interference levels given in Tables I and II of Report 224 apply to any man-made signals falling within a radioastronomy band, whether they are intentional or unwanted emissions. Report 697 lists those services most likely to generate IMPs or harmonics that could interfere with radioastronomical observations. It is noted that the second harmonic of broadcasting satellites operating in the 11.7 to 12.5 GHz band would exceed the harmful levels to radioastronomy unless suppressed by 126 dB, assuming that the astronomy antenna were directed at the satellite, or by 56 dB, assuming 0 dB gain for the astronomy antenna. Geostationary meteorological satellites that use the 460 to 470 MHz band to interrogate data collection platforms may interfere with radioastronomy with their third harmonic. Suppression by 94 dB would be required to meet the harmful interference levels, again assuming that the astronomy antenna is directed at the satellite. There is one situation where the harmful interference levels in Report 224 are not adequate. Report 224 suggests that radioastronomy antennas should be able to observe to within 5° of the geostationary-satellite orbit without experiencing harmful interference. The harmful levels applicable in this situation are approximately 15 dB below the values given in Tables I and II of Report 224.

On the practical experience side, it should be noted that the United States of America's domestic FSS space and earth stations in all FSS bands have been operating for many years with spurious emission limits of 50 dB suppression relative to the fundamental without any reports of significant spurious emission interference to other services.

5. Conclusions

The nature of IMP, harmonic, and other spurious emissions, their effects on the performance of possible victims of interference, methods of controlling them, and where in the spectrum they are likely to occur with respect to allocations of other services, are important factors relative to the establishment of spurious emission limits. Assessment of these factors, combined with judicious selection of a "tolerable" level of spurious-generated interference, should make it possible to establish meaningful emission limits.

The nature of harmonics and IMPs, for phase-modulated carriers, is very similar to the carriers that produce them. In general, they appear to be phase-modulated carriers with increased deviations. They may therefore be considered to be intentional emissions in estimating their bandwidths or error rate effects. One exception to this would be certain harmonics of PSK emissions. IMPs occur in groups about the intentional emission spectrum and each harmonic of it.

Spurious emissions from power amplifiers, probably the most common source, are controllable by output power back-off and by filtering. Harmonic levels at least 60 dB below the fundamental are readily attainable with available harmonic filters. Bandpass filters are effective for IMP reduction when the IMPs are sufficiently removed from the band edge. IMPs close to the band edge cannot normally be effectively filtered because of practical limitations on filter cut-off performance.

Further study of the maximum permissible levels of interference from spurious emissions is needed to provide a basis for space service spurious emissions limits. These can then be applied in analyses to determine what levels of spurious emission suppression may be needed and, consequently, the system design and operational measures that would prevent harmful interference from spurious emissions.

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REPORT 844*

POTENTIAL INTERFERENCE BETWEEN DEEP-SPACE TELECOMMUNICATIONS AND FIXED-SATELLITE AND BROADCASTING-SATELLITE SYSTEMS IN HARMONICALLY RELATED BANDS

(Question 19/2)

(1982)

1. Introduction

The possibility of harmful interference resulting from unwanted emissions to and from geostationary space stations is of increasing concern to deep-space research. This concern is prompted by the expected increase in utilization of the geostationary-satellite orbit in frequency bands adjacent to and harmonically related to the operational frequencies used for deep-space telecommunications.

This Report presents the results of an analysis of potential mutual interference caused by unwanted emissions from the United States Deep-Space Network (DSN) of the space research service, and from the fixed-satellite and broadcasting-satellite services. The study also includes an assessment of potential interference to a future geostationary relay station for communication with a station in deep space.

2. Interference analysis

Frequency bands harmonically related to the DSN operating frequencies are shown in Table I. The harmonically related bands are direct multiples and sub-multiples of the deep-space bands. Fixed-satellite and broadcasting-satellite service allocations which fall within these bands are indicated in the Table.

Of the many potential interference situations resulting from the relationships shown in Table I, certain typical cases have been examined and analyzed parametrically in this Report.

Since the levels of unwanted emissions from transmitters in harmonically related bands are not specifically known, this analysis treats the problem parametrically by using the out-of-band emissions of the interferer as an independent variable. In this Report that variable is called "level of suppression". It is expressed with respect to the energy contained in the fundamental frequency. The results of the analysis can then be used to determine suppression levels of unwanted emissions necessary to meet the interference criteria of the services involved.

Pointing statistics for a given DSN earth station have been obtained from a computer study of the trajectories of 40 realized and potential deep-space missions. Figure 1 presents the pointing angle toward the geostationary arc as a function of time for one DSN earth station. It should be noted that some deep-space missions do not require antenna pointing to within 5 to 10° of the geostationary arc for many months or even years of mission duration.

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* This Report is brought to the attention of Study Groups 4, 10 and 11.

3. Harmonic interference

3.1 *Interference to a DSN earth station from a fixed-satellite earth station*

The 2nd harmonic of an earth station in the fixed-satellite service transmitting in the frequency range 6.375 to 6.625 GHz has the potential for interference to a DSN earth station receiving at 12.75 to 13.25 GHz.

The coordination distance between a transmitting earth station in the fixed-satellite service and a receiving DSN earth station was computed for two modes of propagation according to the procedure described in Appendix 28 to the Radio Regulations.

TABLE I — *Harmonic relationships between deep-space bands and other bands*

DSN earth station transmit frequencies	Harmonic bands			
	2nd	3rd	4th	5th
2110–2120 MHz	4220–4240 MHz	6330–6360 MHz All Regions: fixed-satellite service (Earth-to-space)	8440–8480 MHz	10.55–10.6 GHz
7145–7190 MHz	14.29–14.38 GHz All Regions: fixed-satellite service (Earth-to-space)	21.435–21.57 GHz	28.58–28.76 GHz All Regions: fixed-satellite service (Earth-to-space)	35.725–35.95 GHz
16.6–17.1 GHz	33.2–34.2 GHz	49.8–51.3 GHz All Regions: fixed-satellite service (Earth-to-space)	66.4–68.4 GHz	83.0–85.5 GHz All Regions: fixed-satellite service (space-to-Earth) broadcasting-satellite service
DSN earth station receive frequencies	**Sub-harmonic bands**			
	1/2	1/3	1/4	1/5
2290–2300 MHz	1145–1150 MHz	763–767 MHz	573–575 MHz	458–460 MHz
8400–8450 MHz	4200–4225 MHz	2800–2817 MHz	2100–2113 MHz	1680–1690 MHz
12.75–13.25 GHz	6375–6625 MHz All Regions: fixed-satellite service (Earth-to-space)	4250–4417 MHz	3188–3313 MHz	2550–2650 MHz All Regions: broadcasting-satellite service. In Region 2: fixed-satellite service (space-to-Earth)

Those modes are:

- clear air propagation mode "a",
- rain scatter propagation mode "c", in Zone 4.

The following assumptions were made for both modes of propagation:

- permissible level of interference to a DSN earth station is −220 dB(W/Hz);
- elevation angle of transmitting and receiving antennas is taken to be 5° above the horizon.

Assumed fixed-satellite earth station e.i.r.p.'s at 5° off-main beam axis are (see Report 453):
Case 1: 21.0 dB(W/4 kHz) for satellite network with a large earth-station antenna
Case 2: 14.5 dB(W/4 kHz) for FM-TV or single-channel-per-carrier global systems
Case 3: 8.5 dB(W/4 kHz) for FDM-FM systems

For various suppression levels of spurious emissions from a fixed-satellite earth station the coordination distances for propagation modes "a" and "c" are shown graphically in Figs. 2 and 3.

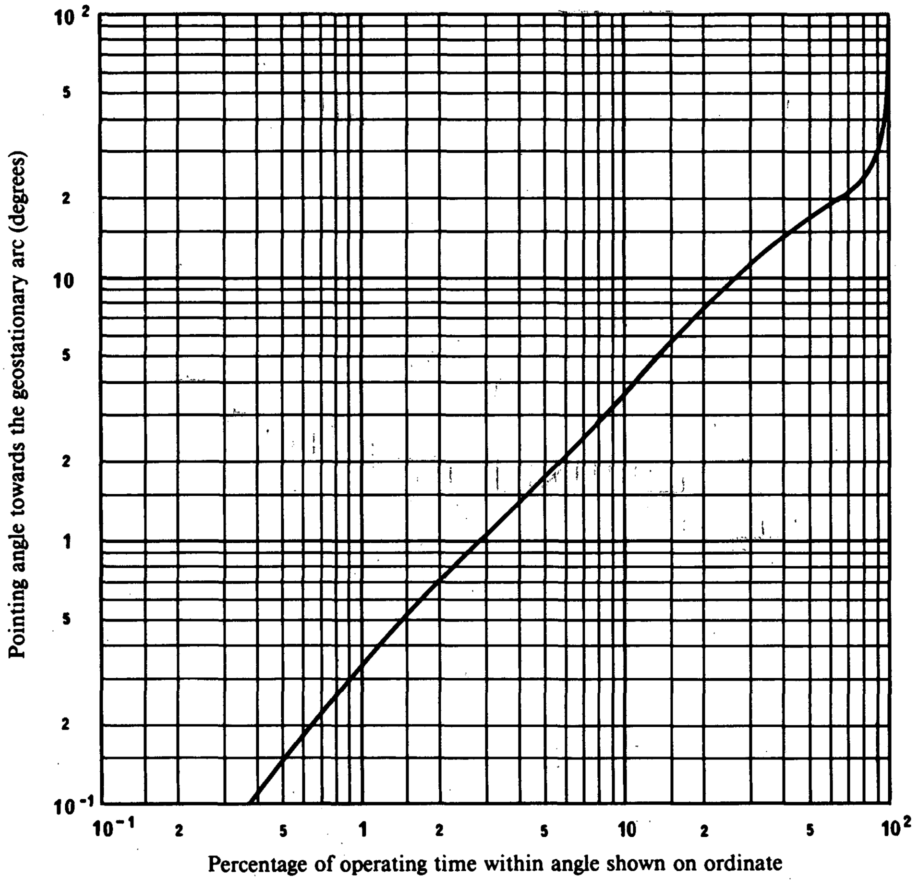

FIGURE 1 — *Pointing statistics of a DSN earth station*

3.2 *Interference to a satellite of the fixed-satellite service from a DSN earth station*

Potential interference exists to a satellite of the fixed-satellite service receiving in the 6330 to 6360 MHz range from the 3rd harmonic of a DSN earth station transmitting in the 2110 to 2120 MHz band.

The assumed DSN earth-station transmitting characteristics are:

- Frequency 2.1 GHz
- RF power 50 dBW
- Antenna gain 62 dBi
- RF bandwidth:
  - Ranging 10 MHz
  - Telemetry 3 MHz
  - Command 0.3 MHz

It is also assumed that the DSN earth station is transmitting 100% of the time.

Typical receiver noise temperature and antenna gain of a fixed satellite are 3000 K and 23.0 dBi, respectively (Report 207 (Geneva, 1982)). The interference criterion is taken to be 4% (Appendix 29 to the Radio Regulations) of the noise power of the satellite receiver. It should be noted that this 4% criterion is used only as an indicator, to determine those situations in which a more detailed analysis should be performed.

Figure 4 shows the percentage of time that a DSN earth station will cause a 4% increase in fixed-satellite noise power for various levels of DSN spurious energy suppression.

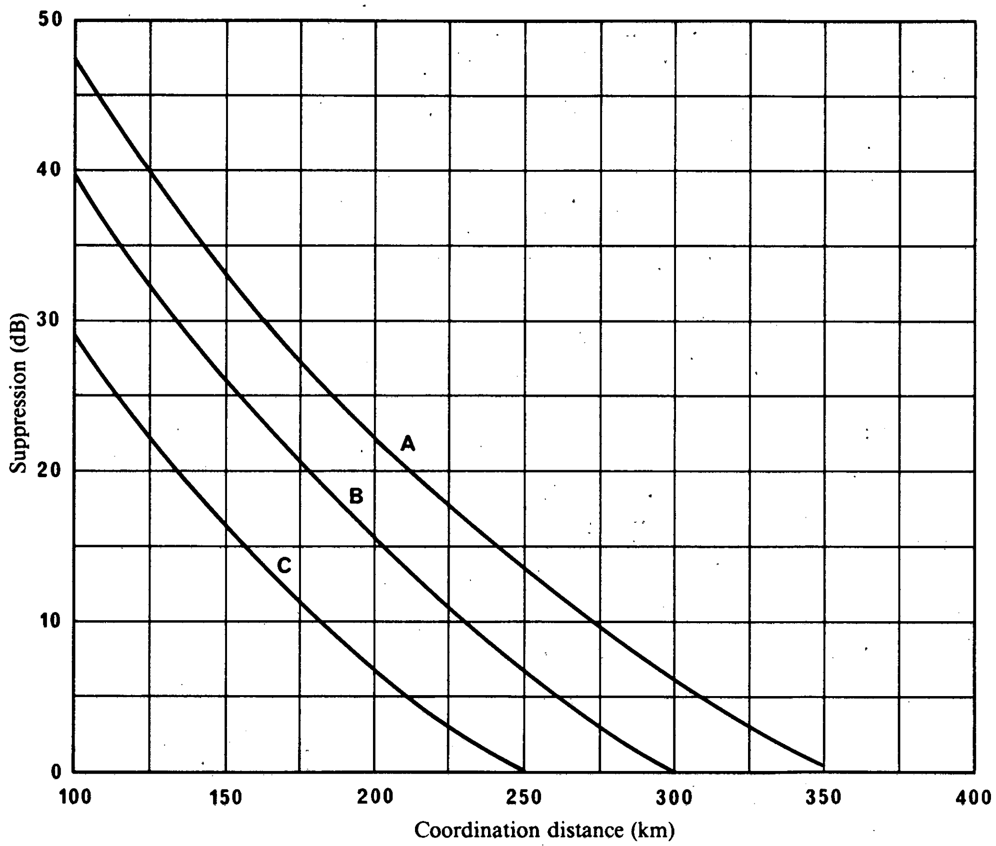

FIGURE 2 — *Coordination distance between a transmitting FSS earth station and a receiving DSN earth station for clear air mode "a"*

A: Case 1
B: Case 2
C: Case 3

3.3 *Interference to a DSN earth station from a satellite in the fixed-satellite service*

The 5th harmonic of a broadcasting satellite or fixed satellite transmitting in the 2550 to 2650 MHz frequency range has the potential for interference to a DSN earth station receiving at 12.75 to 13.25 GHz.

According to Article 28 to the Radio Regulations, the maximum permitted power flux-density limit on the surface of the Earth is -137 dB(W/m^2) in any 4 kHz band for a broadcasting satellite operating in the 2 to 3 GHz band.

Further assumptions made in this part of the analysis are:

- broadcasting satellite transmitting 100% of the time;
- DSN interference criterion = -220 dB(W/Hz).

The percentage of time that the interference criterion is met for various levels of suppression of the interfering harmonic signal is shown in Fig. 5. This is based upon the pointing statistics of the DSN as described in Fig. 1.

Significant interference to a DSN earth station from more than one satellite is not considered likely since broadcasting-satellite systems using spot beams will probably not illuminate the same service areas on the Earth at the same frequency, due to the problem of mutual interference.

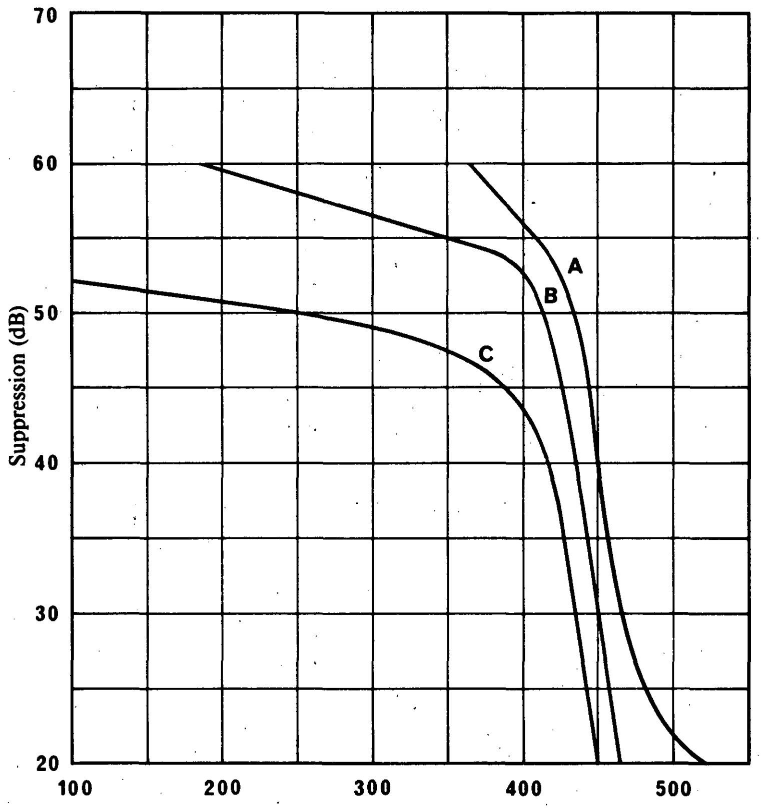

FIGURE 3 — *Coordination distance between a transmitting FSS earth station and a receiving DSN earth station for rain scatter mode "c"*

A: Case 1
B: Case 2
C: Case 3

3.4 *Interference to an earth station of the fixed-satellite or broadcasting-satellite service from a DSN earth station*

The potential interference to an earth station of the fixed-satellite or broadcasting-satellite service from the 5th harmonic of a DSN earth station transmitting in the band 16.6 to 17.1 GHz is not considered in this Report due to lack of information on 80 GHz space systems.

3.5 *Interference to a DSN geostationary relay satellite*

A geostationary satellite may be used in the future to relay signals from deep-space research spacecraft to Earth. Although this relay spacecraft may employ other frequencies than those currently used for deep-space research (especially in the geostationary satellite-to-Earth links) this portion of the analysis is directed at a brief assessment of interference potential at harmonics of the same frequencies as those analyzed in the previous sections of this Report.

3.5.1 *Interference to a DSN relay satellite from fixed-satellite earth-station transmissions*

The 2nd harmonic of a earth station in the fixed-satellite service transmitting in the frequency range 6.375 to 6.625 GHz has the potential for interference to a DSN relay satellite receiving from deep space at 12.75 to 13.25 GHz.

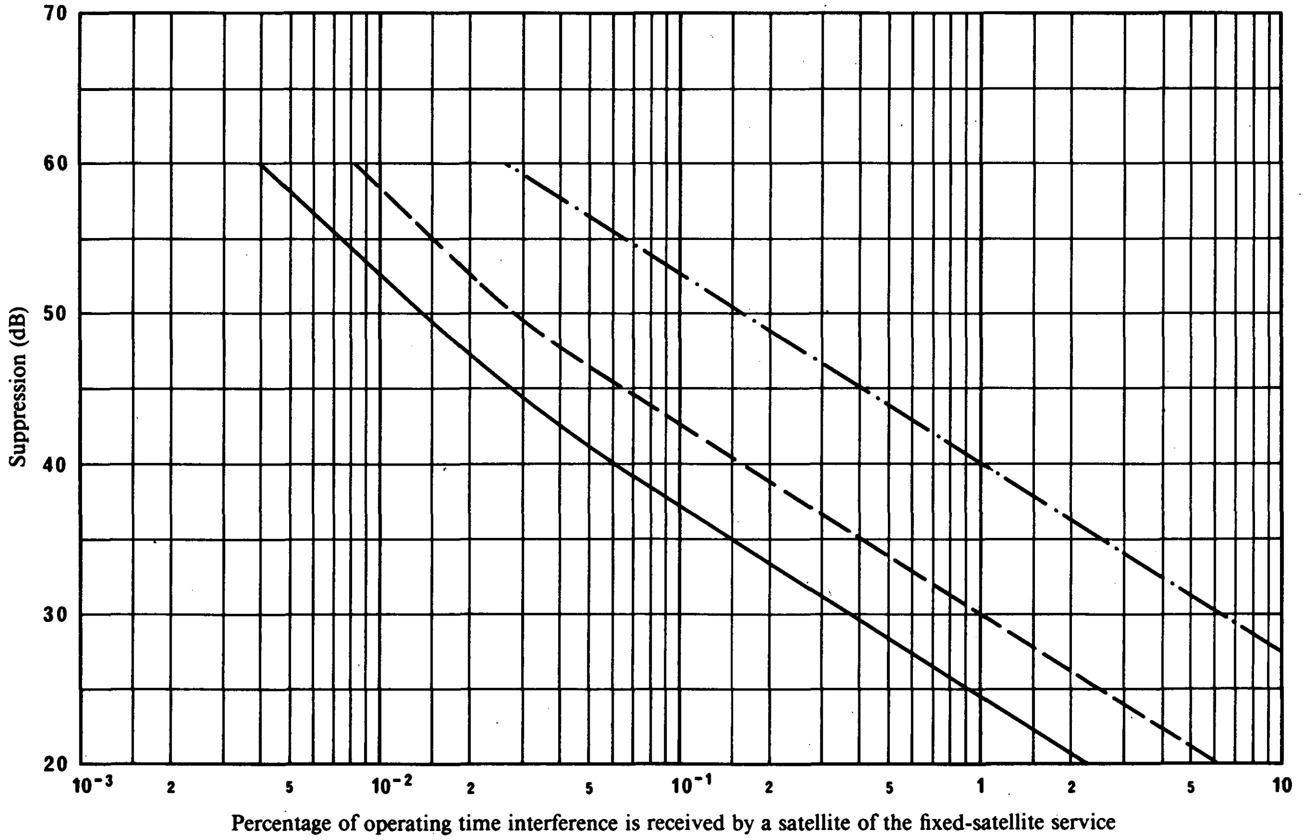

FIGURE 4 — *Interference from the third harmonic of a DSN earth station to a satellite of the fixed-satellite service*

——— 10 MHz bandwidth

— — — 3 MHz bandwidth

—·— 0.3 MHz bandwidth

For this analysis it is assumed that the DSN relay satellite has a 45 m receiving antenna and a gain of 0 dBi toward the transmitting FSS earth station. Additionally, the same values of harmful interference (−220 dB(W/Hz)) and FSS earth station transmitting characteristics, as assumed in § 3.1, are used. For various levels of spurious harmonics, the required geocentric separation of the receiving fixed satellite and the DSN relay satellite have been calculated. Even on a worst-case basis of 0 dB suppression the required spacing is small, as demonstrated below:

FSS earth station transmit power density	− 36 dB(W/Hz)
Free space loss	−207 dB
Received power density	−243 dB(W/Hz)

Using −220 dB(W/Hz) as the interference criterion would mean that the gain of the FSS earth station toward the DSN relay satellite could be as high as 23 dB. This translates via the reference antenna pattern of 32 − 25 log φ to a spacing on the order of 2.3°.

At higher levels of harmonic suppression, the required separation is correspondingly less.

3.5.2 *Interference to a DSN relay satellite from FSS satellite transmissions*

The 5th harmonic of a broadcasting or fixed satellite transmitting in the 2550 to 2650 MHz frequency range has the potential for interference to a DSN relay satellite receiving from deep space in the 12.75 to 13.25 GHz band.

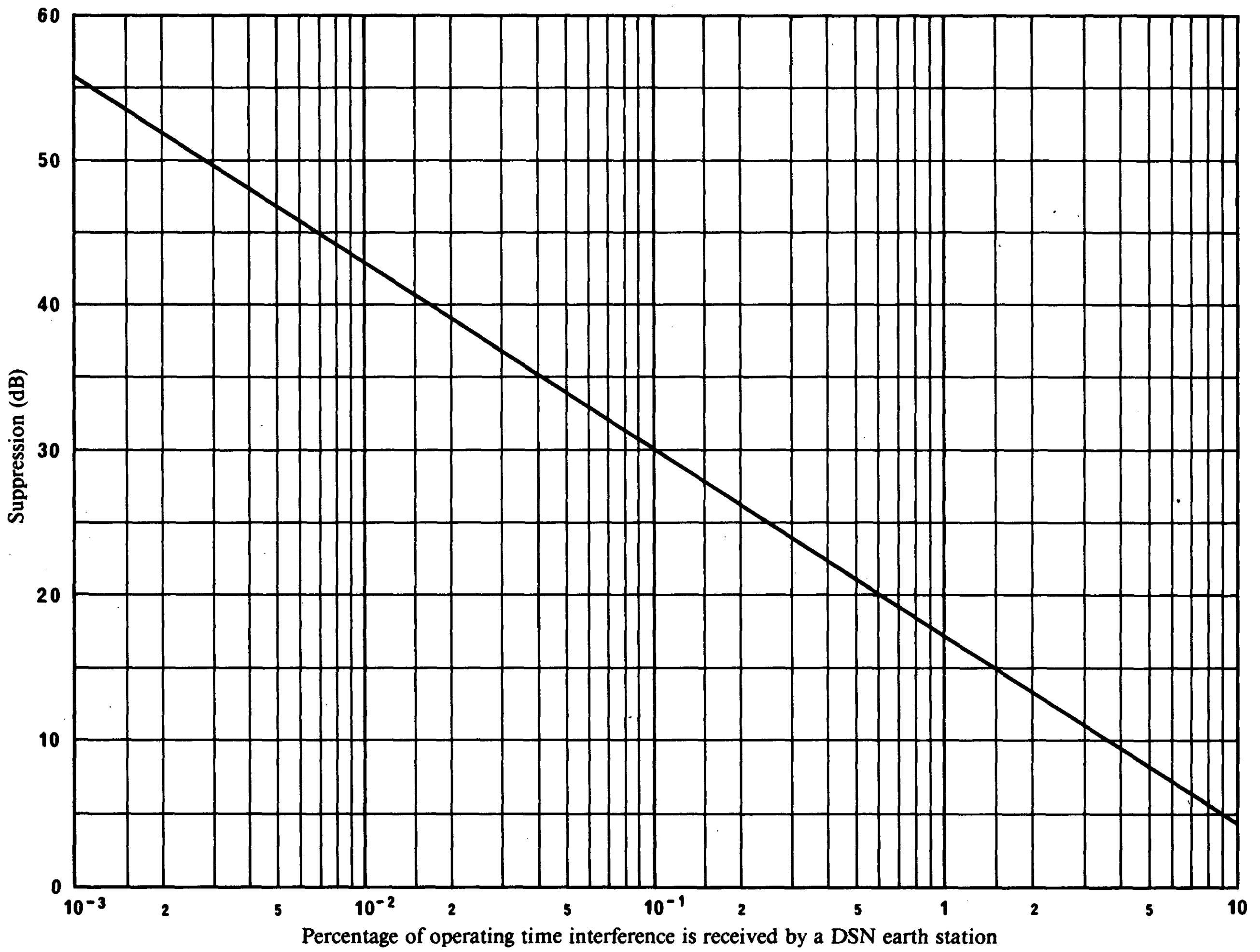

FIGURE 5 — *Interference to a DSN earth station from the fifth harmonic of a broadcasting satellite with − 137 dB (W/m²) power flux-density at the surface of the Earth*

In this analysis it is assumed that:

- the gain of the fixed satellite toward the DSN relay satellite is 0 dBi;
- the maximum value of pfd allowed on the Earth's surface is -137 dB(W/(m^2 · 4kHz));
- the DSN relay satellite interference criterion is -220 dB(W/Hz).

Figure 6 presents the angle that the DSN relay satellite must point away from a fixed or broadcasting satellite as a function of the geocentric spacing between the two. These curves are shown parametrically for various levels of energy suppression.

Although pointing statistics of a DSN relay satellite are not currently known, it can be assumed that a DSN relay satellite would point toward the geostationary-satellite orbit (for a given mission) for the same or less length of time as an Earth-based DSN station.

If a DSN relay satellite is receiving only when the shortest distance between the line of sight to a DSN probe and the surface of the Earth is greater than or equal to 200 km, the assumed pointing statistics of the relay satellite can be used, together with the geostationary arc length visible to the relay satellite, to give some indication of the percentage of time a single satellite may cause interference to the relay satellite.

When this is done for a single FSS satellite spaced 1° away from the relay satellite, it is found that for energy suppression levels of 50, 40, 30 and 20 dB, the percentages of time interference is received by a DSN relay satellite are 0.003%, 0.017%, 0.104% and 0.35% respectively. For the same levels of suppression, the percentage of time a relay satellite receives interference from a single satellite located at greater distances from the relay satellite is found to be correspondingly less.

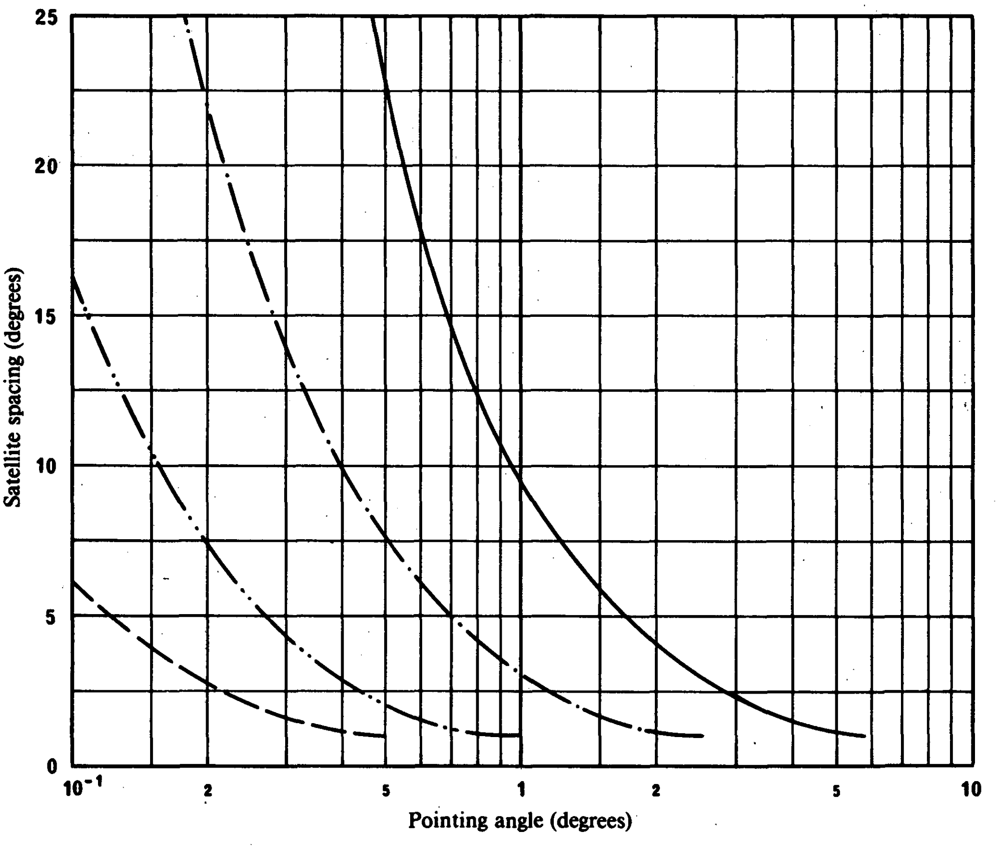

FIGURE 6 — *Interference from the fifth harmonic of a fixed or broadcasting satellite to a DSN relay satellite*

4. Adjacent band considerations

In addition to the potential for interference from unwanted emissions in harmonically related bands, there is the possibility of interference from unwanted emissions of services in adjacent bands. Specific analysis of this possibility has not yet been accomplished with respect to the services considered in this Report.

5. Conclusions

Because of the high gain antennas, high power transmitters, and extremely sensitive receivers employed by DSN earth stations, deep-space research and other satellite services in harmonically related bands may be subjected to interference from unwanted emissions unless measures are taken to suppress the energy of these emissions to acceptable levels.

Precise levels of unwanted emissions that are acceptable for all services cannot be determined in this Report as this requires a detailed interference analysis of the services involved and their individual characteristics. However, from the parametric analysis of "worst-case" situations, it appears that significant interference would be avoided if harmonic emissions were suppressed by at least 50 dB.

In most cases the severity of interference between earth stations can be reduced by proper separation and site shielding. In the case of interference to and from space stations, additional filtering may be required to suppress the power in unwanted emissions to an acceptable level. In the case of harmonic band radiation, extra filtering is easily achieved at frequencies far removed from the fundamental.

Analysis of interference from unwanted emissions from services in adjacent bands remains to be done.

REPORT 981 *

SHARING CONSIDERATIONS NEAR 2 GHz BETWEEN SATELLITES IN THE EARTH EXPLORATION, SPACE RESEARCH, AND SPACE OPERATION SERVICES AND TERRESTRIAL LINE-OF-SIGHT RADIO-RELAY SYSTEMS IN THE FIXED SERVICE

(Question 1/2 and Study Programme 1D/2)

(1986)

1. Introduction

This Report gives a partial response to studies called for in Study Programme 1D/2. It contains an analysis, agreed for application between services within one administration, to determine pfd limits necessary to protect line-of-sight (LOS) fixed service systems operating near 2 GHz from harmful interference from satellites. Satellites in both geostationary and low orbit are considered. The analysis is also applicable to satellites in highly-elliptical orbits, since as far as the pfd analysis is concerned, the portion of the orbit of interest (near perigee) for these satellites is similar to that for low orbit satellites. Sharing with other services, such as mobile, is not addressed. Systems in the fixed service using troposcatter transmission are protected by the provisions of No. 2560 of the Radio Regulations. The suitability of the interference limit of -168 dBW in any 4 kHz band specified by these provisions has not been reviewed in this Report.

2. Analysis

2.1 *General considerations*

Both geostationary and low orbit satellites operate near 2 GHz. While signal levels from geostationary satellites into terrestrial receivers can be relatively constant, the potential interference from satellites in other orbits generally varies in intensity and is not continuous.

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* This Report should be brought to the attention of Study Groups 4, 8 and 9.

The results of an analysis which gives the long-term percentage of visibility that a low orbit satellite has in different segments of its orbit are given in Report 684. Additional analyses, discussed here, have led to the development of two different sets of pfd levels to protect fixed-service systems; one for geostationary satellites and one for low orbit satellites [Farrar, 1984; Locke and Rinker, 1978]. The criteria for allowable interference levels in radio-relay circuits from satellites used in these analyses are given in Recommendation 357.

2.2 *Interference criteria*

Recommendation 393 lists the total allowable noise levels from all sources including satellites that can be used as a guide in the design of a radio-relay circuit. Recommendation 357 gives the maximum allowable values of interference which may be contributed by satellites and earth stations. These interference levels, illustrated in Fig. 1, are for any channel in a 2500 km hypothetical reference circuit, and apply to frequency-division-multiplex, analogue, angle-modulated radio-relay systems that share spectrum with systems in the fixed-satellite service. The circled points shown in Fig. 1 represent the interference levels stated in the Recommendations and the curve connecting these points is one possible interpolation suggested by Recommendation 357. The data in Fig. 1 represent a small fraction of the total noise power levels given in Recommendation 393. The curve shown in Fig. 1 provides the technical basis for this analysis.

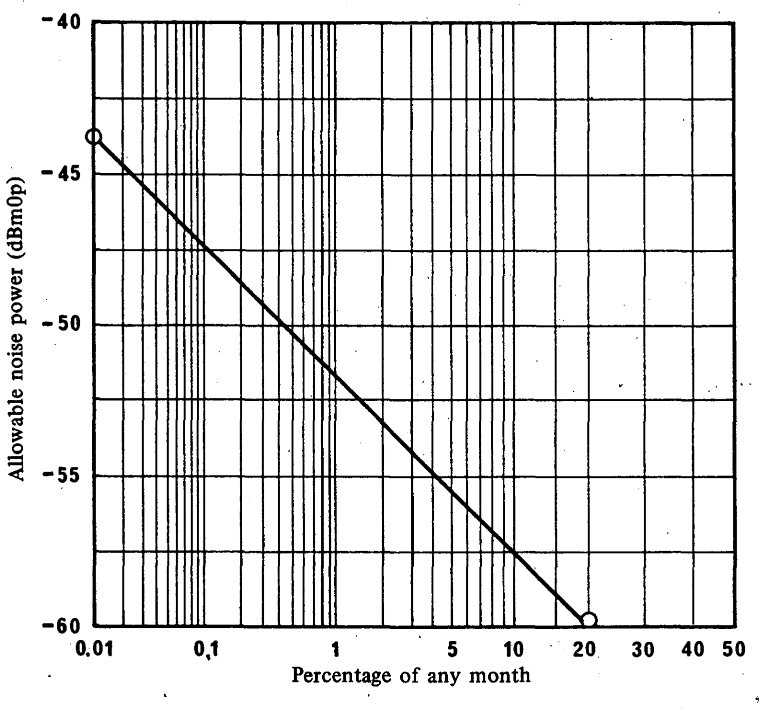

FIGURE 1 – *Curve illustrating allowable interference noise power from fixed-satellite service systems to fixed-service radio-relay circuits (Recommendation 357)*

2.3 *Characteristics of space system and radio-relay circuits in the 2 GHz band*

2.3.1 *Space systems*

Some space research and Earth exploration satellites transmit at about 2100 MHz in the space-to-space direction. Space-to-space transmissions as used from low orbit satellites to data relay satellites are intermittent as a consequence of intermittent visibility and also because of operational considerations. The latter factor was not taken into account in this analysis.

Space research and Earth exploration satellites also operate near 2250 MHz, transmitting in the directions space-to-Earth and space-to-space. The space-to-Earth transmissions can be from the geostationary-satellite orbit (GSO) or from low orbits. Generally, the non-GSO satellites have circular orbits, with altitudes less than 1500 km, or highly elliptical orbits, often with perigees as low as 300 km. Note that in all of the non-GSO cases, transmissions are generally not continuous and that frequencies used usually differ from satellite to satellite.

The nature of the space services and the characteristics of the systems required to implement these services affect the e.i.r.p. needed in the 2 GHz band. Unlike systems in the fixed-satellite service, a majority of 2 GHz satellite transmitters have narrow-band emissions whose widths range from 100 kHz to 5 MHz. The spectral power densities of satellite transmitters in the 2 GHz band are generally not uniform because of their transmission requirements. The narrow-band peaks are the most important in the evaluation of pfd level, because a major portion of the satellite transmitter power is contained in these peaks.

Unlike the fixed-satellite service, space services in the 2 GHz band serve a number of different purposes and their satellites use various different orbits. As a result, transmission paths to a given earth station may sometimes coincide. This is the main reason for satellites in the 2 GHz band generally being assigned different frequencies, and the reason that there are practical limits on the number of satellites that can operate co-channel in the band.

2.3.2 *Radio-relay circuits*

Technical characteristics representative of radio-relay circuits near the 2 GHz band as given in Report 387, are listed in Table I. That Report contains the analysis which led to the current pfd limits, based on satellites in the GSO.

TABLE I – *Representative parameters for radio-relay circuits near 2 GHz*

Type of system	High sensitivity
Hop length (km)	60
Antenna mainbeam gain (dBi)	38
Feeder loss (dB)	3
Receiver noise temperature (K)	750
Channel free-space thermal noise (pW0p)	25

For the present analysis, the radio-relay receiver noise temperature was permitted to vary from 300 to 1200 K to ensure that currently known systems were taken into account. The channel thermal noise in Table I depends on the number of hops, receiver noise temperature, and the number of hops fading simultaneously. Calculated results [Panter, 1972] show that the thermal noise in a channel may be based on four different CCIR noise criteria, varying from 7.9 to 62 pW (unweighted). The most stringent requirements are short-term noise specifications set by Recommendation 393. The diversity used in all of the line-of-sight long-haul systems allows the systems to meet the recommended noise criteria. Limiting the interference noise levels in a receiver to a low level is especially important for receivers with higher sensitivities. For this analysis, the channel thermal noise of receivers was assumed to vary from 10 to 25 pW. As a practical matter, 25 pW generally corresponds to receiver noise temperature of 750 K.

The frequency channel arrangement in Recommendation 283 indicates that in the design of radio-relay circuits, adjacent hops should be separated in frequency. This requirement helps mitigate intra-system self-interference. In practice, two, four, and six frequency plans are common. This arrangement tends to reduce the number of possible entry points for interference from a space system into radio-relay circuits.

2.4 *Models*

Two analytical models were used for this analysis. They are modified versions of earlier models. One model, discussed in Report 387, and referred to as the geostationary model, is valid for sharing between fixed-satellite service systems and systems in the fixed service using line-of-sight techniques. The other model, referred to as the non-geostationary model [Locke and Rinker, 1978], is based on the visibility statistics analysis given in Report 684 (Geneva, 1982). This model provides an algorithm for the analysis of sharing between low orbit satellites and fixed-service systems. Both of these models were modified to reflect the differences between satellite systems near 2 GHz and fixed-satellite systems in the 6/4 GHz bands.

2.4.1 *Geostationary model*

The assumptions used in the development of the original model included 3° satellite spacing in the geostationary-satellite orbit and an FDM-FM analogue line-of-sight radio-relay circuit of 50 hops, with a total length of 2500 km. Interference from each visible satellite was assumed to enter each receiver in the radio-relay circuit. The input interference-to-noise ratio, for each 4 kHz bandwidth at the input to a channel, was assumed to be equal to the interference-to-noise ratio at the output of the channel. (The relationship between input and output ratios is termed the receiver transfer function.) These assumptions, while correct for sharing analyses between fixed-satellite systems and radio-relay circuits, are inappropriate for sharing analyses between space systems and radio-relay circuits in the 2 GHz band.

For the modified geostationary model, the satellite angular spacing in the geostationary-satellite orbit was allowed to vary from 10° to 20°. In addition, the fact that satellite emission spectra of space systems in the 2 GHz band are not uniform and are generally narrow-band, requires modification of the receiver transfer function to provide a more appropriate relationship for the analysis in this Report. The derivation and subsequent application of this function are given in [Farrar, 1984].

2.4.2 *Non-geostationary model*

The non-geostationary model uses most of the system characteristics used by the geostationary model, except the satellites are not fixed with respect to radio-relay stations. A low orbit satellite has the following characteristics when observed from a given point on the Earth:

- it is not visible most of the time;
- it is in motion, relative to the ground; and
- in general, when visible, it does not follow the same path, relative to the observer.

This relative motion causes the received emissions from spacecraft to vary widely, both in magnitude and angle-of-arrival. This variation is taken into account by the non-geostationary model.

The interference power received by radio-relay circuits from transmitting non-geostationary satellites, over a long period, can be described as a time-dependent function. The evaluation of this function for any given location, defined by a finite region in an orbit, was done in two steps. The first step was to evaluate the percentage of time that a satellite remains in that region, and the second step was to calculate the interference received by radio-relay circuits in that region. The non-geostationary model procedure for evaluating the interference power is similar to that used in the geostationary model algorithm.

The percentage of visibility time from any point on the Earth for an arbitrarily large number of orbital tracks of a given satellite may be calculated using equation (1) derived in Report 684 (Geneva, 1982).

$$T = \frac{\Delta\lambda}{2\pi^2}\left[\arcsin\left(\frac{\sin(L_1)}{\sin i}\right) - \arcsin\left(\frac{\sin(L_2)}{\sin i}\right)\right] \times 100 \tag{1}$$

where:

T: percentage of visibility time,

$\Delta\lambda$: longitudinal segment on the orbital shell between the latitudinal limits of L_1 and L_2 (rad),

L_1, L_2: upper and lower latitudes of the visibility region (degrees),

i: inclination angle of the satellite orbit (degrees).

This equation relates the long-term visibility of a satellite transmitting from a region of its orbit to the inclination angle and latitudinal and longitudinal bounds of the region.

Briefly, the non-geostationary model algorithm uses equation (1) to calculate the percentage of time that every region of the orbital sphere is visible to a radio-relay system. The interference power received by radio-relay circuits as a function of time is then calculated for each region. A plot of the interference received by a radio-relay circuit, as a function of the percentage of time, is the desired output from the model.

3. Results

The model parameters for line-of-sight radio-relay systems used in both the geostationary and non-geostationary models, with a minor change, are listed in Table I. The hop length of 60 km was changed to 50 km to be consistent with the hypothetical reference circuit presented in Recommendation 393 which was used in this analysis.

The overall receiver noise temperature used in the analysis was 750 K, which corresponds to a noise figure of 5.5 dB. This is practical and accommodates future growth in the design of radio-relay receivers in the 2 GHz band. Receivers with noise figures as high as 12 dB are presently in use.

The value of the thermal noise power allowed in a receiver, calculated on the basis of noise criteria discussed in Recommendation 393, varies from 8 to 25 pW0p. Higher allowable values of free-space thermal noise power (see Report 387) result in lower (more negative) permissible pfd limits according to the geostationary and non-geostationary models used in this Report. In the calculations of pfd limits in Report 387, the mean thermal noise power was assumed to be 25 pW0p. The interference analysis in this Report was performed using the pfd levels given in Report 387.

3.1 *Sharing between geostationary satellites and fixed-service systems*

A review of available satellite data bases indicates that a 10° to 20° separation is currently a reasonable assumption for the 2 GHz band because of the limited number of satellites required to provide service and also due to sharing considerations within the space service.

The maximum pfd levels which do not exceed the criteria given in Recommendation 357 were calculated for 10°, 15° and 20° angular separation and are listed in Table II. These new values will prohibit interference levels from exceeding the criteria given in Recommendation 357. The results in Table II, corresponding to a 15° satellite spacing and double frequency plan for a radio-relay circuit are considered to be reasonable for sharing purposes. Using a 15° separation implies that the emissions from approximately 13 satellites could continuously enter the receivers in a hypothetical reference circuit. This conservative view is necessary to provide freedom for the technological development of future fixed systems. The calculated maximum pfd levels corresponding to 15° satellite spacing and double frequency plan are 10 dB higher than the current pfd limits in No. 2557 of the Radio Regulations.

3.2 *Sharing between non-geostationary satellites and fixed-service systems*

The orbital parameters for space stations in non-geostationary orbits were derived based on the discussions given in § 2 and the characteristics of space services authorized in the 2 GHz band. Representative characteristics for non-geostationary satellites are listed in Table III.

The parameters listed in Tables I and III were used as inputs to the non-geostationary model. The results plotted by the program are shown in Fig. 2. Curve B is identical to the data shown in Fig. 1 and curve A represents the total interference to a hypothetical reference circuit from eight satellites inserted in orbits ranging from 300 to 1200 km altitude. This curve applies for the case of a radio-relay circuit having a free-space thermal noise level of 25 pW0p and was calculated based on all satellites operating at the maximum allowed pfd levels. Note that curve A is below the curve B criteria by approximately 15 dB for 0.05% of the time. For all other percentages of time, the differences between the two curves are greater than 15 dB. The results show that the pfd levels could be increased by 15 dB without exceeding the interference criteria.

TABLE II – *pfd levels from geostationary satellites which permit sharing with line-of-sight radio-relay systems* *

Radio-relay circuit		pfd levels (dB(W/(m² · 4 kHz)))		
Frequency plan	Latitude (degrees)	Satellite spacing (degrees)		
		10	15	20
Single	20	–147.7	–145.6	–142.8
Single	30	–147.0	–145.5	–143.2
Single	40	–147.2	–148.0	–147.4
Single	50	–149.0	–146.9	–146.2
Double	20	–143.6	–142.2	–139.7
Double	30	–144.0	–142.6	–140.1
Double	40	–143.8	–144.3	–140.0
Double	50	–146.0	–143.1	–142.3
Four	20	–141.1	–139.7	–137.0
Four	30	–140.9	–139.0	–138.1
Four	40	–140.9	–142.0	–137.7
Four	50	–142.2	–144.0	–138.4

* For angles of arrival between 0° and 5°.

TABLE III – *Representative characteristics of non-geostationary satellites*

Satellite orbit altitude (km)	300-1200
Number of satellites visible to receivers (1)	8
Satellite inclination angle (degrees)	10-99

(1) The assumption of eight satellites implies that there are eight satellite emitters whose emissions are simultaneously received by a radio-relay circuit. In addition, all the satellite orbits are assumed to be statistically independent. These assumptions may seem to be too conservative in favour of the radio-relay circuits. However, it is important to avoid using orbital parameters that are marginal and hence might inhibit the potential growth of radio-relay circuits. It should be pointed out that a relatively large increase in the number of visible satellites results in only a small increase (approximately logarithmic) in total pfd levels.

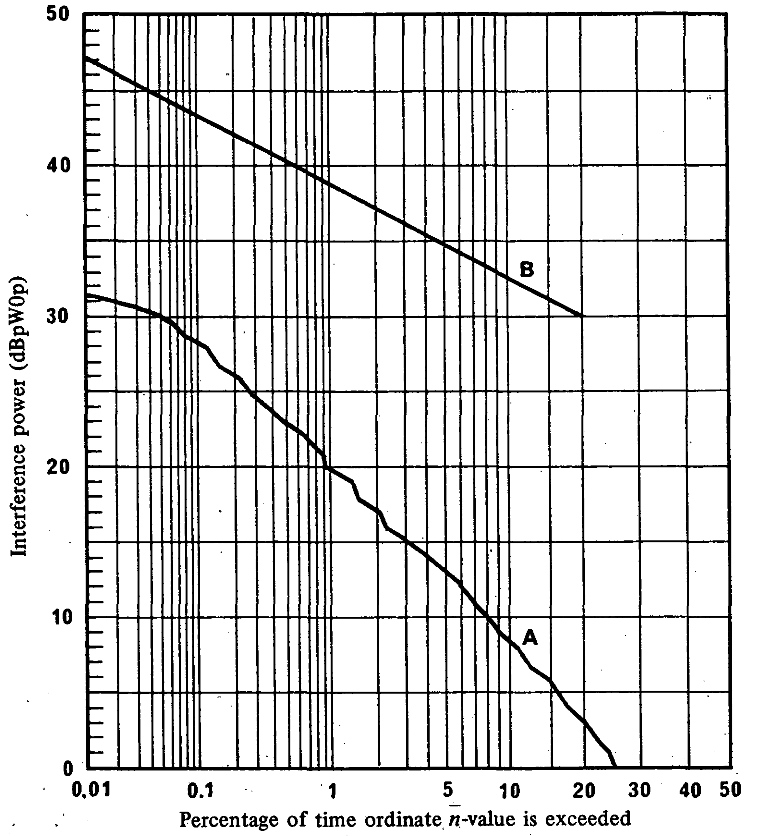

FIGURE 2 – *Calculated interference to a hypothetical reference circuit from non-geostationary satellites*

Curves A: calculated interference level
B: CCIR criteria

4. Conclusions

The analyses in this Report, based on Recommendations 357 and 393, indicate that, near 2 GHz, pfd levels from space stations both in geostationary and low orbit could be increased compared to present limits without exceeding the interference criteria of line-of-sight radio-relay circuits. These results are due to the characteristics of space stations and radio relays, satellite orbit spacing, the number of satellites, and radio-relay frequency plans in the 2 GHz band. Additional studies may be required to determine the applicability of these results to sharing with other radio-relay systems in use and being developed at the present time as well as with other services.

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REPORT 679-2

CHARACTERISTICS AND EFFECTS OF RADIO TECHNIQUES FOR THE TRANSMISSION OF ENERGY FROM SPACE

(Question 20/2)

(1978-1982-1986)

1. Introduction

This Report is a review of the technology for the transfer of energy through free-space by a highly collimated microwave beam. The collection and conversion of the incoming radio energy to conventional electrical energy comprises a unique technology which differs from the traditional methods of receiving and processing radio energy in communications services. The efficient transfer of energy using an electromagnetic beam could permit coupling of terrestrial power transmission systems to power sources and sinks located in the atmosphere, in space, or on the Earth's surface. The concept of remote energy generation by high power arrays of solar cells on geostationary satellites has been of particular interest.

Energy transfer by radio waves was first pioneered by Tesla [O'Neill, 1944; Hunt and Draper, 1964] at the turn of the century. Tesla became interested in the general concept of resonance and sought to apply this to the transmission of electrical energy from one point to another without wires. He built a large "Tesla coil" with which he hoped to produce oscillations of electrical energy around the surface of the Earth and to set up standing waves into which he could immerse his receiving antennas at the optimum point. His ideas were decades ahead of the technology that would enable their realization [Susskind, 1968]. The event which advanced technical capabilities and precipitated interest in the use of microwaves for power transmission was the development of super-power generation at microwave frequencies in the early 1960s [Skowron *et al.*, 1964; Luebke and Caryotakis, 1966]. This programme resulted in high-efficiency tubes with high power handling capability (several hundreds of kilowatts).

The first demonstration of the efficient transmission of significant amounts of power by microwaves took place in May, 1963 [Brown, 1964]. The technology has since been greatly advanced [Brown, 1969a; Robinson, 1970; Brown and Dickinson, 1975].

Of the various criteria that could be used to evaluate the progress of microwave energy, transfer efficiency is the most important. By this standard, the efficiency of the overall system has moved from 15% in 1963 to 54% in 1975 [Brown and Dickinson, 1975]. Further development of energy conversion components in the system might increase the efficiency to 70%. Additional criteria for the evaluation of the technology, particularly as it relates to system applications, include power handling capability, reliability, ability to dissipate waste heat, and cost. Other, more important criteria, are the external effects, such as radio frequency interference from spurious frequencies and particularly, the impact upon the environment. A discussion of some of these aspects, in addition to efficiency, follows.

2. The technology of free-space microwave energy transmission

A microwave energy transmission system may be divided into three principal elements which link at their physical interfaces. These elements involve separate technologies which combine to determine the overall efficiency and power handling capability of the system. The elements are:

- element (1): conversion of d.c. electrical energy to microwave energy,
- element (2): transmission of the microwave energy,
- element (3): collection and rectification of the microwave energy.

2.1 *The conversion of d.c. electrical energy into microwave energy*

In the conversion of d.c. energy into microwave energy, the efficiency should be as high as possible to minimize the size of the prime source and the difficulty in dissipating heat due to convertor inefficiency. There are several methods of conversion but only one of them has demonstrated the order of efficiency desirable for a power transmission system. This device is the re-entrant beam, crossed-field device [Brown, 1970]. In its oscillator form, it is called the "magnetron" while in its amplifier form it is called the "amplitron". Both of these forms have resulted in tube designs with efficiencies of 80 to 90%.

2.2 *The microwave beam link*

All elements of transmission from the output of the generator to the aperture area at the receiving point are considered in the discussion of the microwave beam link. It was theoretically shown [Goubau and Schwering, 1961], and later confirmed [Li, 1965] that energy can be transmitted with efficiencies approaching 100% from a properly illuminated and contoured transmitting aperture to a receiving aperture. This relationship [Goubau, 1970] is shown in Fig. 1. The efficiency factor τ is:

$$\tau = \frac{\sqrt{A_r A_t}}{\lambda D} \tag{1}$$

where:

A_r and A_t : the receiving and transmitting aperture areas respectively,

λ : the wavelength of the radiation,

D : the distance between the transmitting and receiving apertures.

The relationship shown in Fig. 1 assumes a tapered illumination of the transmitting aperture and further assumes that the radius of curvature of the phase front at launch is equal to the distance *D*.

That the transmission efficiency can approach 100% has been demonstrated experimentally [Degenford *et al.*, 1964]. Experimental demonstrations may be scaled to small dimensions providing the aperture diameters and the separation of the apertures correspond to several wavelengths.

2.3 *Efficient microwave beam launching*

To launch a microwave beam efficiently the amplitude and phase of the microwave energy must be properly distributed over the face of the transmitting aperture. There are a number of ways of illuminating the transmitting aperture, e.g. by a phased array with corporate feed from a single microwave source, by an active phased array in which the radiating elements are individually driven, by an illuminating horn and lens, or by a traditional illuminating horn and reflector.

Due to the large amount of power involved, the active phased array stands out as superior. This is most applicable to very large arrays, particularly those located in space and working as a retro-directive array to control the phase coherence at the aperture.

2.4 *Collection and reconversion of microwave energy into d.c. energy*

In order to complete the microwave energy transmission system, it is necessary to absorb the microwave energy by a receiving antenna, and to convert it back into d.c. energy. The conventional way of doing this would be to use a large ellipsoidal reflector to reflect the intercepted microwave energy into a small horn which may be terminated in a waveguide or coaxial line. The microwave energy would then be converted back into d.c. energy. However, this procedure involves a number of problems which a new type of structure known as the "rectenna" eliminates [Brown, 1969b]. (The term "rectenna" is a combination of the words "rectifier" and "antenna".)

In the rectenna structure, the rectifying elements are uniformly distributed throughout the receiving aperture, so that the microwave energy which is intercepted in a local region of the receiving aperture is immediately converted back into d.c. energy. The rectenna efficiency consists essentially of two parts – the microwave collection efficiency and the rectification efficiency. By careful matching of the rectenna input impedance to that of free space, the collection efficiency can approach 100%. The rectification efficiency depends upon the efficiency of the rectifying diodes themselves and the ability to design a rectifying circuit which effectively restricts re-radiation of harmonics by converting them into useful energy.

3. Applications for free-space power transmission by microwave beam

3.1 *General applications*

Properties of microwave energy transmission include:

- no mass either in the form of wire conductors or ferrying vehicles is required between the source of energy and the point of consumption;
- the direction of energy transfer can be rapidly changed by repointing the transmitting antenna;
- there is no loss of energy in the transfer of energy through the vacuum of space. Furthermore, over a relatively broad frequency range there is little loss of energy in the transfer of energy from space to the Earth's surface;
- the mass of the transducers at the transmitting and receiving points can be small.

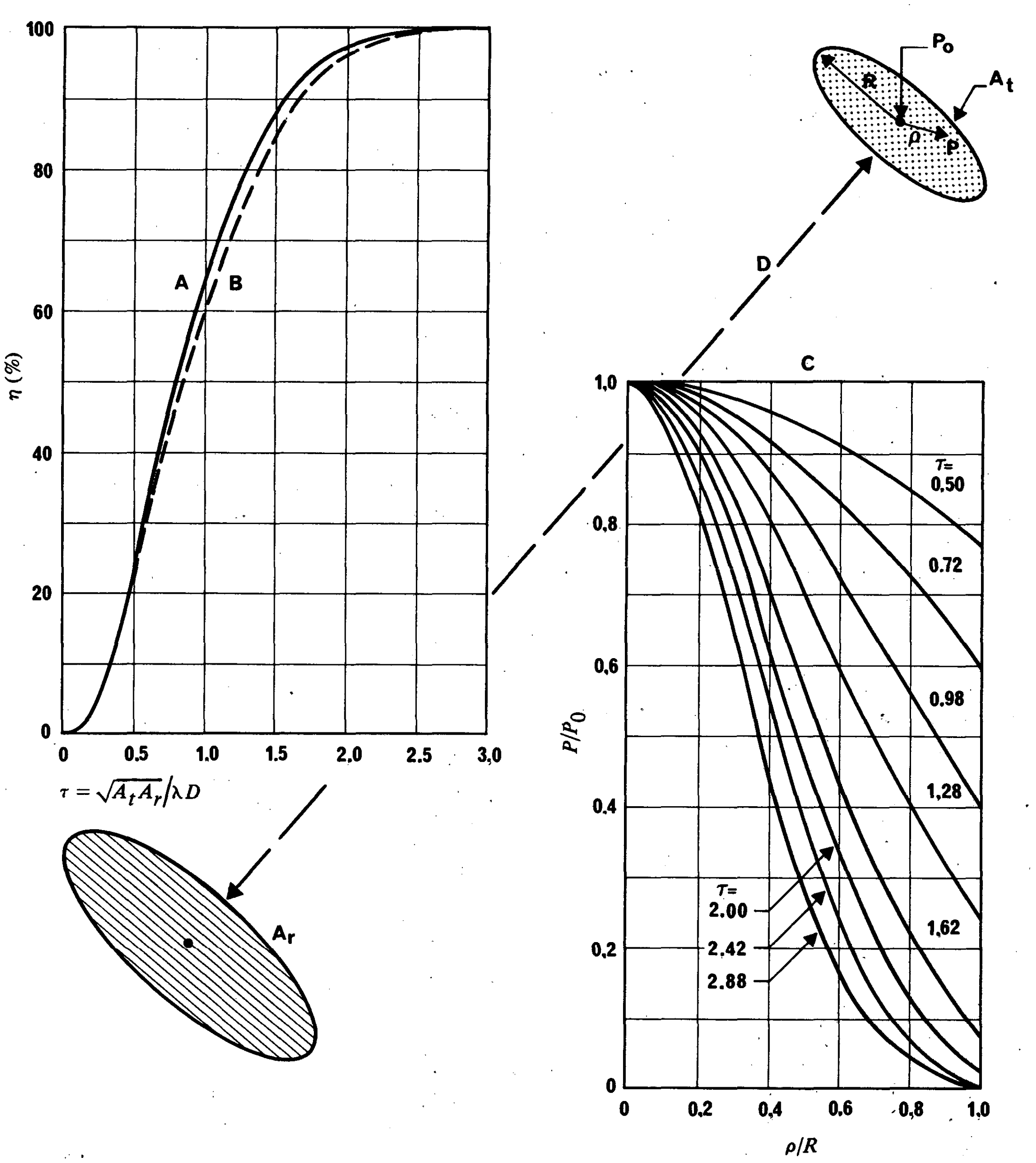

FIGURE 1 – *RF power beam transmission efficiency*

A: circular aperture
B: quadratic apertures
C: optimum aperture taper
P_0: power flux-density at the centre of the aperture
P: power flux-density at the edge of the aperture
R: radius of the aperture
ρ: radius to a point on the aperture
η: efficiency

It is unlikely that microwave systems will find wide application for energy transfer in terrestrial systems. However, there could be useful applications for the transmission of power to remote locations or between two points separated by a very hazardous environment, or where it is desired to eliminate a mechanical connection for any reason. In the area of space applications, the transfer of energy between two satellites, up to a distance of a few kilometres, has been studied by NASA [Robinson, 1970]. Here the potential specific application is to use a central source in a space base complex to service the energy needs of several satellites, by simply repointing the transmitting antenna, thereby freeing the satellites from the need of a separate power supply.

3.2 *Energy from solar satellites*

A system for bringing energy down to Earth from a geostationary-satellite by converting solar energy to electrical energy has been studied. Such a system would provide energy from an inexhaustible source external to the Earth [Glaser, 1968; J. Microwave Power, 1970].

The solar energy falling on the Earth is so diffuse and variable that it is difficult to use. However, a geostationary solar array can be uniformly illuminated 99 per cent of the time, and cancelling of acceleration forces and the absence of atmosphere and wind make it possible to build an extremely lightweight structure, free of many of the corrosive, fouling, and deteriorating mechanisms encountered on Earth. It was therefore proposed [Glaser, 1968] that advantage be taken of such an array in space to achieve a new kind of energy source. This suggestion has led to a baseline design for the Satellite Solar Power Station (SSPS). In this, large solar photo-voltaic cell arrays would convert the Sun's radiant energy to d.c. energy, which would then be transferred to a large active phased array mounted by means of rotary joints to the solar arrays. The active phased arrays would convert the d.c. energy to microwave energy at a preferred wavelength suitable for penetration of the Earth's atmosphere and focus that energy into a narrow beam pointed towards a designated receiving area on the Earth's surface.

The microwave beam in space would be well collimated to arrive at the Earth's atmosphere with the same energy concentration as at launch. The microwave energy reaching the receiving area on Earth would be efficiently converted back to d.c. energy by the rectenna.

4. Conceptual satellite solar power station (SSPS)

A conceptual design of an SSPS [Reference System Report, 1978] has a transmitted power level of 6500 MW. In this design, the transmitting antenna array is 1 km in diameter. The antenna dimensions are derived from the relationship between efficiency and physical parameters given in Fig. 1 for a frequency of 2450 MHz which would penetrate the Earth's atmosphere with low attenuation. The projected overall efficiency of the microwave energy transmission system, including the conversion efficiencies at both ends, is 68%.

A 1 km diameter circular phased array antenna would use an estimated τ of 1.62 (see Fig. 1). The power taper would be 10 dB from the centre to the edge of the aperture and the power of the radiating elements would decrease in steps of approximately 1 dB in 10 nearly equal area concentric rings around the centre of the transmitting array. The half-power beamwidth is 0.008° and the side lobes decrease asymptotically to a level of -49 dB relative to the main beam.

The beam is centred on a beacon transmitter at the middle of the collecting area on Earth. The power flux-density at the centre of the collecting area is 20 mW/cm^2. A rectenna array 5 km in diameter would encompass all power flux-densities greater than about 0.5 mW/cm^2. A guard area extending out to a 10 km radius would encompass power flux-densities in excess of about 50 μW/cm^2. The concentration of the antenna beam would provide protection to radiocommunication services because the side-lobe levels outside the collecting area, and adjacent guard areas on Earth, would be attenuated by 49 dB using the transmitting antenna described previously.

Filtering the out-of-band transmissions can reduce the "spillover" into adjacent frequency bands. The design characteristics of a representative transmitter system output spectrum are illustrated in Fig. 2 where it is assumed that the transmitter power spectrum is spread evenly over the band 2450 ± 10 MHz. At the edge of the 5 km diameter collecting area the power flux-density is -30 dB(W/(m^2 · 4 kHz)), outside the surrounding guard area it is -50 dB(W/(m^2 · 4 kHz)). The ITU limits space station emissions in the adjacent frequency bands to a power flux-density of -154 dB(W/(m^2 · 4 kHz)) (for low elevation angles, see No. 2557 of the Radio Regulations). Hence, the transmitter filters must provide 104 dB attenuation in the 40 MHz between the transmitter spectrum and the edge of the industrial, scientific and medical (ISM) band. The conceptual design for the SSPS envisages a 5-cavity klystron which provides 120 dB attenuation at the band edge (see Fig. 2). The margin of 16 dB appears to provide sufficient protection for the radiocommunication services in adjacent bands. This conceptual design resulted from experiments using magnetrons and klystrons with bandwidths which are of an order of magnitude narrower than that considered in Fig. 2.

Among the current unknowns in the conceptual design, are the power flux-density levels of the harmonic transmissions, the level of the scattered and reflected radiations from the rectennas and the beam pointing capability of the satellite antenna. Should these radiations prove to be harmful, possible solutions are to increase the filtering on the space transmitter, or to designate frequency bands which are harmonic multiples of the 2450 MHz carrier for ISM and energy transmission purposes.

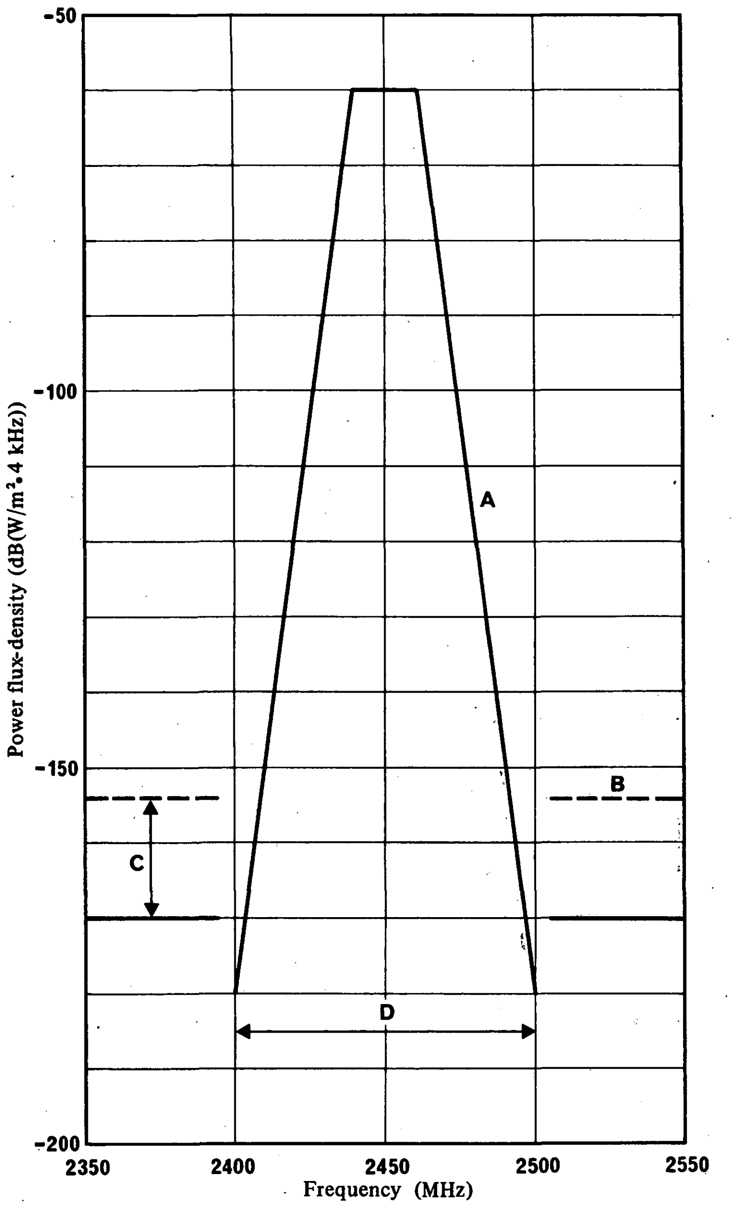

FIGURE 2 – *Conceptual design of solar power satellite power flux-density versus frequency outside of the 10 km radius guard area*

A: 5 cavity klystron transmitter system spectrum

B: ITU limit

C: 16 dB margin at band edge

D: ISM band

5. Additional considerations

The use of beams of microwave radiation for transmission of energy in free space would entail the radiation of very large quantities of radio energy. This presents problems in ensuring that the microwave radiation is within acceptable levels outside the designated collecting area, and that the spectrum "spillover" into adjacent bands does not result in harmful interference to other radiocommunication services. An additional problem would be that of considering whether passenger carrying aircraft can safely transit a 5 km diameter power beam, and, if not, the setting up of procedures to protect against such transits. Good engineering practices can greatly reduce the unwanted radiations in space and frequency, but the levels cannot be reduced to zero. If the transmitted power is high, even a high degree of suppression may not eliminate harmful interference to other services. Even though some of the other services may be operating systems capable of tolerating high levels of interference, such services might be subjected to levels of interference which are harmful to their operations. It should be noted that interference to a safety service such as radionavigation could cause serious consequences even if such interference is momentary.

The Radioastronomy Service, in particular, is vulnerable to low-level interfering signals, because of the use of highly sensitive receivers and long integration times. Similar considerations apply to deep-space research stations. The characteristics of radio telescopes and radioastronomy receivers can be described accurately, and the levels of potentially harmful interference can be specified. These requirements have been carefully reviewed and are given in Report 224. The harmful interference levels vary with frequency and are generally many decibels (typically 50 to 90 dB) below the harmful interference levels generally agreed upon for other services.

A review of possible interference to radioastronomy and radar astronomy from solar power satellites [Thompson, 1981] (Report 853) has shown that several mechanisms need to be considered. The power signal in the system proposed is at a frequency near to radioastronomy bands and there are harmonics which are close to others. The strong fields produced at the Earth could overload the input stages of radioastronomy receivers close to the rectenna site or at more distant sites where the interference pattern of the power transmitting antenna can have large peaks. Other interference, more widespread in frequency and in geographical coverage, could result from transmitter-generated noise, thermal noise from the satellite arrays, and perhaps from the reflection of terrestrial signals by those arrays. Interference from the receiving rectennas could occur if sites are not chosen with care in relation to radioastronomy observatories.

All these mechanisms need further study if implementation of solar power satellites proceeds, because there would be zones centred on the geostationary satellite orbit in which radioastronomy observations would be precluded, or at least seriously degraded. The effects of thermal radiation alone could be sufficient to degrade observations over a substantial part of the sky.

In view of the more stringent requirements of the radioastronomy service, the designers of energy transmission systems using radio techniques should refer to the harmful interference levels of Report 224 when assessing the impact of such energy transmission systems on other services.

It is noted that other effects including biological hazards and effects on the ionosphere are not considered.

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REPORT 680-1 *

TECHNIQUES FOR TELECOMMUNICATION IN THE SPACE RESEARCH SERVICE BY MEANS OF ELECTROMAGNETIC WAVES IN THE INFRA-RED AND VISIBLE LIGHT REGIONS OF THE SPECTRUM

(Question 53/1)

(1978-1986)

1. Introduction

Continued growth in electro-optical technology – especially lasers – has extended the spectral operating regions for telecommunication systems into the infra-red (IR) and visible portions of the spectrum. This Report examines laser operating principles and selected telecommunication applications of lasers in the infra-red and visible spectra.

2. Definition

The word "LASER" is an acronym formed from Light Amplification by Stimulated Emission of Radiation. Lasers are optical masers (Microwave Amplification by Stimulated Emission of Radiation) and all such devices constitute a practical application of Planck's Law, i.e.

$$E = h \cdot \nu \tag{1}$$

where:

E is the energy emitted, joules

h is a constant (6.625×10^{-34} joule-second)

and ν is the frequency of the energy radiated, Hz

3. Elements of operation

All lasers employ the elements illustrated in Fig. 1 in their operation. An active medium is stimulated by energy from an external source, raising some of the constituents (atoms, ions, or molecules) to a higher energy level. After a time interval, each excited constituent spontaneously falls to the original, or ground energy level, emitting the radiant energy predicted by Planck's formula as the transition occurs. If the stimulus is sufficiently intense, more constituents will move to the excited state than those remaining in the base state and a population inversion is then said to exist.

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* This Report should be brought to the attention of Study Group 1.

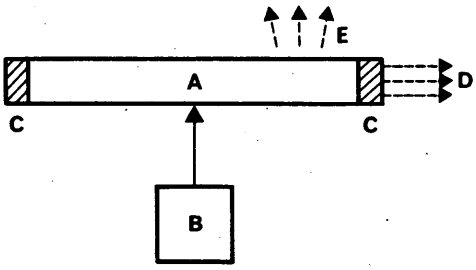


FIGURE 1 – *Typical laser cavity elements*

A: Active medium
B: External energy source
C: Facing mirrors
D: Laser beam
E: Spontaneous radiation

In this condition, a signal applied to the active medium, such as spontaneous radiation (quantum noise), is amplified, since more signal energy is released in triggering downward transitions (with a resultant, in-phase release of radiant energy) than is absorbed in triggering upward transitions.

The system can be turned into an oscillator by providing positive feedback – as with the mirrors in Fig. 1. If the two facing mirrors form a reasonant cavity, amplified radiation is reflected back into the active medium in phase with the amplified signal, stimulating further, in-phase amplification on each pass. Provision of a means of extracting a portion of these intra-cavity oscillations at one or both ends of the cavity can then produce a tightly collimated beam of energy which may be essentially monochromatic and highly coherent.

The active medium may be an appropriate gas, crystalline semi-conductor solid, or liquid, while the external stimulus (or pump) may be a light source, an electric current, an electron beam, etc. The most common crystalline lasers, gas lasers and liquid lasers (see Table I) are optically pumped, while most semi-conductor lasers are electrically pumped.

TABLE I – *Examples of the most common types of laser*

Type	Materials	Active species	Main Wavelengths (μm)
Solid-ionic	Neodymium (Nd) dopant in Yitrium Aluminum Garnet	Nd ions	1.06
	Ruby	Chromium ions	0.69
Gaseous	Helium-Neon mixture	Neon atoms	0.63
	Argon	Argon ions	0.4545 to 0.5287
	CO_2	CO_2 molecules	10.6
	N_2	N_2 ions	0.337
Liquid	Rhodamine GG dye	Dye molecules	≈0.6 (tunable)
Semiconductor	GaAs	Electron-hole recombination	≈0.86

4. Operating modes

Most laser materials can be used to produce emitters which can deliver a continuous wave output or a pulsed output, although not usually both from the same design. Both modes find practical use in operating systems depending on the application.

Directly pulsed lasers, i.e. those in which the pulsed output is attained by directly applying a pulsed excitation, can yield pulse widths as short as 100 µs. Pulses as short as 1 to 10 ns are possible from *Q*-switched lasers. In *Q*-switching, the *Q* of the cavity is spoiled as the excitation builds up. At a critical moment, feedback is restored allowing a very large pulse to build up and be coupled out very quickly. The feedback path can be switched by a rotating mirror or by a Pockels cell (or other electro-optical switch). A Pockels cell is an optical device made of a crystalline material which has the property of rotating its plane of polarization under the influence of an applied electric field. When used in combination with a plane polarizer, a Pockels cell is capable of very high speed switching of an optical path. The output of a *Q*-switched laser employing a Pockels cell as the *Q*-switch, is a plane polarized light beam. *Q*-switched lasers can produce very high peak energy levels in very short duration pulses. Even shorter pulses than for *Q*-switched systems can be produced through other techniques; such as cavity dumping and mode-locking.

5. Laser applications

Numerous uses have been conceived for lasers and many have been successfully demonstrated. Table II lists some of the applications of lasers in communications, night vision, space remote sensing and other areas. All of these systems have been developed to some extent and found to be workable. Several of the more promising concepts for space research are described in the following sections.

6. Communications

Visible and infra-red radiation can be employed in all the space communication links illustrated in Fig. 2. Two way, wideband space-to-space links between synchronous relay satellites have been studied by space research engineers. The most promising approaches have been proposed around Nd:YAG and CO_2 lasers. Block diagrams, operating characteristics, and typical performance data for both emitter types are included in Annex I. Space-to-space links between low altitude observation satellites and higher synchronous relay satellites have also been found feasible, as well as space-to-Earth down links from synchronous relay satellites to earth stations. This latter application is limited by the weather environment near the earth station, due to the relatively high absorption and scattering of electromagnetic energy in this spectral region by atmospheric moisture.

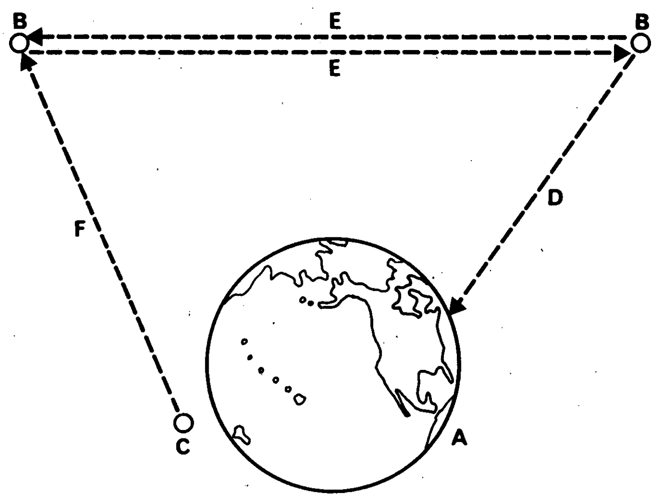


FIGURE 2 – *Space applications of laser communications*

A: Earth

B: Synchronous relay satellite (SRS)

C: Low-altitude observation satellite (LAS)

D: SRS to Earth down-link

E: SRS-SRS two-way wideband link

F: LAS-SRS link

7. Echo ranging

Active echo ranging systems using laser emitters have been developed for terrestrial use and are now being proposed for space research. Figures 3 and 4 illustrate ground based and spaceborne applications for laser ranging. Precision tracking of several reflecting satellites is planned by means of light detection and ranging (LIDAR) sensors. Reflecting satellites may use retroreflectors and specular reflecting surfaces to return pulsed light energy toward its source. Some of the satellites which use this technique for precision tracking measurements are: GEOS-B, GEOS-III, STARLETTE, LAGEOS and TIMATION.

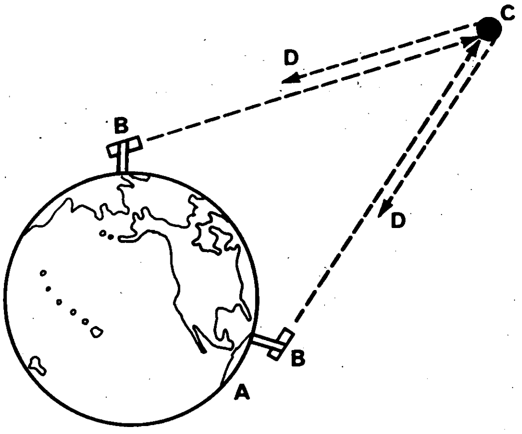


FIGURE 3 – *Earth-based laser applications – echo ranging*

A: Earth

B: Lidar tracking mount

C: Reflecting satellite – e.g. GEOS-B, GEOS-III STARLETTE, LAGEOS TIMATION

D: Incident and reflected light

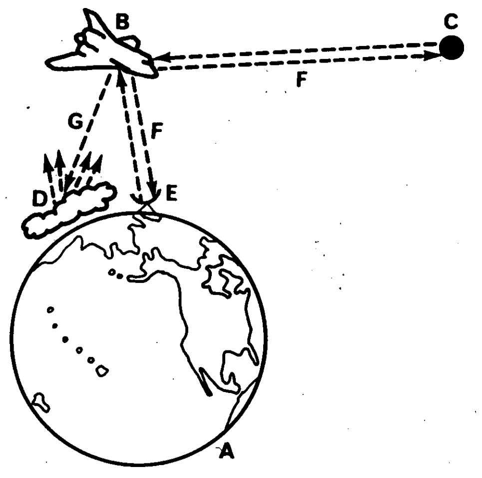


FIGURE 4 – *Spaceborne laser applications – echo ranging*

A: Earth

B: Space shuttle

C: Lageos satellite

D: Diffuse reflection from cloud cover

E: Corner cube retroreflector

F: Incident and retroreflected light

G: Incident light

Laser echo ranging techniques, discussed in Annex II, will be used in Space Shuttle experiments or precision tracking of terrestrial corner cube retroreflectors and satellite-borne reflectors such as those on LAGEOS. A cloud climatology experiment is planned for measuring the backscatter of light energy from clouds, tracking cloud distribution geographically and by altitude, etc.

8. Comparisons

Lasers offer several potential advantages for space-to-space communications when compared with conventional microwave systems. The tightly collimated beams of lasers result in very high directivity gains with consequent high effective radiated power levels. Furthermore, the absence of side and back lobes together with highly collimated beams results in low interference susceptibilities. On the other hand, the tracking servo systems must be much more precise in order to establish and maintain such links. Acquisition procedures may require the use of other, less precise sensors to assist in aligning a transmitter beam toward the receiving station. Also, if the receiving aperture possesses a high gain, receiving aperture alignment may require great precision.

TABLE II – *Possible laser applications*

Space radiocommunications	*Space remote sensing*
Satellite-to-satellite	Geology and mineral resources
Satellite-to-Earth	Geography and cartography
Earth-to-satellite	Oceanography
Intra spacecraft – fibre optics	Enrivonmental quality
Terrestrial radiocommunications	Agriculture and forestry
Atmospheric point-to-point	Hydrology and mineral resources
Underwater point-to-point	*Construction and surveying*
Intra-system – fibre optics	*Drilling, cutting, welding*
Guidance	*Navigation*
Electro-optical image correlator guidance systems	*Measurement systems*
Infra-red imaging guidance	*Printing and graphics*
Television guidance	*Readers, recorders and displays*
Laser trackers	*Medical systems – surgery and instrumentation*
Night vision	*Materials processing*
Low light level television illuminators	*Nuclear fusion*
Image intensifier system illuminators	*Isotope separation*
Night driving	
Surveillance	

Since angular resolution is proportional to λ/d, any given resolution requirement can be fulfilled with smaller apertures as wavelength decreases. As a result, high resolution apertures are much smaller at visible and near visible wavelengths than for microwaves. Also, the higher operating frequency of the laser makes wider transmission bandwidths theoretically possible. However, with the currently available components the full potential of laser communication systems has not been realized. While amplitude modulation has been demonstrated, the bandwidths have been limited by the component technology, meanwhile other types of modulation, e.g. frequency, phase, etc., have not yet been developed. Also, extremely short pulse widths available from Q-switched, cavity dumped, or mode locked lasers offer range resolutions unequalled by microwave radars.

9. Conclusions

Optical communication systems employing lasers as radiation sources are now being developed. These systems have the potential for broadband, interference-free links between points in space and between Earth and space. Links between Earth and space are limited by the effects of the atmosphere on electromagnetic radiation in the visible and near-visible spectrum. Links between points in space are not affected by the atmosphere. Interference susceptibility can be drastically reduced or eliminated through the use of tightly collimated beams and narrow receiver fields-of-view. The use of such beams can also yield high e.i.r.p., even with low power transmitters, due to increased gain directivity. However, tightly collimated beams require precision pointing and tracking loops, and special acquisition equipment for establishing communication links. Consequently, the potential advantages to optical communication systems appear to be high data rates, broad bandwidths, small size and lightweight, rather than low cost and simplicity.

Electro-optical echo ranging systems are being developed for a wide variety of applications. These systems are capable of high precision, interference free measurements of slant distance between the sensor and selected targets. Most laser rangefinders are likely to be characterized by tightly collimated, highly directive transmitter beams. Very narrow beamwidths are well suited for high resolution tracking and poorly suited for "search" operations. Consequently, laser rangefinders will probably be used in conjunction with other, less precise sensors which are well suited for the high volume search operations required in target acquisition. Background noise from natural and artificial sources will necessitate careful optical design.

ANNEX I

APPLICATIONS OF LASERS TO TELECOMMUNICATIONS

1. Introduction

An application of lasers to telecommunications is discussed in this Annex. Figure 5 is a functional block diagram of a typical unidirectional, optical communication system. The transmitter, consisting of a radiation source, transmission optics, a modulator and pointing-tracking servo equipment, is shown on the left. A receiver, consisting of collection optics, a detector, a preamplifier/amplifier, a demodulator, output electronics and pointing-tracking servo equipment, is shown on the right. A bidirectional relay link is similar, requiring a transmitter and a receiver at each end of the link to enable two-way communication. Each of these subsystems and components will be discussed in turn.

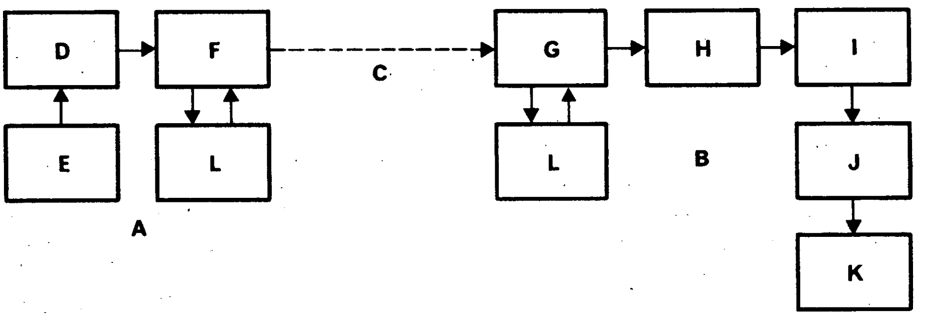


FIGURE 5 – *Functional block diagram of a typical optical communication system*

A: Transmitter
B: Receiver
C: Modulated light beam
D: Radiation source (laser)
E: Modulator
F: Transmitter optics
G: Receiver optics
H: Detector
I : Preamplifier/amplifier
J : Demodulator
K: Output electronics
L: Pointing-tracking servo loops

2. Transmitters

The laser transmitter emissions can either be directly modulated or may be externally modulated by an optical component. This component must be capable of modifying the amplitude, phase, polarization or other properties of the optical signal. The transmitter optics are analogous to a directive RF transmitter antenna. Furthermore, pointing-tracking servo equipment operating on the antenna is used to direct the emitted radiation beam toward the receiver in optical transmitters as well as in RF systems. A primary energy source and equipment are required to stimulate a specific laser and the efficiency of such power conversions are typically less than 10%.

3. Lasers

There are many design factors, between which trade-offs occur, and which are important in selecting a laser for communications service.

Those lasers which at present appear to have the highest potential for communication applications include: CO_2, Nd:YAG, frequency doubled Nd:YAG, HeNe, Argon and GaAs. The CO_2 laser is adaptable to high power outputs (up to $\approx$ 100 W) with AM or FM modulation for analogue or digital transmissions. Detectors which operate well at 10.6 μm are difficult to find, however. The Nd:YAG and doubled Nd:YAG lasers are best suited for pulsed transmissions and are usually externally modulated (especially at high data rates) because of the long fluorescent lifetime (230 μs). Nd:YAG lasers can be operated at high output power levels (up to 1000 W), while the output power of doubled Nd:YAG lasers is much lower owing to limited power dissipation by the doubler crystal ($LiNbO_3$ or $Ba_2NaNb_5O_{15}$ – localized hot spots at impurities can result in fractures). Helium-neon lasers can be operated only at low power levels (up to 100 mW), but they have long operating lifetimes ($> 2 \times 10^4$ hours) and they are capable of direct or external modulation for analogue and digital transmissions. Argon lasers can sustain average output powers of several watts and offer the same advantages as HeNe. GaAs, like other semi-conductor lasers, operates at low average power levels (up to 10 mW), but can be directly modulated very efficiently. The peak spectral output of GaAs lasers can be tailored to any specific wavelength between 0.75 and 0.90 μm.

4. Modulators

Modulators for directly modulated lasers consist of the electronics required to drive the laser oscillator. Direct modulation is normally used only with semi-conductor lasers, such as GaAs, and with HeNe lasers.

External modulators are components inserted in the transmitter optical path which have the capability of rapidly varying some property of the light beam output in accordance with the modulating information. An example is the use of a Pockels cell and linear polarizers to produce amplitude or phase modulation. The Pockels cell contains a crystal which rapidly rotates its plane of polarization under the influence of a varying electric field. For amplitude modulation the laser output beam is pre-polarized by a linear polarizer, modulated by the Pockels cell and then passed through a polarization analyzer before being propagated through space as an amplitude modulated light beam. In phase modulation, the beam is pre-polarized, modulated by the Pockels cell and then propagated at a constant light amplitude with varying polarization plane. The analyzer is incorporated in the receiver optical path in this latter case.

Another type of modulator is the acousto-optical system, which makes use of photoelastic variations in a crystal resulting from the propagation of acoustic waves. This effect has been observed in GaAs, $LiNbO_3$ and As_2Se_3. Magneto-optical systems have also been devised using magnetic iron garnet (YIG), which exhibit polarization plane rotation or optical absorption under the influence of a magnetic field.

5. Transmitter optics

The transmitter optics form the aperture through which the modulated beam is propagated toward the receiver. Transmitter optics consist of a collimating telescope, optical path stabilization, beam steering, and any other components or accessories used in transmitting the beam. For example, telecommunication beamwidths may be so narrow (for example, a few microradians) that special provisions must be made to align the transmitter and receiver apertures. Wide angle beacons and beacon trackers at each end are one way of establishing such a link.

6. Transmission medium

For the space-to-space link, propagation is made through free space. For Earth-to-space and space-to-Earth links, however, a part of the propagation path must be made through the atmosphere. In the visible and near visible portion of the spectrum, atmospheric effects are even more important than they are in the RF spectrum. Those effects which must be considered include: absorption, Rayleigh scattering, Mie scattering, refraction, diffraction, turbulence and turbidity. The combined effects are non-linear and difficult to predict for wide transmission bandwidths. Figure 1 of Report 681 shows the levels of molecular absorption due to the atmosphere, and Report 883 provides further details on atmospheric attenuation.

Atmospheric effects can totally prevent the establishment of optical communication links in certain geographic areas and may severely limit the maximum range in others. The probability of establishing a space-to-Earth or Earth-to-space communication link can be increased significantly by providing several widely separated points for earth stations. However, the expense and complexity of the system is increased considerably by this practice.

Space-to-space links do not experience the complications resulting from atmospherics. Background noise, however, is as important to system performance in this case, as it is in Earth-to-space and space-to-Earth links. Visible and as near visible emissions from the Sun and stars, from artificial light sources and from reflections by the Earth, the Moon and planets are all detectable by the optical receiver and must be considered in system design. Trade-offs between field of view, focal length, and aperture size are optimized for particular applications. Special protective circuits using sun sensors to prevent direct viewing of the Sun are also used to solve background problems in optical communication systems.

7. Receivers

Considerations for receiver optics and pointing-tracking servos are similar to those for transmitter optics. A stabilized, steerable, directive receiver aperture is formed for collecting energy from the transmitted beam. The collected radiant energy, is then focused on the sensitive surface of a photodetector. The resultant electrical signal is amplified and demodulated to yield the transmitted information as an output.

8. Detector

The detector is a transducer which converts modulated radiant energy to an electrical signal. This signal should be easily processed to remove the transmitted information. Typical detectors are photo-multipliers, photo-conductors, photo-emitters, bolometers (for long wavelength emissions, such as CO_2 at 10.6 μm), etc. A wide range of photo-sensitive semi-conductor materials is now available for detectors, giving a variety of spectral-temporal-spatial response characteristics for the visible and near-IR spectra. Choices are still limited in the far-IR. Detectors may be uncooled or cooled to reduce internal thermal noise. Coolers may be passive or cryogenically operated.

9. Signal processing

The raw detector output must be processed to yield a usable output. Amplification of the detector output produces a signal level capable of driving a demodulator or other processing circuitry. The name demodulator is given to any circuitry required to extract the transmitted information from the detector output and deliver it to the output electronics, display or other processor/user e.g. recorders, video displays, CRT displays, audio systems, loud speakers, RF relay transmitters, etc.

10. Performance

The received power level at an optical receiver is given by:

$$p_R = p_T\, g_T\, g_R \left(\frac{\lambda}{4\pi S}\right)^2 L \qquad (2)$$

$$L = \text{Loss factor} = \tau_A K$$

$$p_R = p_T \left(\frac{4\pi A_T}{\lambda^2}\right)\left(\frac{4\pi A_R}{\lambda^2}\right)\left(\frac{\lambda}{4\pi S}\right)^2 \tau_A K$$

$$p_R = \frac{p_T}{\lambda^2 S^2}\, \pi \left(\frac{D_T}{2}\right)^2 \pi \left(\frac{D_R}{2}\right)^2 \tau_A K$$

$$p_R = \frac{\pi^2\, p_T\, D_T^2\, D_R^2\, \tau_A K}{16\lambda^2 S^2}$$

and the signal-to-noise ratio is given by

$$s/n = \frac{\rho^2\, p_R^2\, R_L\, g^2}{2eB(\rho p_R + \rho p_B + I_d)\, R_L\, g^2 + 2\, FkTB} \qquad (3)$$

where:

- g_T: transmitter antenna gain
- g_R: receiver antenna gain
- p_R: received power (W)
- p_T: transmitter output power (W)
- D_T: transmitter aperture diameter (m)
- D_R: receiver aperture diameter (m)
- S: distance (m)
- λ: wavelength (m)
- τ_A: atmospheric transmission loss
- K: correction factor, usually less than 1, due to pointing error
- R_L: detector load resistance (Ω)
- g: detector internal gain
- ρ: detector responsivity (A/W)
- e: charge on an electron (C)
- B: bandwidth (Hz)
- p_B: background illumination power (W)
- I_d: dark current (A)
- F: receiver preamplifier noise factor
- k: Boltzmann's constant
- T: detector temperature (K)

These relationships can be used to evaluate trade-offs between choice of source and detector, transmitter beamwidth, receiver aperture, bandwidth, etc. Parameters of typical systems using CO_2, Nd:YAG and doubled Nd:YAG have been determined from these relationships and are tabulated in Table III.

TABLE III – *Typical laser communication system parameters*

Laser type:	CO_2	Nd : YAG	Doubled Md : YAG
Wavelength (μm)	10.6	1.06	0.53
Detector type	cooled HgCdTe	Photomultiplier	Photomultiplier
Photon energy (J)	1.85×10^{-20}	1.85×10^{-19}	3.7×10^{-19}
Quantum efficiency (%)	0.50	0.05	0.30
No. photons per bit (for bit error ratio = 10^{-5} 20 photoelectrons)	40	400	67
Average received power for 400 Mbit/s (W)	3×10^{-10}	3×10^{-8}	1×10^{-8}
Transmitter aperture D_T (m)	0.12	0.12	0.12
Transmitter beam half-angle (rad)	56×10^{-6}	5.6×10^{-6}	2.8×10^{-6}
Receiver aperture D_R (m)	0.25	0.50	0.50
Range (m)	4×10^7	4×10^7	4×10^7
System efficiency	20%	20%	20%
Transmitted power (W)	0.5	0.12	0.01
Modulation	External	External	External

ANNEX II

APPLICATIONS OF LASERS TO RANGING

1. Introduction

Echo-ranging with light waves is sometimes referred to as Light Detection and Ranging (LIDAR). This Annex examines the operating principles and the technology of LIDAR systems. Furthermore, it explores the performance trade-offs, advantages and disadvantages of this type of range measurement equipment, especially for employment in space research.

2. Block diagram

Figure 6 is a functional block diagram of a typical LIDAR system using infra-red or visible emissions for active echo-ranging. A laser oscillator emits coherent electromagnetic energy which is focused into a collimated beam by an optical lens system and directed toward a target. Energy is reflected by the target, a portion of this energy returning to its source. Energy reflected toward the source is collected by a receiver optical aperture and focused on a detector. The transmitter and receiver may share the same optical "antenna" aperture, or they may employ separate lenses for transmission and reception. The detector output is amplified and compared with the transmitted laser output to measure the time interval or the phase difference between the transmitted signal and the echo. A pulsed radiant output is employed for systems which measure timing interval and a CW output may be employed in phase delay systems. The measured time interval or phase delay between emitted and returning radiation is a function of the slant distance between the target and the LIDAR sensor. Range information thus measured is displayed and/or recorded for use by the sensor operation.

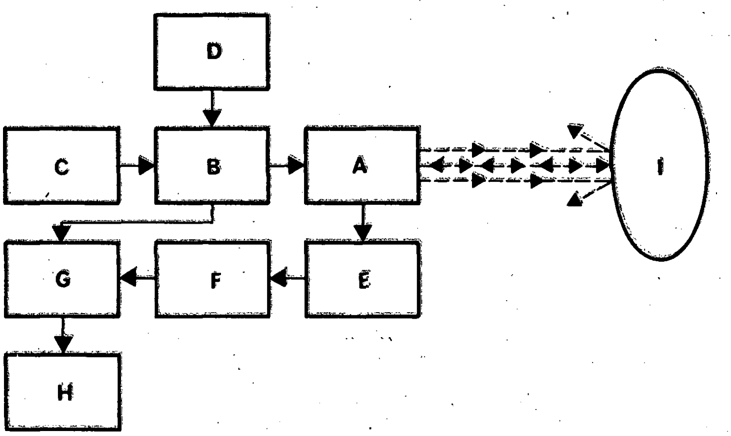


FIGURE 6 – *Functional block diagram, light detection and ranging (LIDAR) system*

A : Optical system

B : Laser

C : Power supply

D : Modulator

E : Detector

F : Preamplifier/amplifier

G : Interval counter (or phase detector)

H : Display

I : Target

3. Transmitter

The major components of the transmitter are the laser and the modulator. They are discussed in § 3 and 4 of Annex I. Ruby lasers also appear to have potential for LIDAR application.

4. Receiver

The receiver portion of a LIDAR system includes the optical aperture, a detector, signal processing such as amplification and thresholding, a comparator such as an interval timer or a phase comparator, and a display. When the aperture is shared by the transmitter and the receiver, an optical duplexer (e.g., a beamsplitter) must be provided to isolate the two as necessary during the transmit and receive portions of the operating cycle. Furthermore, beam steering capability and tracking servos must be available for target acquisition and tracking. LIDAR beamwidths are often so narrow that they are impractical for "Search" applications. Narrow beam sensors are therefore normally used in conjunction with another more coarse sensor such as radar. The purpose of the transmitter optics is to collimate and direct the output beam. The purpose of the receiver aperture is to collect light energy reflected by the target.

The returning light echo contains spatial information from which a target image can be retrieved. In imaging LIDAR systems the receiver optics are an imaging, objective lens assembly appropriate to the task. Image derotation equipment and image stabilization equipment must often also be provided within the optical-path of which the objective lens is a part. A wide variety of optical and electronic devices can be used to stabilize the optical path. Two or more image stabilization techniques are sometimes used in combination to fulfil a particularly demanding requirement.

The basic types of detectors are discussed in § 8 of Annex I. For imaging echo-ranging sensors, the detector may be a low light level television tube such as a Secondary Emission Control (SEC) vidicon, silicon vidicon, etc., or a gated image intensifier. To measure range, an imaging sensor must be capable of being gated "off" and "on". The time interval between a pulsed emission and the opening of the receiver gate is then varied until the target image appears to be "front lighted". This time interval is measured and converted to slant distance for display with the image.

Signal processing is performed as appropriate to the design. For example, a spot detector may employ separate baseband amplifiers with a built-in adjustable threshold to detect an echo pulse. The interval timer may be a frequency counter and precise frequency source, started by the outgoing pulse and stopped by the echo pulse. An imaging detector may employ video amplifiers and/or internal amplification gain (e.g., an image intensifier) to boost the signal level in order to drive the display.

5. Transmission medium

The LIDAR could be operated either in free space or within the Earth's atmosphere. The transmission medium discussions of § 6 of Annex I are also applicable to LIDAR.

Background noise is important to system performance in all applications. Infra-red and visible emissions from the Sun and stars, from artificial sources and from reflections by the Earth, the Moon and planets are detectable by the electro-optical receiver and must be considered in system design. Trade-offs between field of view, focal length and aperture size are optimized for specific applications. Special protective devices using Sun sensors, such as automatic irises, automatic light control (ALC), automatic gain control (AGC), etc., are also sometimes used to prevent the effects of direct viewing of the Sun.

6. Performance

The received power level at an optical receiver is given by the following adaptation of the radar equation:

$$p_R \approx \frac{\pi\, p_T\, \tau_T\, M\, \rho \cos\theta\, D_R^2\, \tau_R \exp(-2\sigma S)}{4\, S^2} \tag{4}$$

and the peak signal-to-r.m.s. noise power ratio is given by:

$$\frac{\hat{s}}{n} \approx \frac{\beta^2\, p_R}{2eB\,(\beta p_B + I_d)\, R_L\, g^2 + 2\, FkTB} \tag{5}$$

where:

p_R: received peak signal power (W)

p_T: peak transmitter power (W)

τ_T: transmittance of transmitter optics

τ_R : transmittance of receiver optics

ρ : target reflectance

θ : angle of beam incidence at target surface

S : distance (m)

D_R : diameter of receiver aperture (m)

σ : atmospheric attenuation coefficient (m^{-1})

R : slant distance (m)

β : responsivity of photodetector (A/W)

R_L : detector load resistance (Ω)

g : internal gain of photodetector

e : charge on an electron (1.60×10^{-19} C)

B : video bandwidth of receiver (Hz) $\geqslant 0.5/t$

t : pulse width

I_d : detector dark current (A)

F : receiver noise factor

k : Boltzmann's constant (1.38×10^{-23} J/K)

T : detector temperature (K)

p_b : sunlight power received from target and background (W), and

$$p_b = -\frac{\pi\,(H_{\lambda S} B_0 + H_S X)\,\alpha_R^2\, D_R^2\, \tau_R}{16} \left\{ \rho \exp(-\sigma S) + \frac{\sigma S}{4\sigma}\left[1 - \exp(-\sigma S)\right] \right\} \tag{6}$$

$H_{\lambda S}$: solar spectral irradiance (W/m^2 Angstrom at operating wavelength λ)

B_0 : receiver optical filter bandwidth (Angstrom)

H_S : solar irradiance (W/m^2) over spectral region of detector

X : transmittance of receiver optical filter outside passband

α_R : receiver bandwidth (field of view) (rad)

α_T : transmitter beamwidth

σ_S : atmospheric backscatter coefficient (m^{-1})

The geometry factor, M, is dependent on the relationship between target diameter, and transmitter and receiver beamwidths. There are three distinct cases to be considered and, therefore, three distinct values for the geometry factor. These cases are illustrated in Fig. 7. Briefly summarized they are:

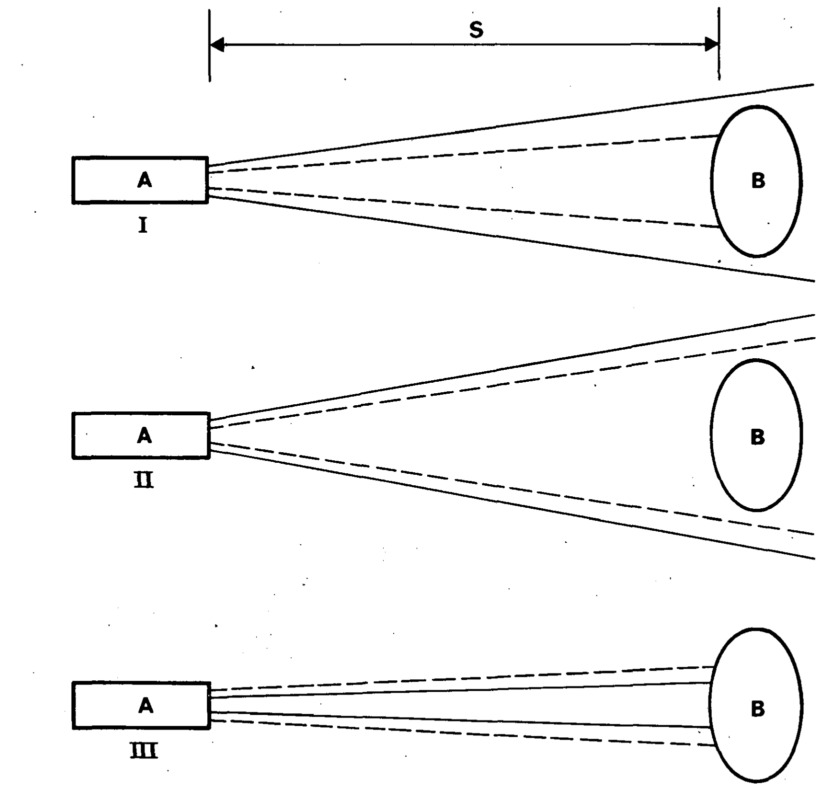
Case I: Transmitter beamwidth larger than receiver field of view and target diameter larger than receiver field of view $M = \alpha_R^2/\alpha_T^2$.

Case II: Transmitter beamwidth and receiver field of view larger than target diameter $M = D_T^2/\alpha_T^2 S^2$.

Case III: Receiver field of view equal to or larger than transmitter beamwidth, and transmitter beamwidth and receiver field of view smaller than target diameter $M = 1$.

The previous relationships can be used to evaluate performance trade-offs between choice of source and detector, transmitter beamwidth, receiver aperture, bandwidth, etc. Typical performance calculations have been made for four different rangefinders and tabulated in Tables IV and V. Table IV lists parameters held constant for the analysis. Table V summarizes specific system characteristics and the resulting performance. Calculations were made for the following combinations:

Ruby laser	S-20 photomultiplier
Ruby laser	silicon photodiode
Nd:YAG laser	S-1 photomultiplier
Nd:YAG laser	silicon photodiode



A: Laser

B: Target

S: Slant distance to target

Case I : $\alpha_R S < D_T$ and $\alpha_T > \alpha_R$

$$M = \frac{\alpha_R^2}{\alpha_T^2}$$

Case II : $\alpha_R S > D_T$ and $\alpha_T S > D_T$

$$M = \frac{D_T^2}{\alpha_T^2 \, S^2}$$

Case III : $\alpha_T S < D_T$ and $\alpha_R \geqslant \alpha_T$

$$M = 1$$

FIGURE 7 – *Relationship between beam size, field of view, target size and geometry factor M*

═══ Transmitter beamwidth

= = = Receiver field-of-view

TABLE IV – *Summary of parameters for typical laser rangefinder performance calculations*

Range S	5 km
Pulsewidth t	20 ns
Bandwidth B	25 MHz
Receiver lens diameter D_R	2.8 in (7.1 cm)
Geometry factor M	1
Receiver beamwidth α_R	1 mrad
Transmitter beamwidth α_T	1 mrad
Target reflectance ρ	1
Receiver noise factor F	1.5
Detector load resistor R_L	1000 Ω
Transmittance of receiver optics τ_R	0.7
Transmittance of transmitter optics τ_T	0.7
Target incidence angle θ	0°
Signal-to-noise ratio $\hat{s}/n$ for probability of detection 0.98 and false alarm rate of 1 per 1000 pulses	53

TABLE V – *Typical laser rangefinder performance*

Laser:	Ruby	Ruby	Nd : YAG	Nd : YAG
Wavelength λ (μm)	0.694	0.694	1.06	1.06
Detector	PM(S-20)	Si photodiode	PM(S-1)	Si photodiode
Attenuation coefficient σ(km^{-1})	0.139	0.139	0.114	0.114
Atmospheric transmittance τ_A	0.499	0.499	0.565	0.565
Solar spectral irradiance $H_{\lambda S}$ (W/m^2 Å)	0.12	0.12	0.06	0.06
Filter leakage transmittance X	0	0	0	0
Backscatter coefficient σ_S (km^{-1})	0	0	0	0
Background power p_b (W)	1.66×10^{-10}	1.66×10^{-10}	4.6×10^{-11}	4.6×10^{-11}
Optical filter bandpass B_O (Å)	40	40	20	20
Detector gain g	5×10^4	1	1.5×10^5	1
Cathode dark current I_d (pA)	0.030	10^5	12.9	10^5
Detector responsivity β (A/W)	0.028	0.517	3.5×10^{-4}	0.152
Peak received signal power p_S (W)	1.23×10^{-9}	2.5×10^{-7}	1.64×10^{-7}	8.48×10^{-7}
Single pulse range accuracy δR(m)	0.82	0.82	0.82	0.82
$\delta R = \frac{C}{2B\sqrt{\hat{s}/n}}$ (single pulse)				

REPORT 681-2*

THE POSSIBLE NEED FOR TECHNICAL STANDARDS FOR TELECOMMUNICATION IN THE INFRA-RED AND VISIBLE FREQUENCY RANGES

(Question 25/2)

(1978–1982–1986)

1. Introduction

Systems for telecommunication operating in the infra-red and visible light regions of the electromagnetic spectrum are undergoing active research and development. A limited amount of equipment of this type is being used operationally for various purposes including: voice communication links, analogue and digital data communication links, active echo-ranging and atmospheric measurements. More complete development of these devices may make it possible to use wider frequency bands than those of conventional systems operating in the radio-frequency region, and may contribute to alleviating the present congestion in the use of radio waves. The

* This Report should be brought to the attention of Study Groups 1 and 5.

Radio Regulations now in force regulate radio systems for communication, including determination, operating in the electromagnetic spectrum below 300 GHz. Furthermore, allocation of frequencies for specific purposes is made by international agreement only in the regions below 275 GHz. This Report examines the relative necessity for international technical standards for the proper operation of systems in the regions above 30 000 GHz (wavelengths < 10 μm).

2. General considerations

Active and passive systems have been designed and built and are now operating in the regions above 30 000 GHz ($\lambda < 10$ μm). Most commonly, designs have utilized the spectrum between approximately 0.3 μm and 10.6 μm. Active systems in this region have usually employed emitters which radiate between 0.53 μm and 10.6 μm. Although operational systems are now available, they are relatively few in number (compared to corresponding RF systems) and the existent technology has not achieved its full potential. For example, the number and variety of modulation techniques which can be successfully implemented are more limited than those now known to be possible in the RF spectrum.

Interest in optoelectronics has been heavy and an already large capital investment in research and development is still growing rapidly. Although electro-optical technology is still undergoing rapid growth, very powerful radiation sources have been developed (e.g., Nd:YAG lasers, CO_2 lasers, gas dynamic lasers, etc.). The personal hazards, especially to the eyes and the skin, which result from high-energy visible and near visible radiation have led to widespread concern for laser safety standards and support for radiation hazards (RADHAZ) research in the infra-red and visible spectrum.

All of the foregoing considerations, together with the thought of reducing congestion in the spectrum below 300 GHz by making frequency allocations higher than this, have raised the question whether the regulation of electromagnetic devices and the allocation of frequencies above 300 GHz should be undertaken now, or later, when the technology is more fully developed and the population of operational systems is more numerous. This Report explores this question with respect to the development and utilization of electro-optics (i.e., wavelengths < 10.6 μm).

While the desirability and requirement for regulation arises from the necessity for international connections and for sharing operating frequency bands, technical considerations are important in determining what type of controls will be feasible and effective and when they can be most appropriately initiated. Some of the points which relate to the regulation of the infra-red and visible bands are: the type of service planned and its relationship to the limiting effects of the atmosphere, the existence of numerous natural and artificial sources which emit background radiation in these bands, the divergence of the optical beams and their relationship to the probability of harmful interference.

3. Atmospheric effects

The transmittance of the atmosphere is a factor less than unity and denotes the fraction of electromagnetic energy which is propagated along a designated path. The value of transmittance is a function of numerous variables including: wavelength; path length and direction; atmospheric pressure and temperature; quantity of gases and aerosols present; precipitation, such as rain or snow; and particulate quantity and size, such as moisture (clouds and fog) dust, smoke, bacteria, etc. Atmospheric transmittance is the result of the combined effects of absorption and scattering due to all the above effects within the bandwidth of the radiation to be transmitted. Measurements of atmospheric transmittance show a complex, erratically changeable relationship between all these variables. Atmospheric transmittance models capable of precise predictions are similarly complex, requiring the combined computation and weighted combination of a large number of non-linear elements over the range of values of interest.

One of the most important factors to consider is the attenuation resulting from molecular absorption in the clear atmosphere. Figure 1, which has been reproduced from Report 883, depicts the main features of this molecular absorption for vertical transmission through the atmosphere from sea level and from 4 km altitude for temperate, summer conditions. The spectral resolution is 0.1 μm. Other features not fully resolved in Fig. 1 would be apparent for very narrow band observations. To obtain an approximate estimate of the rate of attenuation (dB km^{-1}) at sea level, the upper, full-line curve of Fig. 1 should be divided by three.

There are bands of low gaseous absorption, where the absorption is only about 1 dB or less, e.g. at:

0.4 to 0.9 μm (visible range),
near 1.7, 2.2, 3.5 and 5 μm,
8 to 13 μm.

These bands are of particular interest for communication and radar applications but they are also subject to additional attenuation arising from atmospheric particulate material and from hydrometeors (rain, cloud, fog, etc.) which affect visibility. For a homogeneous atmosphere the atmospheric transmittance τ_A is given by:

$$\tau_A = \exp(-\sigma S) \tag{1}$$

where σ is the extinction (or atmospheric attenuation) coefficient, km^{-1}, and S is the path length in km. The corresponding attenuation in dB km^{-1} is 4.3σ.

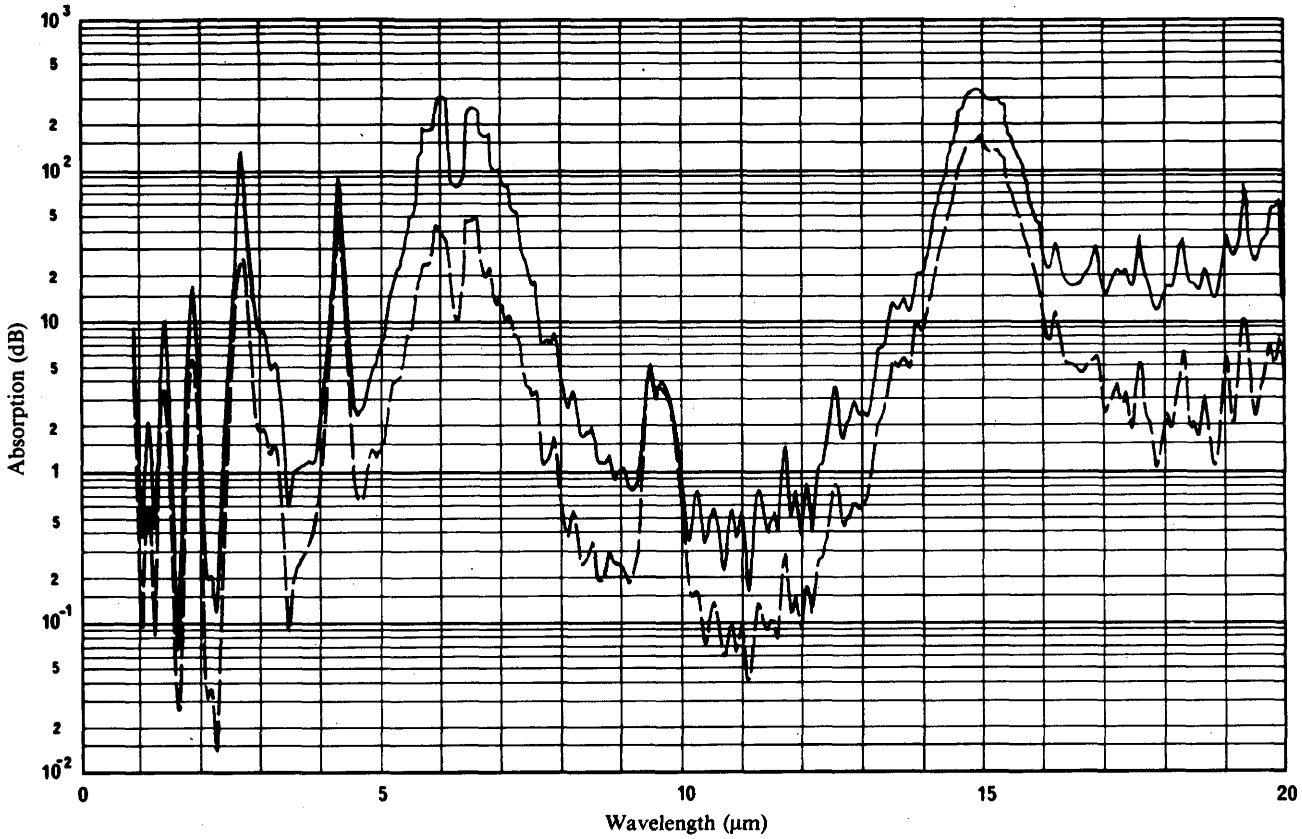


FIGURE 1 — *Molecular absorption in clear air through Earth's atmosphere at zenith* (spectral resolution: 0.1 μm)

——— From sea level
— — — From 4 km altitude

Average values for σ, arising from particulate matter and hydrometeors, and the corresponding attenuation coefficient in dB km^{-1}, are plotted in Fig. 2 for varying visibility conditions and for wavelengths between 0.4 μm and 4.0 μm. Using the value of σ for the wavelength of the GaAs laser ($\lambda \approx 0.9$ μm) on a clear day (15 km visibility) gives a transmittance of approximately 15% for a 10 km path. Over a 15 km path, the transmittance is 6%, and at 25 km just under 1%. Thus the effect of particulate matter in attenuating this laser radiation on a clear day is less than the gaseous absorption. However, it may become significant in haze. The attenuation coefficient σ can then be greater than 1 km^{-1} and the transmittance for GaAs over 10 km may be less than 0.01%. Another important factor to consider is the multiple scattering effect. Report 883 describes this effect.

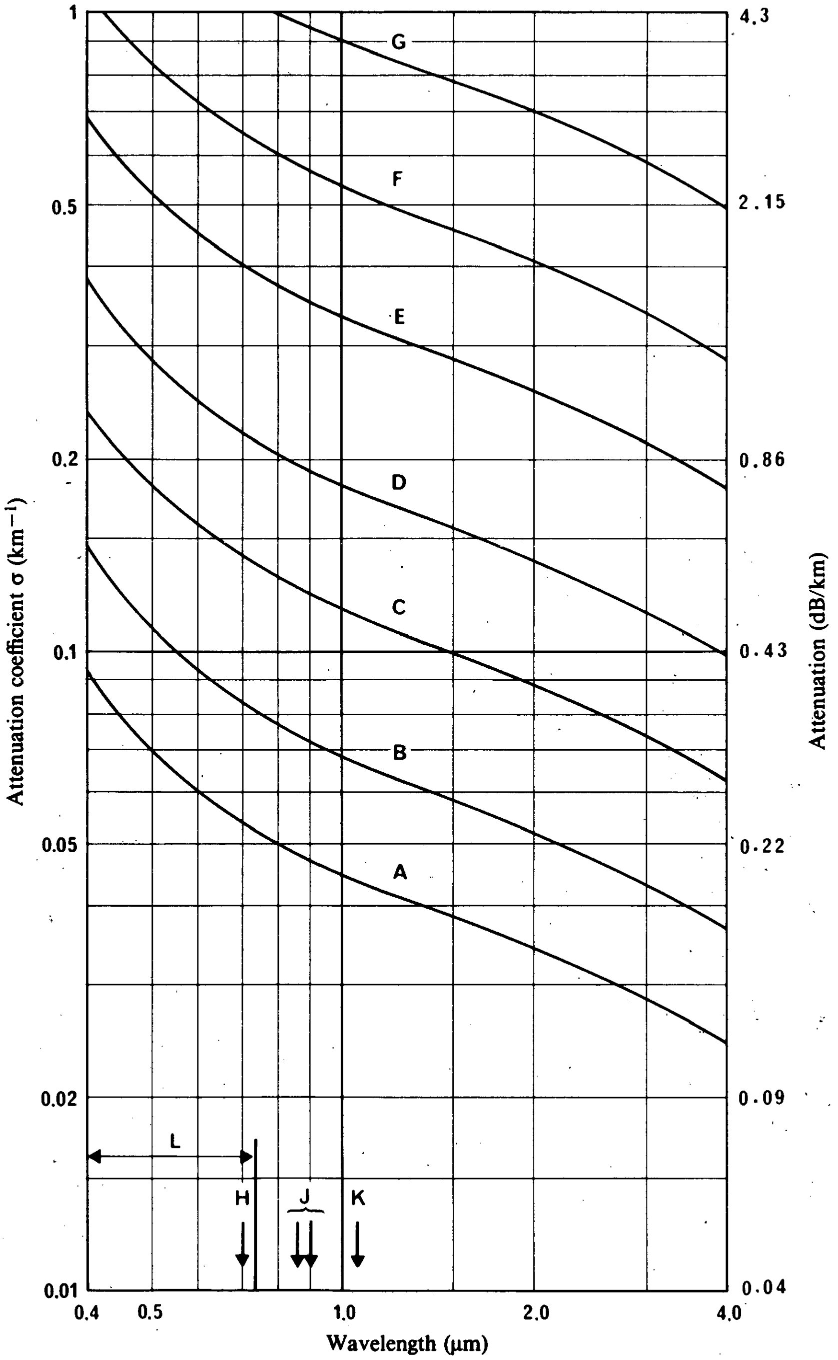


FIGURE 2 — *Attenuation coefficient versus wavelength (at sea level) – average curves for particulate matter including hydrometeors*

A: exceptionally clear – visibility 60 km

B: very clear – visibility 40 km

C: standard clear – visibility 23.5 km

D: clear – visibility 15 km

E: light haze – visibility 8 km

F: medium haze – visibility 5 km

G: haze – visibility 3 km

H: ruby

J: GaAs

K: Nd

L: visible spectrum

4. Background emissions

Allocation and regulation of telecommunication systems which operate at wavelengths less than 10 μm would be complicated by the large number of natural and artificial sources which contribute to a relatively high noise background in that portion of the spectrum. The majority of these emitters are not subject to practical regulation or control by international agreement.

Foremost among such sources is the Sun, which is responsible for a total power flux density of approximately 1390 W/m^2 at mean Earth-Sun distance just outside the Earth's atmosphere. The Sun's output is similar to that of a black body at approximately 5900 K. The power flux density at the Earth's surface is a function of atmospheric conditions, time of the solar year, solar time of day, geographic location, etc. With the Sun at the zenith of a clear sky, the illuminance on a horizontal surface resulting from sunlight is approximately 1.24×10^5 lm/m^2 (lumen per square metre).

The Moon, though not nearly as bright as the Sun, also contributes an appreciable illuminance through reflected sunlight. The peak values at the full Moon may be as high as 0.267 lm/m^2. Furthermore, the Earth also reflects solar radiation. Sunlight reflected from the surface of the Earth, known as albedo, adds appreciably to the background noise power experienced by spaceborne visible and infra-red receivers.

Although the Sun and Moon are distributed sources, the stars and planets appear as point sources which can each contribute from 1.39×10^{-4} lm/m^2 (Venus at the brightest) to 1.05×10^{-8} lm/m^2 (6th magnitude star) or less. Furthermore, the sky contributes an illuminance at the Earth's surface varying from 10^{-4} lm/m^2 on an overcast starlight night to $1\text{-}2 \times 10^4$ lm/m^2 in full daylight (not direct sunlight), as a result of scattering of sunlight by the atmosphere.

Artificial sources are so numerous and so variable that they defy prediction. At night, lamps of many types and brightness levels illuminate cities and populated areas in abundance. Furthermore, open flames and hot surfaces (factories, aircraft engines, heated earth, heated pavements, heated masonry, automobile engines, furnaces, chimneys, etc.) may emit infra-red and visible radiation at appreciable levels. Also, metallic and glass surfaces, water surfaces and other specular reflectors may reflect any of these artificial or natural emissions with high intensities within the infra-red and visible bands, depending on the geometry between source, reflecting surface and receiving aperture.

5. Beam divergence and field-of-view

Collectively, the noise background in the infra-red and visible regions is very severe. Nonetheless, successful systems can be designed and operated, provided that suitable trade-offs are made between field-of-view, aperture size, focal length and carrier and background radiation levels, etc. Most operational systems will employ the minimum field-of-view or beamwidth consistent with the application. Beamwidths ranging from a few microradians to tens of milliradians are typical. Furthermore, optical sources and receivers have little side-lobe and no back-lobe structure, and consequently interference can result only from main-beam to main-beam couplings. As a consequence, interference between laser systems sharing a band can be shown to be extremely unlikely.

Figure 3 shows the relationship between beam divergence, distance from source (or receiver) and beam diameter. From these data, the beam diameter at the greatest ranges possible (< 100 km), for terrestrial systems using laser sources, will be less than 1000 m even for beams up to 10 mrad (0.57°) wide. More realistic maximum beam diameters are < 30 m at ranges up to 30 km for beams approximately 1 mrad wide.

For beams so tightly collimated, even intentional interference would be difficult since the system interfered with would need to be within ≈ 0.5 mrad (0.2°) of the target azimuth if main beam illumination were to occur. The improbability of this can be demonstrated graphically by the following analysis.

Figure 4 illustrates the relationship between beamwidth and the fractional volume ($\theta^2/4\pi$) of the "search sphere" surrounding the source which is illuminated by the beam. For space-to-space laser applications, this fraction equals the probability of unintentionally illuminating a receiver sharing the band when that receiver has a uniformly distributed probability of appearing on any set of co-ordinates within the co-ordination volume. For a terrestrial laser system (hemispherical "search volume") the probability of unintentionally illuminating a receiver sharing the band is equal to, or less than, half the fractional volume given in Fig. 4.

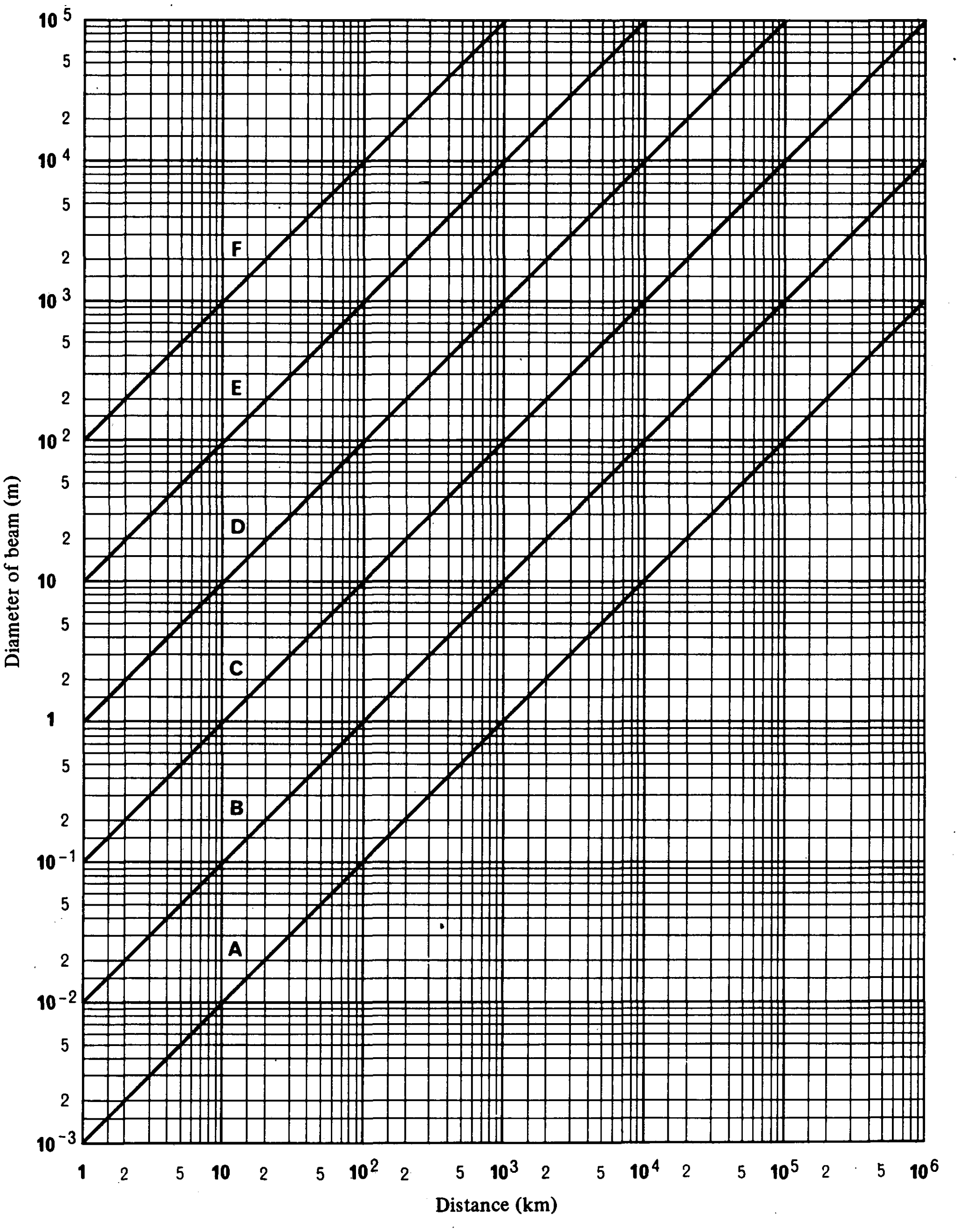


FIGURE 3 — *Beam diameter versus distance from source and beam divergence*

A: Beam divergence 1 μrad
B: Beam divergence 10 μrad
C: Beam divergence 100 μrad
D: Beam divergence 1 mrad
E: Beam divergence 10 mrad
F: Beam divergence 100 mrad

For interference to occur, the receiver in question must be illuminated by the transmitter, and the receiver aperture itself must be so aligned that the source of interference lies within the field-of-view. Thus the probability of *interference* is less than the square of the probability of simple *illumination.* As an example, a transmitter with a beamwidth of 1 mrad has a probability of unintentionally illuminating another receiver sharing the frequency band (given it is within detectable range of the emitter) of approximately 7×10^{-8}. The probability that this receiver will be illuminated and then detect this radiation is less than 49×10^{-16}, provided the receiver field-of-view has the same angular dimensions.

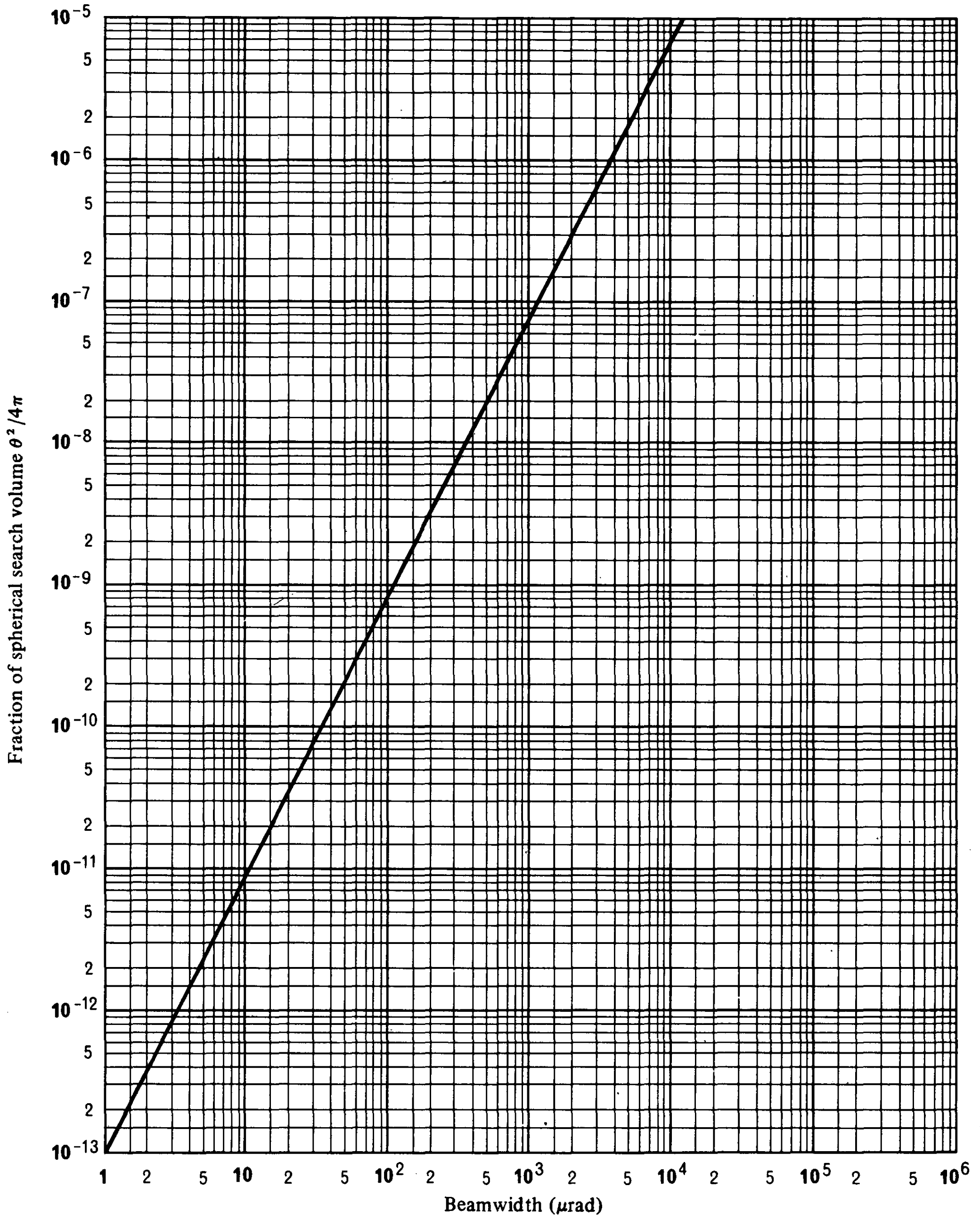


FIGURE 4 — *Fractional search volume versus beamwidth*

6. Conclusions

Technical standards for electro-optical systems and determination of preferred operating wavelengths for electro-optical equipment by international agreement do not appear to be necessary at this time. Interference between terrestrial electro-optical telecommunication systems sharing a band is possible only at relatively short station separations ($\ll$ 30 km) due to the limitations of the atmosphere and the high background noise.

Most sources which emit radiation in the infra-red and visible spectrum are not associated with deliberate telecommunication.

Control of radiation hazards may be considered to be a matter of national, rather than international, concern since these hazards exist only in proximity to high intensity sources within the atmosphere. Radiation hazards in space, e.g., in manned, Earth-orbiting laboratories, are at present the responsibility of the nation or nations doing such work.

Electro-optical telecommunication systems are likely to employ very narrow transmitter beamwidths and receiver fields-of-view, making unintentional couplings or interference of any kind between terrestrial or spaceborne systems extremely improbable.

RECOMMENDATION 367

FREQUENCY BANDS FOR RE-ENTRY COMMUNICATIONS

(Question 3/2)

(1963)

The CCIR,

CONSIDERING,

(a) that spacecraft re-entering the Earth's atmosphere are enveloped in a self-induced plasma;

(b) that electromagnetic radiations to and from the vehicle may suffer severe attenuation and other detrimental effects due to the existence of the plasma;

(c) that communications with, and tracking of, the vehicle may be imperative during the re-entry phase to ensure a successful mission;

(d) that the selection of frequency bands for re-entry communications and tracking is dictated partly by the parameters of the induced plasma;

(e) that the use of such bands requires international agreement, since the phases of re-entry flight may extend over one or more orbits of the Earth;

(f) that the only proved solution to the re-entry communication problem to date involves the use of frequencies greater than the critical frequency of the plasma sheath;

(g) that critical frequencies of the plasma sheath can approach or exceed 10 GHz;

(h) that frequencies of 10 GHz and higher are affected appreciably by the Earth's atmosphere;

(j) that the bands available at present for space research purposes above 15 GHz are technically suitable for some re-entry communications,

UNANIMOUSLY RECOMMENDS

that both the critical frequency of the plasma sheath and the atmospheric effects be considered in the selection of frequencies for re-entry communications (see Reports 205 and 222).

REPORT 222-5 *

EFFECTS OF ARTIFICIAL PLASMAS ON COMMUNICATIONS WITH SPACECRAFT

(Question 3/2)

(1963-1966-1970-1974-1978-1986)

1. Introduction

Some communication problems arise from the presence of a plasma, e.g. ionized air, in the vicinity of a spacecraft and its antenna. Natural plasmas are present in the ionospheres of Earth and other planets, but also as "solar wind" in interplanetary space, especially in the neighbourhood of the Sun. Artificial plasmas are produced mainly by two mechanisms:

- as "ionized gases" generated by spacecraft propulsion and control systems, and
- as "plasma sheath" forming around a spacecraft entering a planetary atmosphere.

Two main effects of plasmas must be considered, namely:

- that on antenna performance, and
- that on propagation of radio waves.

This Report gives a summary of the effects of artificial plasmas on communications with spacecraft. More detailed analyses are presented in Report 222 (Geneva, 1974 and 1982).

2. Summary of atmospheric entry plasma effects

Atmospheric entry plasma effects on communications will vary greatly with the mission, which determines the vehicle trajectory and configuration. Selection of signal frequency, antenna location, and antenna type can be used to circumvent or minimize the re-entry signal loss in many cases. Criteria which influence this selection include the plasma thickness, collision frequency, ablation material, and the nature of the non-equilibrium phenomena (i.e. producing or recombining type plasma). Also practical considerations such as power requirements, signal modulation techniques, tracking station capabilities, and relative location with respect to the spacecraft (look angle) enter into the selection.

Some experimental results indicate that the critical frequency of the plasma sheath is often as high as 1 to 10 GHz and may sometimes be even higher. It is concluded that frequencies of 10 GHz or higher are technically required for certain re-entry communications, especially for re-entry from lunar or planetary missions.

At these frequencies, absorption in the planetary atmospheres can be very important. For the atmosphere of the Earth, Report 719 gives some relevant data. It also shows that there are several "windows" above 60 GHz where the absorption in atmospheric gases may be acceptably low. The data however, indicate that attenuation in tropospheric precipitation could be prohibitively high. Frequencies near 90 GHz and perhaps those near 140 GHz might be preferable in this respect.

Other experimental programmes have demonstrated an increased understanding of the re-entry plasma sheath. Data from in-flight measurements at orbital re-entry velocities using diagnostic antennas and rakes of immersed electrostatic probes are in excellent agreement with theory, except at the extremities of the plasma attenuation period [Akey and Cross, 1970; Grantham, 1970; NASA, 1971]. The electrostatic probe measurements agree not only in peak plasma density, but also in the plasma profile.

Moreover, the effects of the plasma sheath have been reduced by modifying the plasma itself; for example, by aerodynamic shaping (sharp nose or spike configurations) to reduce the plasma thickness; by the injection of liquid materials into the flow field that have restored radio-frequency signals otherwise blacked out by the plasma during the re-entry attenuation period [Akey and Cross, 1970]; and by the choice of ablation materials which can significantly affect plasma density [Grantham, 1970]. Also, by sufficiently applying a strong magnetic field the configuration could be influenced and/or a propagation window could be produced, by the so-called "whistler mode" (see Report 262). Possibly, combinations of these techniques may be used to reduce the plasma sheath effects.

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* This Report should be brought to the attention of Study Group 6.

3. Summary of rocket exhaust plasma effects

Exhaust plasma is always produced in the flames of rocket motors, but may also appear in other propulsion systems, for example, electric propulsion. In its origin and as a result of different boundary conditions such a plasma is different from a typical re-entry plasma.

To describe an exhaust plasma, the factors associated with the flame must be known, such as fuel and oxidant composition, mixture ratio, alkali metal impurities, nozzle characteristics, thermo-chemical kinetics, dynamics of the expanding gases, etc. With these factors and knowledge of ambient atmospheric conditions the exhaust plume structure may be deduced [Jensen and Wilson, 1975]. Changes in gas flow due to induced turbulence are now understood and can be included in calculations of exhaust structure. Problems introduced by the use of multiple jets are outstanding and still require further study.

Practical and theoretical investigations have been conducted and have led to methods for predicting the effects of exhaust gases. Because the plasma configuration is not one of a sheath surrounding the vehicle it presents problems different from those of re-entry. Plasma densities differ and the antenna is unlikely to be immersed in the plasma; consequently alternative propagation paths may be found (other than through the most highly ionized regions) [ELDO, 1966]. Plasma effects include absorption, refraction, diffraction, amplitude and phase modulation. Total signal loss can be a combination of these effects. Absorption depends upon electron concentration and collision frequency [Williams, 1965], the approximate distribution of which can be deduced from a knowledge of the motor design. Significant diffraction may occur in an exhaust where the absorption is high [Dang, 1974]. Spurious modulation will be encountered due to forward scattering into the antenna from the turbulent jet stream. Doppler displaced frequencies given by varying eddy velocities within the exhaust, produce plume related spectra. Comparison between experimentally derived and computed spectra is good. [Williams, 1966; Williams *et al.*, 1971]. Radar echoing (back scatter) has been treated in a similar manner. The propagation path relative to the exhaust is another important factor; refraction effects on the ray path may not always be negligible. [Kopp, 1966; Golden *et al.*, 1968].

As an example, for a large chemical rocket firing into a vacuum, the exhaust in the immediate vicinity of the nozzle exit is a high-pressure plasma having an electron collision frequency of about 10^{11}/s and an electron density of 10^{16} to 10^{17} per m^3. It is therefore a region of high damping with marked resonances (critical frequencies). Subsequent expansion of the gases results in a transition from this collision dominated region to effectively collision free conditions. Radio blackout due to critical frequency effects alone, is possible only in those regions of the plume where the collision frequency is less than 10^8/s. Due to the expansion of the efflux, this order of collision frequency is necessarily associated with a low electron density (10^{13} per m^3); this means that there is a high probability that radio frequencies down to 100 MHz, or even below, will penetrate the entire flame. Nevertheless, the overall absorption measured can be large (10 to 30 dB), due entirely to the long path lengths through the flame, encountered in certain directions. Experimental confirmation for predictions has been sought by measurements on the ground and during actual rocket launches [McD. Cummings and Wilson, 1967; Wilson, 1967].

Other work has been directed towards improvement of the prediction techniques, particularly the fluid dynamics, the representation of turbulent fluctuations and in the treatment of chemical processes within the exhaust. Fluid dynamic calculations have been improved by the inclusion of shock structure and a better description of the effects of forward flight on the plume, including treatment of base recirculation. Methods are now available for determination of those turbulent quantities i.e. turbulent length scale and turbulent intensity, needed to describe electromagnetic scattering by exhaust gases. The effect of finite rate chemical reactions are included during the calculation of plume structure, this being particularly important for the calculation of electron density since this is strongly influenced by chemical reaction at low and intermediate altitudes. [Jensen and Pergament, 1971]. The major interest has been in the field of tactical rockets; nevertheless, these studies are complementary to the problems of space vehicle exhausts and can be directly related to situations encountered in space flight.

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REPORT 700-1

RADIOCOMMUNICATION REQUIREMENTS FOR SYSTEMS TO SEARCH FOR EXTRA-TERRESTRIAL INTELLIGENCE (SETI)

(Question 17/2)

(1978–1982)

1. Introduction

Question 17/2 on Radiocommunication Requirements for Systems to Search for Extra-terrestrial Intelligence has been adopted by the CCIR. The present Report discusses the general background and technical matters related to this topic.

1.1 *Background*

Many scientists believe that life is common in our galaxy and that it could have developed into civilizations. Civilizations with similar technical achievements to ours could communicate with each other by radio waves up to distances of 100 light years.

The possibility of receiving communications from an extra-terrestrial intelligence (ETI) was first pointed out in 1959, and a search was proposed for possible signals [Cocconi and Morrison, 1959]. Independently, Drake and others attempted to detect signals from possible civilizations associated with stars. Similar attempts have since been made at other observatories [Sagan and Drake, 1975]. The first "aimed" signal was transmitted into space from the Arecibo Observatory in November 1974 [NAIO, 1975].

Using present technology it is feasible to detect radio signals arriving at the Earth from other civilizations in the galaxy. Such a programme is called SETI (Search for Extra-terrestrial Intelligence).

Several SETI programmes have been described [Sagan and Drake, 1975]. By 1978 the following were in progress:

1.1.1 Bridle and Feldman, at Algonquin Radio Observatory in Canada, searching nearby stars at 22.2 GHz, near the H_2O line.

1.1.2 Dixon and Cole, at Ohio State University Radio Observatory, making an all-sky survey near the 1.4 GHz hydrogen line [Dixon and Cole, 1977]. This survey had been in progress continuously for three years.

1.1.3 Drake and Sagan, using the Arecibo Observatory in Puerto Rico, observing several nearby galaxies at 1420, 1653, and 2380 MHz [Ponnamperuma and Cameron, 1974].

1.1.4 The Soviet Union SETI programme [USSR, 1974; USSR, 1975].

1.1.5 Kardashev, using the Eurasian Network, in the USSR, searching for pulsed signals, with hemispherical coverage [Kardashev, 1976].

1.1.6 Troitsky, using the Eurasian Network, searching for pulsed signals in an all-sky survey at 1.9, 1.0 and 0.6 GHz [Troitsky *et al.*, 1974].

1.1.7 Zuckerman and Palmer, using the NRAO Observatory in Greenbank, searching nearby F, G, and K type stars near 1420 MHz [Palmer and Zuckerman, 1972].

1.1.8 The United States National Aeronautics and Space Agency conducting a search near 1.5 GHz [Tarter *et al.*, 1977].

1.2 *Average distance between civilizations in space*

The average distance between civilizations must be inversely proportional to the cube root of the space density of the civilizations, which is also proportional to their average life.

For the existence of civilized life within 100 light years of the Earth to have a high probability, one must assume an average life of at least 10^7 years.

1.3 *Other civilizations*

Based on the following argument some experimenters may assume that the other civilization would be more advanced than ours. We have only been able to communicate with an equivalent civilization by radio waves during the last 30 years. Consequently, if they can communicate, but are nevertheless behind us, the state of development of the other civilization cannot be more than 30 years behind ours. As 30 years is an extremely short time compared with the time scale of evolution of life, the probability that this would be the case is very small. Similar logic shows that they are unlikely to be only slightly ahead of us. In the previous section it is assumed that an average life of communicating civilizations would be of the order of 10^7 years. It is concluded therefore, that if other civilizations exist, they are probably considerably more advanced than ours.

Such civilizations may have formed a community through radiocommunications and may have been continuously sending signals to suggest that we join the community.

1.4 *Consequences of success*

Interstellar communication is merely hypothetical before the first contact is made. However, as soon as a contact is established, practical implications to us may be significant. The large-capacity communication following the first contact may contain information far superior to our knowledge.

1.5 *Types of stars to be sought*

Stars which are similar to the Sun may have planets suitable for life similar to that on the Earth. Such stars have surface temperatures of 4500 to 6500 K and luminosity of 0.3 to 3 of the Sun, and are known as main sequence stars with spectral types of F, G and K [Sagan, 1973].

2. Characteristics of the signal

2.1 *Transmitted signal*

Nothing can be known in advance with certainty about radio signals transmitted by an extra-terrestrial, intelligent society (ETI). However, it can at least be assumed that the signals could have any of the characteristics currently known to human science. Thus, the transmitted signals could have any carrier frequency, modulation, e.i.r.p., or polarization. In addition, as the location of the source is unknown, the nature and magnitude of the source Doppler frequency drift would also be unknown.

Using practicable terrestrial facilities (100 m diameter antennae, 1 MW transmitter and a 20 K receiver), communication could be maintained at a rate of 10 bit/s within a distance of 100 light years.

The United States routinely generates an e.i.r.p. of 130 dBW near 2 GHz during planetary radar experiments at Arecibo, Puerto Rico. An e.i.r.p. of at least this level is possible for a signal from an ETI.

Some experts believe that the signal would be from a point source, polarized, variable with time, and have a narrow bandwidth (of the order of 10 Hz). A very simple form of modulation, coding etc., might be used to make processing at this end simple. The assumption is that the signal is intended for reception by a civilization other than the one which is transmitting.

In such a case, initial contact would be through a beacon signal to establish a large capacity communication. This signal would possibly contain minimum information to let us know their existence; factors related to the communications following, etc. Subjects such as mathematics, geometry, physics, etc., might be also contained in order to help us to understand systems of modulation, coding, grammar, etc.

2.2 *Propagation considerations*

2.2.1 *Interstellar medium*

The interstellar medium is a magneto-ionic plasma with non-uniform characteristics which vary with time, distance and direction. The medium is inhomogeneous, anisotropic, and dispersive. The result of these properties is a change in the characteristics of the transmitted signal as it passes through the medium.

Changes in the polarization and spectrum of the transmitted signal are especially important.

2.2.1.1 *Faraday rotation*

One effect of the medium will be Faraday rotation of the polarization vector. This may be in either direction depending upon the characteristics of the path. Rotations as great as 10 radians or more have been observed at a frequency of 1420 MHz [Whiteoak, 1974].

Since the medium is anisotropic, there may also be some conversion between linear and circular polarization.

2.2.1.2 *Spectral changes*

The interstellar medium causes changes in the spectrum of a signal traversing it. If the signal is unmodulated, the medium broadens the signal spectrum; if the signal is modulated, the medium broadens and distorts the modulation spectrum. The effect is to limit both the maximum and minimum bandwidths for observation of a coherent signal.

The best available data concerning limitation of the maximum bandwidth come from the measurement of pulsars [Lee and Jokipii, 1976]. These measurements indicate that the maximum coherent bandwidth at 1 GHz is approximately 2000 Hz over a path length of about 10^3 light years. The bandwidth appears to increase with frequency and decrease with increasing distance.

Pulsar observations have also shown the minimum coherent bandwidth to be of the order of 10^{-2} to 10^{-3} Hz.

2.2.2 *Atmosphere of the Earth*

2.2.2.1 *Attenuation*

For clear weather conditions, atmospheric attenuation is a significant factor above about 20 GHz (Report 719). When rain is taken into account, attenuation becomes more significant at frequencies greater than 3 GHz. Atmospheric attenuation is shown in Fig. 1. Further information appears in Reports 563 and 721.

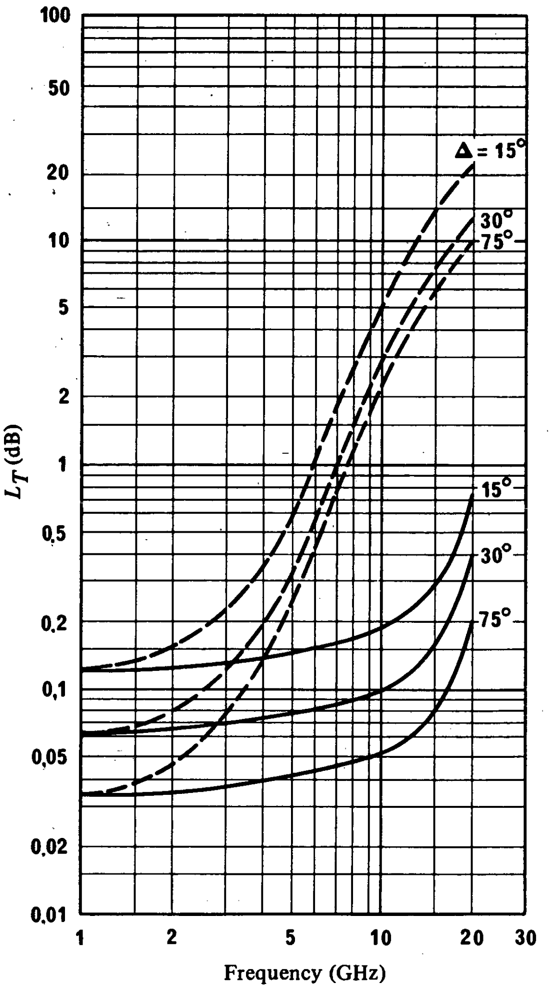

FIGURE 1 – *Space-to-Earth attenuation* (L_T)

——— clear weather, atmosphere only

– – – – – rain and atmosphere: 32 mm/h

parameter Δ: elevation of earth station antenna

2.2.2.2 *Polarization and spectrum*

The ionosphere will affect the polarization and spectrum of the signal in transit. The effect is expected to be small compared to the effect of the interstellar medium.

2.3 *Arriving signal*

2.3.1 *Noise*

Signals from an ETI would arrive at the Earth mixed with background radiation.

2.3.1.1 *Extraterrestrial noise*

Outside the atmosphere of the Earth, background noise consists primarily of three components. These are: the 2.7 K black body isotropic radiation that fills the universe, galactic noise and quantum noise (caused by fluctuations in the rate of arrival of RF quanta at the receiver) [Oliver and Billingham, 1973a]. These noise contributors are shown in Fig. 2.

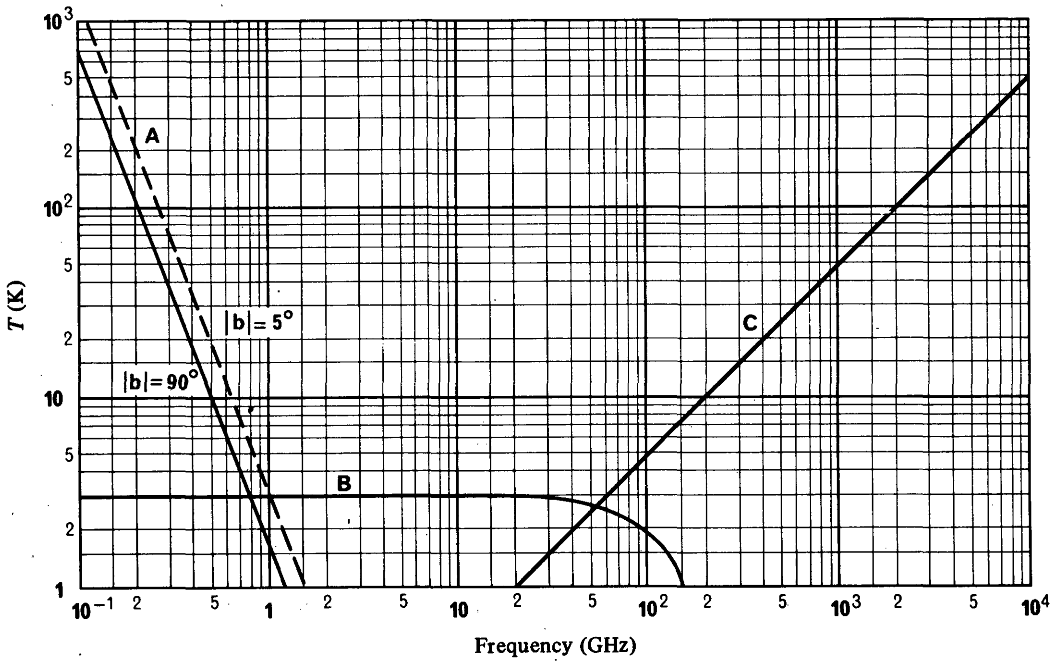

FIGURE 2 – *Background noise temperature (T) contributors outside the atmosphere of the Earth*

A : Galactic

B : Black body

C : Quantum effect

parameter | *b* | : Absolute value of galactic latitude

Galactic noise temperature decreases steeply with increasing frequency. It is directional in nature and is maximum at the galactic equator, diminishing rapidly at greater galactic latitudes. At a latitude of ± 5° it is about twice the amount as measured near the poles.

The black body background noise temperature is constant in the microwave region at frequencies of less than about 60 GHz. At higher frequencies it diminishes. This black body background radiation is isotropic.

Quantum noise temperature increases with increasing frequency, but it is significantly less than the other contributors below 60 GHz. It is also independent of direction.

The spectra of emissions of molecules and free radicals contained in interstellar space modifies the noise at certain frequencies. Hydrogen, hydroxyl, and formaldehyde are examples.

Near 1420 MHz the emissions of neutral hydrogen cause the noise to be above the background.

The OH lines, through maser action, are very narrow and are often variable with time [Weaver *et al.*, 1965].

The H_2CO line, through the anti-maser effect, exhibits a negative excitation temperature and, consequently, the background radiation temperature in the direction of dark clouds is below the 3K background temperature. On the basis of current knowledge this is a unique situation [Palmer *et al.*, 1969].

The resultant total sky noise temperature outside the atmosphere of the Earth is shown in Fig. 3. As can be seen, there is a broad minimum between approximately 1 and 100 GHz, which is called the free-space microwave window.

2.3.1.2 *Noise from the atmosphere of the Earth*

The contributions of the atmosphere to sky noise are discussed in detail in Report 720. The noise contribution of rain is also discussed in Report 564. The effect of the atmosphere is to reduce the frequency range of the sky noise temperature minimum.

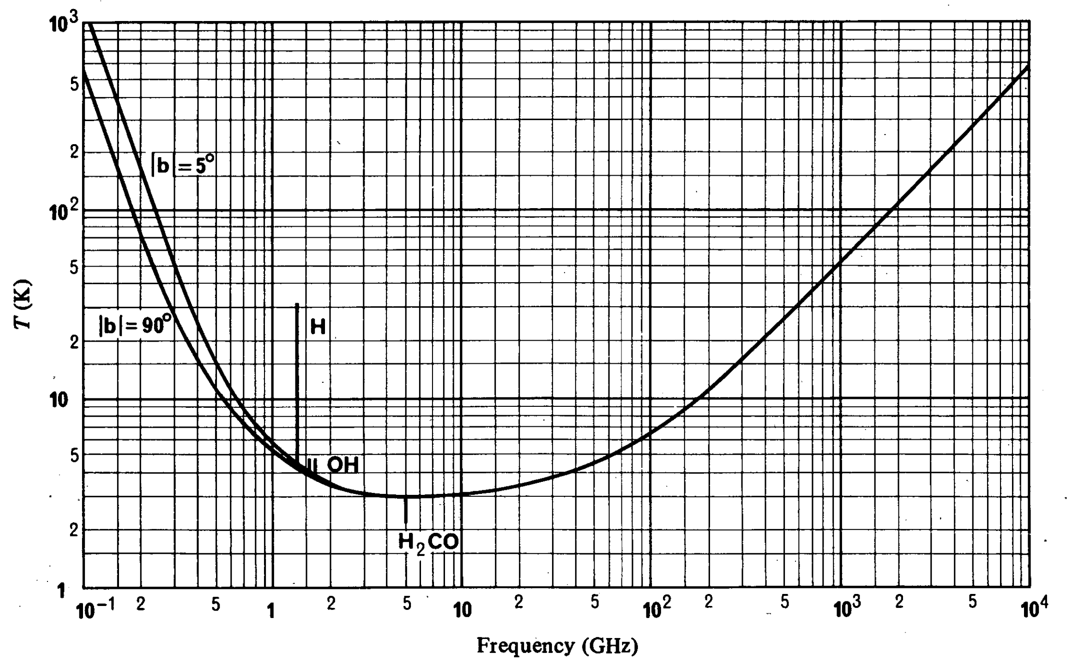

FIGURE 3 – *Total sky noise temperature (T) outside the atmosphere of the Earth*

parameter | b |: the absolute value of the galactic latitude

2.3.1.3 *Total sky noise*

When noise effects of the atmosphere are combined with extra-terrestrial noise, the frequency of the noise minimum is reduced to the range between 1 and 10 GHz for clear weather, and 1 to 3 GHz for precipitation in rain climate 4 (as an example), and considering rainfall rates not exceeded for more than 0.01% for an average year (see Report 563-1 (Kyoto, 1978)). The resultant total sky noise temperature is shown in Fig. 4.

2.3.2 *Received flux-density*

Signals would have travelled over interstellar distances, and therefore could be at extremely low power flux-density levels upon arrival at the Earth. A graph of power flux-density at the Earth versus e.i.r.p. for sources at various distances is shown in Fig. 5. The distance to the nearest star is about 4 light years, the diameter of the galaxy is about 100 000 light years, and the distance to nearby galaxies is around 10^7 light years.

2.3.3 *Frequency*

The frequency and the time rate of change of frequency of the signals arriving at the Earth would be unknown.

2.3.3.1 *Frequency drift considerations*

If the transmitting source were on a planet of some other star, then relative motion between the source and our search system could occur because of:

– radial velocity of the other star with respect to the Sun;
– orbital velocity of the Earth and of the other planet, and
– the rotation of the Earth and the other planet.

The first of these would lead to a Doppler shift which would be, for all practical purposes, constant over the interval of the time of the search.

Planetary orbital motion and rotation produce Doppler frequency shifts which vary nearly sinusoidally with time (Doppler drift).

There could be, for example, four sinusoidal components to the received signal. These would be due to the orbital and diurnal motions of the Earth and the transmitter. The magnitude of the Doppler drift would be directly proportional to the transmitted frequency.

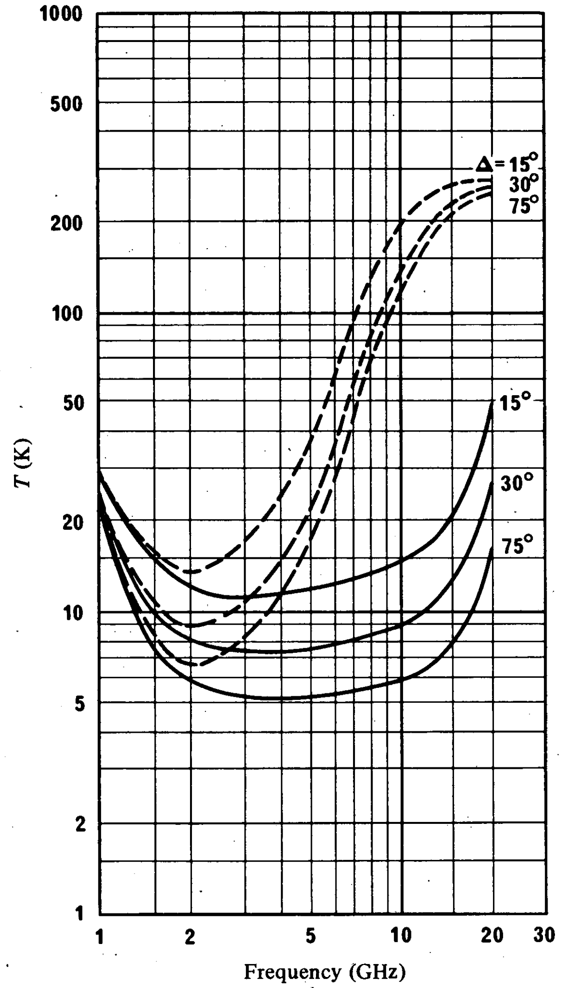

FIGURE 4 – *Total sky noise temperature (T) seen from the surface of the Earth*

——— clear weather, atmosphere only

– – – – – rain and atmosphere: 32 mm/h

parameter Δ: elevation of earth station antenna

The effects of Earth motions can be calculated and allowance can be made for them.

Frequency drift can also be caused by instabilities in the receiver and in the transmitter.

2.3.4 *Modulation*

The arriving signal could be unmodulated, or have any of the known modulation types.

If the source modulation bandwidth were to exceed the coherent bandwidth of the medium, the modulation would be distorted or destroyed.

Spectral lines in the transmitted signal would arrive with some broadening caused by the propagation medium, but essentially intact.

2.3.5 *Polarization*

The arriving signal could have any known linear, circular, or elliptical polarization with any orientation.

2.3.6 *Direction*

Because the source location would be unknown, the direction of the arrival would also be unknown.

2.3.7 *Time of arrival*

Signals could be intermittent.

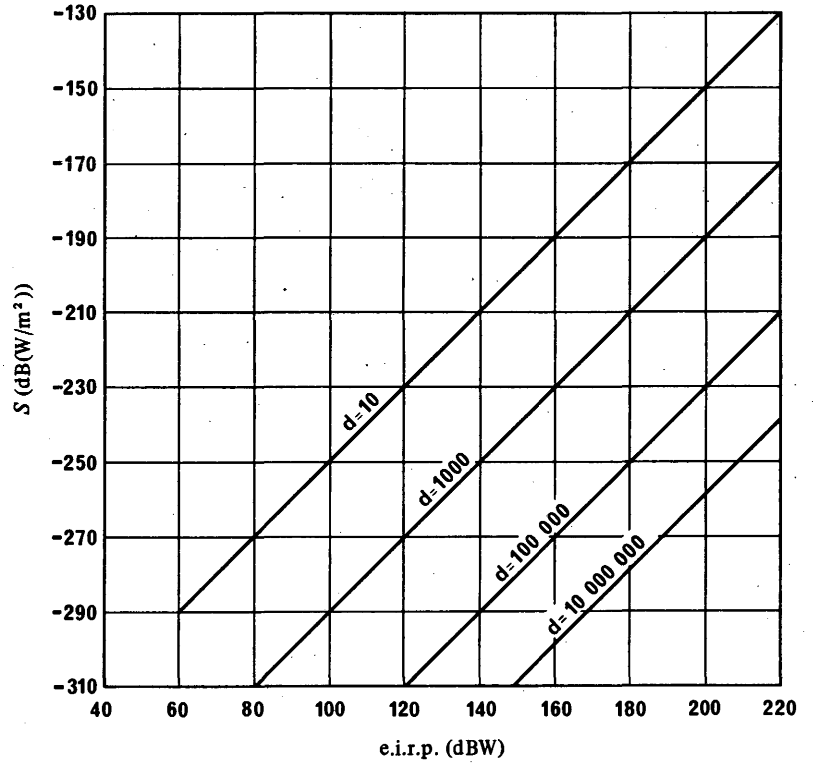

FIGURE 5 — *Received flux-density (S) versus effective isotropically radiated power for unattenuated sources at various distances*

parameter *d*: distance in light years

3. Preferred frequency bands

Considerations given in this section result in the identification of preferred frequency bands below 50 GHz. Assumptions and considerations that lead to higher frequency bands are given in Annex I.

3.1 *Receiving sensitivity considerations*

3.1.1 *Noise*

It may be assumed by some experimenters that there would be no prior knowledge of the characteristics of the signal sought, or of the signal source distance. This leads to the conclusion that the signal power flux-density from an extra-terrestrial source could be very small, and therefore the search should be made in a portion of the electromagnetic spectrum where physical factors allow maximum sensitivity.

Considerations of sensitivity make background radio noise a strong factor in the determination of a preferred frequency band.

Accommodation of the need for maximum available search time means that atmospheric precipitation effects on system sensitivity should also be taken into account for a terrestrial system.

Considering the discussions of § 2.2.1 and 2.3.1, the smallest background noise is obtained between 1 and 100 GHz for a spaceborne system. For a terrestrial system, noise is least between 1 and 10 GHz when only clear weather is considered. If rain effects are also taken into account, the noise minimum is reduced to between 1 and 3 GHz.

3.1.2 *Frequency drift*

Maximum receiver sensitivity is obtained by using very narrow-band receiving channels; but, in order for the receiver output to develop fully, the signal must remain in the receiver bandwidth for a time somewhat longer than the reciprocal of the receiver bandwidth. For an arbitrary Doppler frequency drift rate and assuming matched filter detection, it can be shown that [Oliver and Billingham, 1973b]:

$$B = Af_T^{1/2} \tag{1}$$

where:

f_T: transmitted frequency;

B: minimum channel bandwidth for full response to the drifting signal;

A: constant of proportionality.

Thus, in order to allow minimum channel bandwidth and the highest sensitivity, it is necessary to confine Doppler drift to a single channel during the integration time. For unknown components this can only be done by receiving at the lowest practical frequency.

3.1.3 *Maximum sensitivity*

The combined effects of noise and Doppler drift on total system sensitivity can be expressed as a figure-of-merit (F_m):

$$F_m = T_s f_S^{1/2} \tag{2}$$

where:

T_s: total equivalent sky noise temperature;

f_S: frequency being searched.

The best sensitivity is indicated by the smallest figure-of-merit.

This figure-of-merit is shown in Fig. 6 both with and without the atmospheric noise contribution. The maximum sensitivity is obtained in either case in the 1 to 3 GHz region. For an Earth-based system the maximum sensitivity is near 1.5 GHz.

3.2 *Spectral line considerations*

Experimenters may also assume that an ETI could place importance on some of the same molecular emission frequencies that are considered important by human science. In this case it may be desirable to search near specific spectral lines.

In 1959 it was proposed that a frequency of 1420 MHz (the neutral hydrogen spectral line) be used; this was the only known spectral line at that time [Cocconi and Morrison, 1959]. Subsequently, a number of molecular spectral lines have been detected in the microwave and millimetric wave region, and the selection of the frequency band must be reviewed.

In selecting the line, the following characteristics should be considered:

- the frequency must be known as unique or particular to both parties;
- it must have an intrinsic advantage that is known to both parties;
- there must be a high probability of receiving a signal by chance.

3.2.1 *The hydroxyl lines*

The lambda-type doubling lines of OH radicals (1612, 1665, 1667 and 1720 MHz) and K-type doubling line of formaldehyde (H_2CO, 4830 MHz) have been suggested as being more suitable than the other molecular lines [Morimoto *et al.*, 1978].

A frequency of 1666 MHz would be a good choice as it is in the middle of the main components (1665 and 1667 MHz), clear from the OH lines, but close enough to be monitored for the lines. Furthermore the lines are regularly monitored with a high frequency resolution in many objects from many observatories, and there is a high possibility that a narrowband artificial signal would be received by chance. This fact must be known to the advanced extra-terrestrial civilizations.

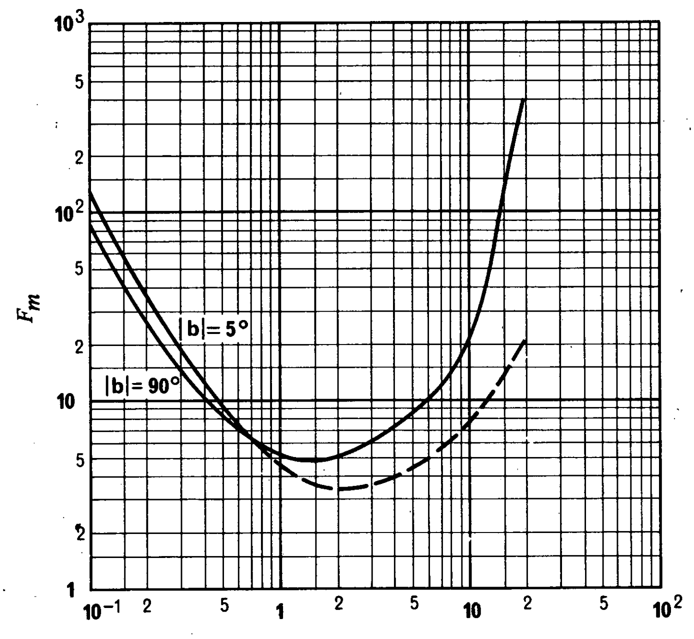

FIGURE 6 – *Combined noise and Doppler drift system sensitivity figure of merit,* F_m

——— Including zenith atmosphere noise

– – – Extraterrestrial noise only

parameter | *b* | : The absolute value of the galactic latitude

3.2.2 *The formaldehyde line*

The formaldehyde molecule at 4830 MHz exhibits anti-maser action as mentioned in § 2.3.1. A civilization on a star seen by us in front of a formaldehyde cloud could realize this situation and tend to send us signals at this frequency.

3.2.3 *The hydrogen line*

Observation directly at the hydrogen frequency would suffer from a high background noise. Observations near this line may be profitable.

3.2.4 *The "water hole"*

The region between the hydrogen line near 1420 MHz and the set of hydroxyl lines near 1650 MHz has been called the "water hole". Water based life forms may see this region as significant. These lines of the dissociation products of water are landmarks in that region of the microwave window from 1 to 2 GHz which physical considerations have indicated as most sensitive for the search.

3.2.5 *Others*

There are, of course, other molecular interstellar lines which might have importance, such as the water line at 22.23 GHz, or the formaldehyde line at 14.5 GHz. However, sky noise and Doppler drift considerations make a search near these other molecular transition frequencies less attractive.

3.3 *Summary of frequency considerations*

In the range up to 50 GHz, considerations of earth-based SETI system sensitivity lead to a preferred frequency near 1.5 GHz. If importance is attached to the hydrogen and hydroxyl lines this frequency region becomes even more attractive. However, if observers assume that an ETI may attach significance to the noise reducing properties of formaldehyde clouds, then 4830 MHz is also a preferred frequency. The bands between the OH lines near 1650 MHz are considered of secondary preference.

Some advantages are associated with the use of frequencies above 100 GHz (see Annex I).

The above considerations are not complete, and a SETI may be carried on at any frequency. Although SETI is a type of space research, it is often performed in the same frequency bands as radioastronomy because of spectral line considerations and the relative lack of radio interference.

4. Search system characteristics and requirements

The factors of § 1 and 2 lead to the following requirements on the search system:

- maximum practicable sensitivity;
- capable of receiving from any direction;
- capable of receiving any polarization;
- capable of searching a large frequency band with very narrowband frequency resolution;
- nearly continuous operation and minimum practical total search time.

4.1 *Sensitivity*

Under certain conditions the minimum detectable power of a signal is given by [Oliver *et al.*, 1971]:

$$P = kT \frac{1 + \sqrt{1 + Bt}}{t} \tag{3}$$

where:

k: Boltzmann constant

B: bandwidth of the receiver channel in Hz

T: equivalent system noise temperature in Kelvins

t: integration time in seconds.

Maximum sensitivity to a coherent signal is achieved by a combination of low noise temperature, narrow-band frequency resolution, long integration times, and antennas with a large collecting area.

Because of the modulation unknowns, maximum sensitivity and maximum likelihood of detection can be achieved with a system designed to search for, and to detect single spectral lines (carriers).

4.2 *Bandwidth*

For matched filter detection, the power flux-density detectable by a search system is proportional to the search bandwidth, maximum sensitivity being achieved when the search bandwidth matches the signal bandwidth (which may be as narrow as the interstellar medium permits). At the same time it is necessary to search over a very wide frequency range. Many spectrum analyzers sweep a narrowband receiver across the band of interest. This procedure is not useful for SETI. What is necessary is to simultaneously search many adjacent narrow channels, perhaps as many as 10^9 channels having bandwidths as small as 0.01 Hz. This simultaneous search of many adjacent channels allows the system to reach maximum sensitivity, while at the same time being able to detect a signal which is drifting in frequency due to Doppler effect, and also reducing the time necessary to examine a very wide frequency band.

4.3 *Operation*

The SETI search may take decades or longer. The number of directions to be searched is very large; the possibility of intermittent transmissions will require long observation times in each direction; and integration of the receiver output to increase system sensitivity will make each observation relatively lengthy.

Steps must be taken to minimize the total search time, e.g., the system should be automated and designed for nearly continuous all-weather operation.

When a signal is detected, it must be immediately examined to determine if it is an ETI signal. The search system must be sufficiently reliable to do this at any time.

As this work may take a long period without practical results, a special arrangement for continuing the search may be necessary.

4.4 *Location*

For ground based operations, requirements are similar to those for radioastronomical services, i.e., a place surrounded by mountains, far from large cities, etc.

In space, the far side of the Moon offers freedom from man-made interference and atmospheric emission. The Lagrangian collinear equilibrium point (Fig. 7) in the Earth-Moon system is of interest (60 000 km behind the Moon, where the gravitational force is balanced with the centrifugal force); because the observing spacecraft remains eclipsed from the Earth and well removed from the thermal emission from the lunar surface.

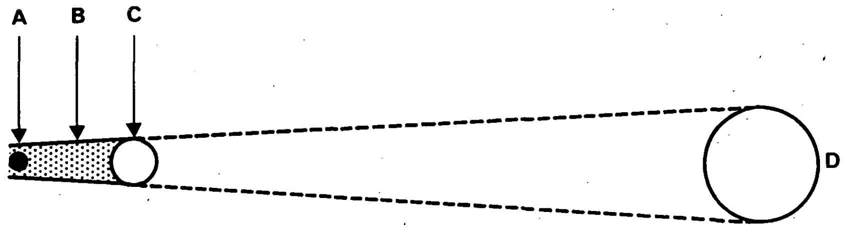

FIGURE 7 – *Lagrangian collinear equilibrium point*

A: Lagrangian point
B: Shadow region
C: Moon
D: Earth

4.5 *The search programme*

SETI programmes to date have examined only a few targets and directions; they have searched over a relatively narrow band, and their sensitivity has been poor compared to that which is available with recent technology.

Systems now performing searches are using existing radio telescopes.

Future programmes will have radio antennas dedicated to SETI. They will examine many more targets and directions; will search much wider bandwidths; and will be considerably more sensitive than current systems.

To gain increased sensitivity, they may use more sophisticated data analysis techniques; reduce the system noise temperature; reduce the single channel bandwidth; and use larger, more efficient antennas.

Future systems may search the entire sky, or they may examine individual stars. If observers desire to consider the background noise reduction caused by formaldehyde there are numerous stars which can be seen against the background of many dark clouds that cover a substantial fraction of the sky. Table I lists a sample of such stars, which are single stars, brighter than 8th magnitude, of spectral types of F, G, and K and are in front of dark clouds. Column 1 gives names of stars in the catalogue number in the AGK 3 catalogue, column 2, brightness in magnitude, column 3, spectral types, and columns 4 and 5 give equatorial co-ordinates of the stars.

4.5.1 *Optimum search method*

The above considerations are based on many debatable assumptions and there are many possible alternative systems; consequently, no single method can be specified as the optimum and it may be best to try several.

4.6 *Search system design*

Several Earth-based SETI systems are currently being planned in the USA, with capabilities and system parameters as outlined in Table II.

4.7 *Summary of system requirements*

While the exact source direction, frequency, signal polarization, power, flux-density, modulation and Doppler shift are unknown, the considerations discussed in this Report lead to the following conclusions:

- the search system must be very sensitive and have the lowest possible noise temperature;
- the system must be capable of searching large frequency bands continuously with narrowband frequency resolution;
- the system must be capable of looking in any direction;
- the system must sense all possible polarizations.

TABLE I – *A partial list of candidate stars for search at 4830 MHz*

AGK 3 No. (1)		Magnitude (2)	Type (3)	Right ascension (4) (1950)		Declination (5) (1950)	
+58°	16F	2.8	F5	0 h	6.5 min	+53°	52′
54	395	6.7	F5	4	5.4	54	42
38	491	6.2	F5	4	38.4	38	11
22	518	6.1	K0	5	16.3	22	3
+1	618	7.0	G5	5	44.0	+1	9
−1	639	8.3	K2	5	46.2	−1	48
+2	647	6.9	G0	5	47.9	+2	1
1	630	6.3	K0	5	49.8	1	51
6	643	7.7	G5	5	49.8	6	12
6	646	7.9	G0	5	50.8	6	15
3	717	7.9	K0	5	51.6	3	13
0	594	7.6	K0	5	52.5	0	58
2	684	7.3	K0	6	7.2	2	53
15	1946	7.9	G0	18	53.8	15	18
12	2040	8.4	G0	18	59.0	12	33
18	1834	8.0	K5	19	13.3	18	26
9	2447	6.7	F8	19	20.4	9	49
21	1990	8.6	G5	19	26.5	21	53
22	1969	8.7	K2	19	27.7	22	36
21	2002	7.6	G5	19	31.3	21	44
8	2614	7.6	K0	19	42.9	8	36
33	1851	7.9	K0	19	52.3	33	39
34	1945	8.0	K0	19	53.1	34	46
34	1947	5.0	K0	19	54.4	34	57
45	1663	8.1	K2	20	15.0	45	11
44	1848	7.8	G5	20	52.1	44	12
43	1905	7.9	K5	20	53.6	43	11
42	1952	7.5	K0	20	54.5	42	35
43	1910	7.9	K0	20	54.6	43	42
42	1956	8.4	K0	20	55.6	42	15
43	1923F	5.1	K5	21	3.1	43	44
57	1436	7.3	F8	21	23.6	57	52
54	1439	7.1	K0	21	39.1	54	39
49	1851	7.1	K0	21	40.8	49	22
60	1419	8.3	K0	21	50.9	60	6
56	1555	7.0	K2	22	14.6	56	58
59	1619	8.3	K0	23	25.9	59	47
58	1565	7.6	K0	23	28.9	58	53
59	1625	8.5	K5	23	29.4	59	11
58	1567	8.2	K2	23	29.4	58	49
60	1574	7.9	K0	23	31.0	60	8
60	1575	8.2	K0	23	31.3	60	12
+61	1471	7.6	K2	23	40.1	+61	24

5. Interference considerations

A system for a search for extra-terrestrial intelligence (SETI) will be a receive only system and so will not cause interference. The SETI system must be characterized by low system noise temperature, antennas with a large capture area, wide instantaneous bandwidth with narrowband resolution, with signal integration and quasi-matched filter detection techniques. The receivers will have the highest practical sensitivity in order to detect the anticipated low power flux-density signals from an ETI. Hence, a SETI system will be very vulnerable to interference.

The system discussed in this section is considered to be operating near 1.5 GHz. Other frequencies will also be used, especially ones used by radioastronomy.

TABLE II – *Earth based SETI system characteristics*

System noise temperature (K)	10
Frequency resolution bandwidth (Hz)	0.01 to 300
Integration time (s)	10 to 10^5
Number of adjacent frequency channels searched simultaneously	10^6 to 10^9
Bandwidth searched simultaneously (MHz)	1 to 300
Tunable frequency band capability (GHz)	1 to 25
Polarizations received simultaneously	2 to 6
Minimum detectable signal power (dBW)(1)	–226
Minimum detectable signal flux-density for a 300 m diameter antenna (e.g., Arecibo, Puerto Rico) (dB(W/m²))(1)	–272

(1) These values are based on a 300 Hz resolution bandwidth, 10^5 second integration time, and 60% antenna aperture efficiency. Values for other system parameters may be calculated using equation (3) and the antenna capture area.

5.1 *SETI station factors pertinent to sharing*

The SETI parameters considered in this Report are taken from Table II. Other values may be examined also.

The minimum detectable signal for this system is -226 dB(W/300 Hz), or -272 dB(W/(m^2 · 300 Hz)) using an antenna of 300 m diameter (such as the radio telescope at Arecibo, Puerto Rico).

5.1.1 *Maser saturation*

Systems under consideration in the USA envisage the use of a maser to achieve the required low noise temperature. Typical masers exhibit nonlinear saturation effects when the total receiver input power in the maser passband exceeds about -120 dBW. Systems being used for SETI may have passbands up to 300 MHz.

5.1.2 *Receiver saturation*

The signal processor will have a finite linear dynamic range. Thus a sufficiently strong receiver input signal in a single channel will cause saturation. This will in turn cause the generation of spurious signals which will also affect nearby channels.

5.1.3 *Minimum detectable signal degradation*

A wideband, man-made signal at a level of about 10 dB below the minimum detectable signal in each channel will appear to the signal processor as an increase in noise over a number of channels. This will cause a degradation of the receiver performance of about 0.4 dB in those channels.

5.1.4 *False signal detection*

A man-made coherent signal at, or slightly below, the minimum detectable level in a channel would be observed and cause a false alarm. This would in turn require observations sufficient to establish the detection as a false alarm. It would also mask a weaker ETI signal that might be present.

5.2 *Interference protection*

Based on § 5.1, reasonable protection will be afforded if the power in a single channel is about 10 dB below the minimum detectable signal. This requires that the power spectral density of wideband interference or the total power of CW interference in any single band and all sets of bands 1 Hz wide does not exceed -260 dB(W/Hz) referenced to the input terminals of the receiver.

Because of the possible fleeting nature of ETI signals, interference should not exceed an aggregate of 5 minutes per day. For the reasons discussed in Report 548 this should be taken as 0.001% of the time for protection from terrestrial transmitters.

Near 1.5 GHz this protection will be afforded for a power spectral flux-density of -306 dB(W/(m^2 · Hz)) on the boresight of a 300 m antenna, or -235 dB(W/(m^2 · Hz)) for an isotropic receiving antenna.

5.3 *Sharing considerations*

5.3.1 *Line-of-sight paths*

Consider the conservative case of a transmitting station with 1 W of power, a 0 dBi antenna, and the modulation uniformly spread over 1 MHz. This station would exceed the interfering power spectral flux-density given in § 5.2 for an isotropic receiving antenna at a range of approximately 160 000 km.

This leads to the conclusion that sharing with spaceborne stations is not practicable. Sharing with airborne stations above the horizon of a SETI station is also not practicable.

5.3.2 *Over the horizon paths*

Sharing with most ground-based transmitters appears feasible if an appropriate co-ordination procedure is adopted.

Sharing with high powered Earth-based systems such as tropospheric scatter and radiolocation may be difficult.

This sharing case requires further study.

5.3.3 *Reflection from spaceborne objects*

The reflection of terrestrial signals from spaceborne objects near Earth may also cause a problem. This case needs further study.

5.4 *Summary of interference considerations*

Frequency sharing between a receiving SETI system and spaceborne or line-of-sight airborne transmitting systems is not feasible.

Frequency sharing between a receiving SETI system and Earth-based transmitting systems is probably feasible in most cases with appropriate co-ordination.

6. Other cases

Although the above considerations are based on a number of reasonable assumptions, there are also several reasonable objections. Three important ones are outlined below.

6.1 There is an argument that the transmitting of a radio signal may be more efficient than just searching for a signal. It was also pointed out that the first artificial radio signal occurred 60 years ago. This signal has already travelled 60 light years, and might be detected by a civilization within this distance. However, such an unaimed signal at a distance of 60 light years is very weak and would be difficult to detect by other civilizations.

If the communicating civilization is regarded as far superior to ours, transmission of an aimed signal must not be attempted without due consideration of unexpected problems.

6.2 In 1960 the possibility of a first contact through a space probe from the other civilization was considered [Bracewell, 1960]. Generally a space probe could be considered as uneconomical and therefore unlikely. However, several variations are possible and a more careful study is warranted.

6.3 Morimoto [1967] has suggested a gaseous creature, which causes a population inversion in certain molecules in its body and sends and receives radio signals through maser action.

These possibilities are not examined in the present Report.

7. Conclusions

7.1 *Preferred frequency bands*

If experimenters assume that there is no *a priori* knowledge of the ETI signal, then considerations of maximum sensitivity and maximum search bandwidth lead to the conclusion that the region near 1.5 GHz having a bandwidth of several hundred MHz is a preferred region for SETI examination. Because of the possible significance that other water-based life may attach to the spectral lines of hydrogen and hydroxyl radical, it is desirable that the band include these spectral lines. It should be defined so as to allow a reasonable search bandwidth on either side of these lines.

If observers assume that the ETI has knowledge of the location and characteristics of formaldehyde clouds, and is considering their shielding in transmitting to the Earth, then a narrowband of frequencies centred at the 4830 MHz formaldehyde line would be a preferred frequency.

Other frequencies will also be used, especially those currently used by radioastronomy. As the determination of optimum frequencies continues, other preferred bands will emerge.

There are some arguments for the use of frequencies above 100 GHz.

7.2 *Interference considerations*

Some currently planned SETI systems will need protection at the receiving level of -235 dB(W/(m^2 · Hz)) near 1.5 GHz, if the antenna is assumed to have isotropic gain away from the main beam.

Some other SETI systems will use frequencies also used by radioastronomy. The protection currently considered appropriate in Report 224 would be adequate for their protection.

As the SETI systems and frequencies become better defined, additional protection criteria will emerge.

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ANNEX I

CRITERIA FOR THE CHOICE OF FREQUENCY BANDS ABOVE 100 GHz

1. Introduction

Figure 3 of this Report shows sky noise temperatures that would apply to the case of SETI receiving terminals located outside the atmosphere of the Earth. The sky noise temperature is less than 15 K over the frequency range 0.6 to 300 GHz. This Annex presents considerations which lead to the choice of frequencies in the upper part of this range.

Heterogeneous distribution of electron concentration along the propagation path can cause signal dispersal and spurious modulation. The magnitude of this signal distortion depends on the transmission frequency. Higher frequencies result in less distortion, and this may be a factor in frequency selection.

2. Choice of preferred frequency bands

The basic criterion for the choice of the frequency range for such communication is the greatest channel information capacity at fixed transmission and reception costs. Applying this criterion, the most promising bands are around the frequencies characterized by unique and universal phenomena in the universe (reference frequencies).

One such reference frequency might be that of the ground state spectral line (fine and hyperfine splitting) of the lightest artificial atom – positronium [Kardashev, 1979] which has a frequency [Egan *et al.*, 1977]:

$$\nu = 203.385 \text{ GHz}$$

Another frequency reference point might be connected with the residual background noise, in view of its fundamental role in the universe. This point can be defined as the centre of gravity of the energy spectrum of the residual background noise. The uncertainty of the present knowledge of the background noise temperature (2.7 to 3 K) defines the frequency band corresponding to this point:

$$\Delta\nu_1 = 197 \text{ to } 220 \text{ GHz}$$

It should be noted that the spectral line of positronium falls in the same band.

A further reference frequency may be defined as the centre of gravity of the energy distribution of the incoming wideband information signal. This is optimum in the sense that it provides the highest speed of transmitted information at a given value of total power flux-density of the signal at the Earth [Lebedev and Levitan, 1966; Kardashev, 1969]. With the same uncertainty of residual background noise temperature, this frequency occupies the band:

$$\Delta\nu_2 = 101 \text{ to } 112 \text{ GHz}$$

Spectral lines of carbon monoxide and molecular oxygen are found at 115.271 and 118.75 GHz. In view of the widespread occurrence of carbon monoxide in our galaxy and in other galaxies, and in view of the important part played by oxygen in the evolution of life on Earth, these frequencies may be used to define a further band of interest to SETI, 112 to 120 GHz.

The frequencies stated above, and the band 1400 to 1727 MHz, correspond to those adopted by the World Administrative Radio Conference, 1979, for the search for signals from extra-terrestrial intelligence.

It may be further noted that observations of signals in a narrow band around the oxygen line, if carried out outside the Earth's atmosphere, would be effectively screened from terrestrial interference by atmospheric absorption (Report 719).

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SECTION 2C: SPACE OPERATIONS

Recommendations and Reports

REPORT 845-1

SPACE OPERATION SYSTEMS

Frequencies, bandwidths and protection criteria

(Question 18/2)

(1982–1986)

1. Introduction

The World Administrative Radio Conference, Geneva, 1979, defined the space operation service as follows:

"A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand.

These functions will normally be provided within the service in which the space station is operating."

To understand the meaning of the second sentence in the definition, it should be borne in mind that the original idea was to carry out space operation functions solely in the bands allocated to missions. Experience showed, however, that space operation could be facilitated in some cases by the specific allocation of bands to this service. In particular, this makes it possible to use a small number of stations for the space operation of satellites with missions pertaining to different services, such as the space research, meteorological-satellite, Earth exploration-satellite, fixed- and mobile-satellite and broadcasting-satellite services.

Furthermore, the frequency bands technically suitable for space operation do not always coincide with the bands which are suitable to missions, and there may be different protection criteria for space operation and mission telecommunication receivers.

This Report covers successively the functions to be carried out, the preferred frequency bands, the bandwidths, the protection criteria and various operational aspects of space operation systems.

All aspects are dealt with in such a way that the conclusions are applicable both for cases where space operation functions are performed in a frequency band related to a satellite's mission, and for cases where they are carried out in a frequency band allocated to the space operation service.

Links in space operating systems may be established either directly between spacecraft and earth stations or through data relay satellites. Only direct links are considered here. For links via data relay satellites, see Report 848.

2. Space operation functions

The main functions of space operations are:

- maintenance telemetry,
- telecommand,
- tracking,
- RF sensing for attitude control.

2.1 *Maintenance telemetry*

To ensure the maintenance of a spacecraft, a large number of measured data, most of them with a low data rate, have to be transmitted to the Earth. They include:

- temperature measurements, either for monitoring and regulation or for correction of on-board instrument readings in the light of their temperature;
- magnetic field measurements, to provide particulars of the instantaneous attitude of the spacecraft or its rotation speed;
- measurements of moving units: separation indicators, safety stops for deployed components;
- inertial measurements (rate gyros, accelerometers), useful for satellite attitude and station keeping;
- optical measurements, to ascertain the attitude of the spacecraft in relation to the Earth, the Sun and stars;
- measurements of pressure in tanks and electrochemical batteries;
- current and voltage measurements;
- reports on the condition of a component or the reception or execution of a command.

All these measurements may be used to monitor the condition of spacecraft and their payloads which depends on the external environment and on configuration orders addressed to the spacecraft by telecommand or provided by an on-board sequencer according to a predetermined programme.

These data are useful for ensuring proper operational conditions, optimizing the spacecraft and payload mission facilities and analyzing unforeseen situations. They also serve to broaden knowledge of the behaviour of materials in orbit and to improve the development of new systems.

Telemetering data from the on-board memory may be transmitted in real time or stored and subsequently transmitted.

An example of maintenance telemetry is given in Annex I.

2.2 *Telecommand*

Most spacecraft should be able to receive orders by telecommand. No. 2612 of the Radio Regulations makes this mandatory in the case of the active satellites defined in No. 172.

2.2.1 In the case of short-mission spacecraft, such as launchers, most of the orders can be recorded before the flight and distributed as necessary by an on-board sequencer.

Nevertheless, space telecommand is generally used for safety purposes (e.g. stopping the propulsion of a launcher deviating from its assigned trajectory or destroying it if required).

Certain telecommand functions can also be carried out by a radar transponder operating in the radiolocation service.

2.2.2 In most other cases, telecommand is needed to modify the operation of the spacecraft and its payload:

- according to successive utilization phases during the mission,
- according to different flight phases (orbit insertion, eclipse periods, etc.), or
- as a result of abnormal events, such as operational anomalies.

The orders transmitted to the spacecraft when it is in line of sight of an earth station may be either carried out immediately or stored in a memory from which they are extracted later for execution at a time also stored in the memory.

Delayed-action telecommand is particularly important for complex spacecraft missions requiring an on-board computer. In such cases, a megabit of information may have to be transmitted in a few minutes. Satisfactory reception of telecommand signals is generally acknowledged by telemetry.

An example of telecommand is given in Annex I.

2.3 *Tracking*

Space tracking, i.e., the determination of the orbit, velocity or instantaneous position of an object in space by means of the propagation properties of radio waves (see Nos. 130 and 10 of the Radio Regulations), has to be carried out during every space mission to meet one or more of the following requirements.

2.3.1 *Spacecraft orbit control system*

Broadly speaking, this is one of the methods for controlling the orbit of a spacecraft by means of telecommand facilities and on-board propulsion systems. In practice, orbit control may be used for:

- placing in parking or transfer orbit;
- modification of orbits: e.g., for changing from a transfer orbit to the geostationary-satellite orbit;
- fine orbit correction: e.g., for geostationary satellite station-keeping and for rendezvous manœuvres;
- returning a recoverable spacecraft to Earth.

2.3.2 *Surveillance, safety, recovery*

The surveillance and safety functions cover anti-collision measures for spacecraft in neighbouring orbits and prediction of the impact or landing site of re-entering launcher stages or spacecraft.

2.3.3 *Orbital accuracy*

Evaluation of the accuracy of launches or other orbital manœuvres.

2.3.4 *Attribution of location data to mission measurements and observations*

Measurements must be related to the position where the spacecraft is situated at the moment when the measurements are taken. This is particularly important when the spacecraft is carrying out scientific measurements of its environment, such as measurements of the magnetic field, particle density, etc. It is also essential in Earth observation missions, independently of the facilities offered during these missions by identification of control points on the transmitted pictures.

2.3.5 *Publication of ephemeris tables*

Forecasts of visibility and the pointing angle towards the spacecraft are essential for the organization of the work of earth stations and for the pointing of such directional instruments as high-gain antennas, telescopes, etc.

2.3.6 *Remarks*

Tracking functions which are the main objectives of space missions, such as space geodesy and satellite radionavigation, have been deliberately omitted from the above list.

Certain space tracking functions, particularly some of those cited under § 2.3.1, 2.3.2 and 2.3.3, may be carried out under the radiolocation service, with or without the use of a spacecraft radar transponder.

A brief description of tracking systems is given in § 3.4 of Report 548 (Geneva, 1982).

An example of a range and range rate system is given in Annex I to this Report.

2.4 *RF sensing for attitude control*

Report 546 on spacecraft attitude control contains a paragraph (§ 4.4) dealing with attitude sensing in relation to the Earth by means of antennas and circuits aboard the spacecraft receiving signals from a ground based beacon. This method may also be used for pointing of spacecraft antennas, for instance on board broadcasting satellites.

3. Preferred frequency bands

From the technical point of view, the space operation functions described in the preceding paragraph may be carried out in the frequency range between approximately 100 MHz and 30 GHz.

In the special case of communications effected during the re-entry of a spacecraft into the Earth's atmosphere, frequencies of 10 GHz or higher must be chosen (see Report 222). In other cases, the technical choice of frequencies mainly depends on the factors described below.

3.1 *Lower limits*

The lower limit of frequencies for space operations is bound up with the effect of ionospheric propagation on the accuracy of tracking measurements.

3.1.1 *Ionospheric effects on tracking accuracy*

Report 263 describes all the ionospheric effects on Earth-space propagation. A summary pertinent to the subject of this Report is given below.

A typical error in ranging carried out by group delay measurement is 400 m for a vertical path at 100 MHz. For very low elevation angles, the value should be multiplied by about 3. Real values, however, can vary considerably and may be up to 10 times smaller or greater. In practice, it is impossible to correct these errors by using models, owing to the great time and space variability of the ionosphere. To reduce ionospheric errors, the frequencies used must be sufficiently high, since the error follows a $1/f^2$ law. (A frequency pair may also be used (see Report 988).) At 1 GHz, for example, the typical error for a vertical path is 4 m and for very low elevations, 12 m.

The remarks made with regard to group delay distance measurements also apply to phase delay measurements, except that the error has the opposite sign (apparent shortening instead of lengthening).

Error in the pointing direction of an autotrack antenna at 30° elevation has a typical value of 0.5 milliradian at 100 MHz and exceeds 2.5 milliradians in less than 10% of cases. These values also follow a $1/f^2$ law and should be divided by 100 for a frequency of 1 GHz.

Range rate and interferometric measurements are affected by the ionosphere in a similar way as range and angle measurements. They are further affected by the microstructure of the ionosphere, i.e., the differential effect of the ionosphere on the two paths measured for difference. Nevertheless, these subsidiary effects are generally less serious than the main ones, and like the latter they decrease with increasing frequency.

3.1.2 *Necessary tracking accuracy. Effect on choice of frequencies*

The required accuracy of tracking measurements depends on a satellite's mission, and also on the number of earth stations involved in tracking and on their geographical location on the Earth's surface and in relation to the satellite orbit.

For many application missions, the satellites have to be maintained in a specific orbit. The two most usual cases are station-keeping with a geostationary satellite and keeping an Earth exploration satellite in heliosynchronous orbit. In both these cases, the required accuracy is about 50 m, on the assumption that a small number of stations is appropriately distributed.

Since the overall accuracy of the measuring system depends not only on the ionosphere but also on other factors, particularly on the quality of the measuring instrument, the share due to the ionosphere should be less than 50 m. In the light of the foregoing, this condition begins to be fulfilled from the moment that the frequency exceeds 1 GHz.

In conclusion, it may be assumed that from the point of view of tracking accuracy most application missions require frequencies above 1 GHz. This conclusion also applies to certain scientific missions, although some scientific missions (for astronomy, for example) and some types of application missions can be effected with lower accuracy and therefore at frequencies below 1 GHz.

3.2 *Upper limit*

Although the frequency range to be used for space operations is approximately 100 MHz to 30 GHz, the upper part of this range is generally less favourable when a link has to be established or maintained in all operating phases of a space system. A frequent requirement, in fact, is the possibility of establishing at any moment, or permanently maintaining, telemetry or telecommand links, i.e. independent of the spacecraft attitude. For this reason, a great number of satellites rely on quasi-omnidirectional antenna coverage for space operations.

For large satellites with complex structures such antennas are frequently difficult to implement at frequencies above 8 GHz. At higher frequencies, spacecraft antenna coverage will not be any more quasi-omnidirectional, but be restricted to certain aspect angles. This can result in a loss of RF contact with the satellite for unfavourable aspect angles.

Furthermore, at frequencies above 15 GHz additional propagation conditions in the atmosphere may lead to a deterioration of the link, unless either the transmitted power or the G/T of the receiving station is considerably increased.

In these circumstances, the antenna gain to be taken into account in drawing up the link budget is not that of the main lobe minus 3 dB, as is usual for mission telecommunications, but is the gain guaranteed in the troughs within the minimum required coverage. The gain in the trough depends not only on antenna design, but also on antenna layout and the dimensions and shape of the spacecraft structure and its appendages such as booms, solar panels, other antennas, etc.

The masking effect produced by the body of the spacecraft may be reduced by placing the antenna at the end of a suitably long boom. There could also be an automatic system aboard the spacecraft to guarantee the link performance with the earth station in the event of loss of nominal attitude. This link may be intermittent.

The range of 100 MHz to 30 GHz should be divided into 3 sub-ranges:

– *below 1 GHz*

The body of the satellite affects the radiation pattern, which may be an advantage for small satellites (less than 1 m) and a disadvantage for larger ones.

– *1 to 8 GHz*

The radiation is mainly defined by the characteristics and arrangement of the antennas.

– *8 to 30 GHz*

Obtaining the required radiation entails stricter constraints on the design and manufacture of the spacecraft antennas.

It appears that the highest frequency used so far for links which are independent of the attitude of the spacecraft is 6425 MHz, but current projects provide for the use of frequencies as high as 14 GHz.

3.3 *Other factors to be taken into account in choosing frequencies*

To facilitate decoupling of Earth-to-space and space-to-Earth links while using the same antenna in both directions, the ratio between the frequencies of the two links should be between 1.06 and 1.1.

To optimize spectrum utilization, it would be desirable for all space systems operating in these bands to adopt the same ratio. However this approach may not always be possible, in particular at earth station sites located within areas covered by dense terrestrial networks, operating in the same frequency band. In the bands 2025 to 2120 and 2200 to 2300 MHz, various space systems already in operation use coherent transponders with a frequency ratio of 240/221 between the down link/up link permitting range rate measurements.

3.4 *Summary of preferred frequency bands*

To sum up, the preferred frequencies for space operations lie approximately between 1 and 8 GHz.

Lower frequencies may be used, particularly for small spacecraft carrying out missions which do not call for high-precision tracking.

Higher frequencies may be preferred for space operation functions of spacecraft using these frequencies as well for mission links with the Earth.

4. **Necessary bandwidth**

From the point of view of bandwidth requirements, a distinction should be made between launchers and other spacecraft.

In the case of launchers, the bandwidth of the space-to-Earth link is related to the transmission of many rapidly changing parameters, mainly vibrations and pressures.

In the other cases, the bandwidth of the space-to-Earth link is generally determined, not by telemetry, but by ranging signals. An example is given in Annex I.

With regard to the Earth-to-space link, the necessary bandwidth is also generally determined by the transmission of ranging signals.

In conclusion, the necessary bandwidths are generally determined by the transmission of ranging signals and are of the order of 200 kHz to 1 MHz for classical modulation methods. New modulation techniques such as spread spectrum will require bandwidths in excess of 1 MHz while allowing a multiple reuse of the same band. Lower values may suffice if tracking is effected by interferometry or by range rate measurement (Doppler effect measured on the carrier).

5. **Protection criteria**

5.1 *Protection level of earth station receivers*

Attempts are generally made to reduce the necessary power of on-board transmitters to a minimum, and earth station receivers therefore have to operate at maximum sensitivity.

Above 1 GHz, it is considered that the total noise temperature of earth stations is 100 K or more which at the receiver input is equivalent to a noise power spectral density of $kT \geqslant -208.6$ dB(W/Hz).

It is considered that in most cases additional protection of about 5 dB is required against all types of interference.

The total interference power spectral density must therefore not exceed -214 dB(W/Hz) at the receiver input.

Below 1 GHz, owing to the increase in galactic noise temperature, the permissible interference level may be raised by 20 dB per decreasing frequency decade.

5.2 *Protection ratio of space station receivers*

The power of earth station transmitters can generally be increased within the limits imposed by the Radio Regulations and on-board receivers therefore do not always operate at maximum sensitivity. In particular, for communication with low-altitude satellites operating close to sources of interference from terrestrial services, the transmitted power of earth stations can be kept as high as for geostationary satellites for example, in order to keep an adequate signal-to-interference ratio.

The protection of space station receivers is therefore more conveniently expressed by protection ratios than by protection levels.

A signal-to-total interference protection ratio of 20 dB is sufficient in most cases.

5.3 *Reference bandwidth*

The reference bandwidth in which the protection level or ratio must be specified depends on the characteristics of the receivers used and their susceptibility to continuous wave, amplitude modulated or low-index modulation phase-modulated interferences. Phase-locked receivers are often used; in such cases the reaction of the receiver to a narrowband interfering source is characterized by the equivalent noise bandwidth of the loop. This bandwidth is normally fixed at a value between a few hundred hertz and a few kilohertz. A value of 1 kHz may therefore be adopted for the reference bandwidth.

5.4 *Reference percentage of time*

Generally the percentage of time during which space operation links can tolerate an interference level above the protection level may be fixed at 1% each day. This value is based on the assumption that the spacecraft is equipped with memory and automatic devices to ensure its safety during interruptions of telecommunications. This condition was not always fulfilled in the past, but it is considered reasonable to require it to be met by future systems.

However interference lasting for as long as 15 consecutive minutes is intolerable during certain foreseeable critical stages, such as launch phases, critical spacecraft manœuvres, or for such short-lived spacecraft as rocket probes. It would be unreasonable to lay down protection criteria on the basis of such exceptional situations, and it would be preferable to invite concerned administrations to carry out special analyses of the interference likely to be caused and to take counter-measures which should be temporary and limited to specific regions.

5.5 *Conclusions on protection criteria*

For earth stations carrying out space operation functions, above 1 GHz, the total interference power at the receiver input in any 1 kHz band should not exceed −184 dBW for more than 1% of the time each day; below 1 GHz, this value may be increased by 20 dB per decreasing frequency decade.

For space stations carrying out space operation functions, the ratio of signal power to total interference power in any 1 kHz band should not fall below 20 dB for a period exceeding 1% of the time each day.

6. Frequency sharing possibilities

Sharing within the space operation service near 2 GHz: see Annex II.

Sharing with other services: see Reports 396, 678 and 846.

7. Operational aspects

A comparison is given below of the advantages and disadvantages of the use for space operation functions of mission frequency bands and frequency bands allocated to the space operation service or a combination of the two.

7.1 *Use of mission telecommunication bands for space operation*

7.1.1 *Advantages*

Since most spacecraft are equipped with transmitters and receivers for telecommunications directly concerned with their mission, it is generally preferable to use the same equipments for maintenance telemetry, telecommand and tracking, in order to reduce the cost of on-board and earth station equipment and to economize the spectrum.

7.1.2 *Disadvantages*

Experience shows that this mode of operation is not always the best:

- when frequencies above 7 GHz are used for mission telecommunications, it is often difficult to ensure on board the spacecraft the necessary radiation pattern to guarantee maintenance of links during launching and during nominal attitude loss phases;
- in certain frequency bands allocated to mission telecommunications, the allotment plans do not provide specifically for the transmission of space operation data;
- economy of on-board equipment is less than it appears at first sight in those cases where it becomes necessary to install a wide-coverage antenna system for space operation functions in addition to the directional radiation antennas usually used for mission telecommunications;
- economy of earth station equipment is also not necessarily guaranteed, since space operation functions may necessitate a geographical location of stations different from that required for mission functions.

7.2 *Use of specific space operation service bands*

7.2.1 *Advantages*

In view of all the expenditure on board and on the ground, it may be cheaper to have a single network of earth stations for space operation. These would operate with satellites carrying out missions for several services to which different frequency bands are allocated. The common network would use frequencies allocated specifically to the space operation service.

7.2.2 *Disadvantages*

The advantage of a multi-purpose earth station network using frequencies allocated exclusively to the space operation service and working with several spacecraft is limited if some of the spacecraft require the permanent operation of telemetry links, which would make it necessary to increase the number of earth stations. This would reduce, particularly for geostationary satellites, the efficient use of frequencies and increase the interference potential.

7.3 *Combined use of mission and specific frequency bands*

In conclusion, the best solution, especially for mission telecommunications using frequencies above 8 GHz, may be to equip spacecraft with two maintenance telemetry, telecommand and tracking systems, one operating in the band allocated to the mission and the other in the frequency band which is most suitable for space operations, i.e., the band 1-8 GHz. The first system would be used preferably in the routine phases and could be brought into operation by mission telecommunication earth stations or by a specialized earth station; the second system would be used during the launch phase and during other critical phases, without unduly overloading the multi-purpose earth station network. The additional cost of the on-board equipment is less than might appear at first sight, because the telemetry encoder and the telecommand decoder would not have to be duplicated and because the on-board antennas would have to be duplicated in any case to ensure the necessary coverage during critical phases. The additional cost of ground equipment would be shared between the user systems. To offset these additional investments, this solution would ensure the greatest operational reliability and flexibility at all phases of the mission without entailing any appreciable increase in operational costs. An example is given in Annex II, § 2.5.

ANNEX I

EXAMPLE OF SPACE OPERATION SYSTEMS

TELECOM 1 System

1. General information

The satellite system comprises an active satellite system TELECOM 1A and a back-up satellite TELECOM 1B, both in geostationary orbit. It can provide services for metropolitan France and adjacent parts of Europe as well as for the French Overseas Departments from the Caribbean to the Indian Ocean.

For its missions, the system uses the frequency bands 14/12 GHz and 6/4 GHz. Telecommand and telemetry signals can be transmitted in the 6/4 GHz band or in the 2 GHz band allocated to the space operation service under Nos. 747 and 750 of the Radio Regulations.

2. Choice of frequency band for use in space operation

2.1 *Principles*

The telemetry, telecommand and ranging sub-system operates in the 2 GHz band during orbit acquisition operations and at 6/4 GHz during the operational phase. The 2 GHz link may also be used to back up the 6/4 GHz link for short periods during the operational phase..

2.2 *Launching and positioning phases*

In the launching phase, the sub-system operates in the 2 GHz band. After entry into the drift orbit and after the attitude control sub-system has stabilized the spacecraft in the direction of Earth, the 6/4 GHz receivers and transmitters can be switched on by the 2 GHz telecommand system.

2.3 *Operational phase*

During the operational phase, telecommand reception is automatically assured provided a telecommand signal at 6 GHz is present and there is an adequate signal-to-noise ratio on the sub-carrier. In the absence of the 6 GHz signal, telecommand signals can be received in the 2 GHz band.

During the operational phase, the telemetry sub-system can transmit simultaneously and continuously on two carriers, one in the 2 GHz band and the other in the 4 GHz band. Either transmission can be cut off by telecommand. The nominal operating mode is in the mission band (4 GHz).

3. Characteristics of space operation links

The main link characteristics are given in Tables I and II.

TABLE I – *Main characteristics of space operation up links*

	2 GHz band	6 GHz band
Maximum earth station e.i.r.p. (dBW)	71	70
Receive gain of space-station antenna for Earth coverage with oriented satellite (dBi)	0	16.7
Equivalent receiving space station noise temperature (K)	1100	1700
Telecommand signal		
Modulation	PCM(NRZ-L)-PSK-PM	PCM(NRZ-L)-PSK-FM-PM
Rate (bit/s)	1000	1000
Sinusoidal PSK sub-carrier frequency (kHz)	8	8
FM sub-carrier frequency (kHz)	–	70
Frequency deviation (kHz)	–	± 12 peak-to-peak
Sinusoidal ranging signals		
Modulation	PM	PM
Major tone frequency (fine measurement) (kHz)	100	100
Minor tone frequencies (ambiguity resolution) (kHz)	Between 15 and 20	Between 15 and 20

TABLE II – *Main characteristics of space operation down links*

	2 GHz band	4 GHz band
Maximum space station e.i.r.p. (dBW)	3	11
Receive gain of earth-station antenna (dBi)	45	46
Equivalent receiving earth station noise temperature (K)	160	200
Telemetry signal		
Modulation	PCM(bi-phase-L)-PSK-PM	PCM(bi-phase-L)-PSK-PM
Rate (bit/s)	160	160
Sinusoidal sub-carrier frequency (kHz)	40.96	40.96
Sinusoidal ranging signals		
Modulation	PM	PM
Major tone frequency (fine measurement) (kHz)	100	100
Minor tone frequencies (ambiguity resolution) (kHz)	Between 15 and 20	Between 15 and 20

ANNEX II

INTRA-SERVICE SHARING CONSIDERATIONS FOR THE UHF BAND (2025 TO 2110 MHz AND 2200 TO 2290 MHz) ALLOCATED TO THE SPACE OPERATION SERVICE

1. Introduction

The European Space Agency (ESA) which is responsible for the development and operation of a great variety of spacecraft is constantly faced with the requirement of optimizing its use of the 2 GHz frequency bands allocated to the space operation service. With a view to arriving at this goal, several methods of increasing the capacity of the 2 GHz bands have been studied and the results are given below.

2. Possibilities for sharing

Since the earth station antennas used for space operations functions are typically 10 m and upwards in diameter, spatial separation offers a first means of discrimination between users sharing the band. A second possibility is the assignment of different frequencies to different users. The third means of sharing is to use distinctive address and synchronization words in the data itself. In this may be included the use of different data rates, sub-carriers, formats, etc. Frequency re-use by polarization discrimination tends to be ruled out by the poor polarization characteristics of the broad beam antennas which are typically used on the spacecraft.

Each of these methods of sharing will be examined in some detail.

2.1 *Spatial separation*

ESA uses two classes of earth station equipment for supporting spacecraft in the 2 GHz band allocated to the space operation service. The basic network, designed primarily for geostationary transfer orbit, is equipped with 10 m dish antennas with an e.i.r.p. of 65 to 75 dBW and a G/T of 22 dB(K^{-1}). Several 15 m antennas with an e.i.r.p. of 68 dBW to 78 dBW and a G/T of 27.5 dB(K^{-1}) are also available. Spacecraft antennas are generally of the quasi-omnidirectional radiator type.

Down links are almost always modulated but up links are unmodulated during a short period (of the order of a few seconds) preceding each signal transmission for on-board transponder acquisition. Thus to afford 20 dB protection to a modulated up link from an unmodulated up link, operating at the same frequency, around 30 dB of power difference is required. If the interfering station is already 10 dB more powerful than the other station one can see that at least 40 dB attenuation in the side lobes of the ground station antenna is required to ensure freedom from interference.

The 10 m antennas reach a side-lobe level of -40 dB at about 16° from boresite, while the 15 m ones reach -40 dB at 9°. Consequently, the feasibility of many spacecraft sharing the same frequency is limited. It must also be kept in mind that during their positioning phase on the geostationary-satellite orbit (GSO), satellites will move along rather large arcs of the orbit and may pass other satellites using the same frequency. Frequency re-use by orbital separation on the GSO can only be used as a means for increasing the capacity of the 2 GHz band, if the angular distance between the satellites operating at the same frequency is sufficient.

Frequency re-use by spatial separation can be practical in many cases with little or no inconvenience caused, between satellites on the GSO and non-geostationary satellites, as well as between several non-geostationary satellites. Certain precautions have to be taken before proceeding to an assignment of identical frequencies to two satellites on different orbits: a "protection cone" around each satellite has to be defined, its "vertex" angle being as a first approximation that of the orbital separation calculated above for two geostationary satellites. (The size of the "protection cone" is very strongly influenced by the side-lobe pattern of the earth station antennas.)

Subsequently the times of "angular coincidence" referred to a particular earth station have to be studied, i.e. those orbital constellations when the "protection cones" of the two spacecraft fully or partially overlap; however, interference periods will generally be very short (a few minutes) for satellites on orbits below 2000 km. For highly eccentric orbits these periods may become quite long depending on the orbital parameters, thus possibly precluding a sharing of the same frequency with a geostationary satellite.

2.2 *Frequency separation*

The viability of a scheme based on minimum frequency separation depends on two factors: a good characterization of the spectra involved and a knowledge of the frequency discrimination of the receiving systems. ESA's approach to the former is to define a standard mask, with a rather rapid fall off in frequency, around each radiated signal and to ensure minimum spectrum occupancy by the use of suitably shaped video waveforms. For the functions of telecommand and ranging it is possible to define values of the occupied bandwidth which will be met by most missions (66 kHz for telecommand and 360 kHz for ranging). For down-link telemetry it is only possible to define a typical occupied bandwidth for those cases where a low bit rate housekeeping telemetry is used. However, also in the case of the down link the ranging signals determine the occupied bandwidth.

Thus in general, one is left with ranging as the most demanding function taking an occupied bandwidth of 360 kHz (-15 dB points contain 99% of the power, which defines the occupied bandwidth in accordance with No. 147 of the Radio Regulations).

From the arguments enumerated above, about 30 dB protection is required which means that the channel bandwidth should be taken as around 400 kHz. For those spacecraft subject to the Doppler effect, the up link operates at the assigned frequency but the down link, in the coherent ranging mode, shows a frequency shift of twice the spacecraft Doppler. Thus an extra 150 kHz should be added to the channel bandwidth to ensure protection. This additional bandwidth is also adequate to take care of on-board oscillator instability when in the non-coherent mode.

Both on board the satellite and on the ground, the receiving systems use relatively wideband IF circuits before recovering the residual carrier in narrow-band phase lock loops. These have typical bandwidths ($2B_L$) in the range 100 Hz to 1 kHz. Pre-detection filters in front of the loops have typically 20 times greater bandwidths.. The bandwidth of the receiving system is sufficiently small that it has no impact on channel spacing requirements.

Thus one can conclude that a channel spacing of about 550 kHz should ensure sufficient protection from interference.

2.3 *Separation by data addresses and types*

Each of ESA's spacecraft has its own signature of bit rates, sub-carriers, format structure, application of coding, etc., and each is equipped with unique address words which form a part of the format. It is thus almost impossible for the receiving systems to accept data coming from an interfering link and interpret it as valid data. On the other hand, for two spacecraft placed close together in orbit and using the same radio frequency, each set of data would appear as 100% interference to the other; with the presently used modulation standards there would be no way of recovering the wanted data with any degree of accuracy. What can be done is to time-share the link. Such a scheme is very suitable for the up link of telecommands. Generally very few telecommands are sent per day and with the hardware available on board the spacecraft for storing and expanding commands, it is possible to group commands together so that an up link need be established only from time to time e.g. when ranging is required. So far one does not have similar possibilities on the down link, since there is still a marked preference for a complete real time record of the spacecraft telemetry.

It is very common, in particular for non-geostationary satellites, to use parts of frequencies with a fixed ratio for up and down links in the 2 GHz band because this is compatible with coherent ranging systems. (In many agencies the frequency ratio used is 221/240.) Since the up-link and down-link frequency bands have approximately the same width, there is little point in time-sharing an up-link frequency if the down link is permanently on.

2.4 *Polarization separation*

In the 2 GHz space operations band ESA makes major use of two different antenna systems on board the spacecraft in order to achieve the wide beam coverages required. The first is a system which switches between two quadrifilar helix elements, each of which covers a hemisphere and is circularly polarized with a polarization gain discrimination of better than 6 dB.

The second is a dual mode cardioid antenna covering a half angle of up to 140°. This antenna is circularly polarized on axis but the predominant polarization broadside-on is linear. These antennas represent the result of considerable work on the optimization of coverage for the preferred sense of circular polarization while avoiding illumination of the spacecraft body (which causes undesirable ripples and nulls in the gain pattern). The scope for improvement of the cross-polar performance is limited. There is virtually no possibility to reach cross-polar levels of around −20 dB as would be required for frequency re-use.

2.5 *Operational intra-service frequency sharing*

Recent studies by Japan have shown the technical feasibility of frequency sharing to permit re-use of the available spectrum in the space operation and mission frequency bands. A specific problem is the simultaneous control of a geostationary satellite already in position and a satellite which is being placed into position, and which use similar tracking, telemetry and telecommand (TTC) systems.

Interference may occur between space operation up links of a geostationary satellite and a satellite being positioned. Interference may also occur on the respective down links, although the down-link telemetry of the geostationary satellite in the space operation band can be turned off, at least for a short period of time, since it is also transmitted in the mission band. Consequently, no harmful interference is foreseen for down links.

However, for up links, severe interference conflicts may arise. In many cases, to reduce weight, the telecommand decoders are shared between receivers working in the mission band and those working in the space operation band, as described in § 7.3 of this Report. In this case, an automatic search switch connects the shared telecommand decoders to the receivers alternately.

The satellite undergoing positioning manoeuvres usually operates in the space operation band and if necessary, the receivers working in the mission band can be cut off by command, but it is usually preferred to keep the receivers working in the space operation band alive in order to keep the command channels always available.

A geostationary satellite is usually controlled by the mission earth station in the mission operation band, but, if the telecommand decoder of the geostationary satellite is locked on to an undesired space operation up link, the decoder cannot receive commands sent in the mission band.

As simultaneous operation of both the geostationary satellite and the satellite being positioned is very important, time sharing cannot be used.

To solve this problem, an "up-link hold" method is proposed in which the mission telecommunication earth station should continuously transmit its telecommand signal in order to keep the telecommand decoder working in the mission band, thus permitting simultaneous and independent control of the satellites. Note that this approach may require cooperation between operating authorities.

3. Future developments

Conscientious frequency assignment will undoubtedly remain the cornerstone of intraservice sharing for many years to come. Spatial separation of spacecraft using common frequencies can be expected to become more usual particularly in the case of for example, a series of global earth monitoring spacecraft spaced around the equator in geostationary-satellite orbit (e.g. GOES, GMS, Meteosat) or a series of low orbit earth resources spacecraft in orbits which do not lead to one earth station viewing two spacecraft simultaneously.

As shown above, intraservice sharing possibilities will be greatly increased if standardized transmission link parameters are used for similar missions, resulting in a certain degree of standardization in system performance. These parameters would typically include, both on spacecraft and in earth stations, G/T and e.i.r.p. It is essential to limit not only the e.i.r.p. but also the occupied bandwidth to values which are realistically required for a particular mission (e.g. for geostationary satellites: earth station e.i.r.p. of the order of 65 dBW).

Spread spectrum techniques, although leading to more complex space and Earth segment equipments, are certain to play a prominent part in future plans for sharing. By spreading the energy of the transmissions uniformly and by incorporating ranging into the spreading code, it will be possible to pack more spacecraft into a given bandwidth since guard bands and allowances for Doppler and oscillator instability will become negligible. Tracking and data relay satellites (TDRS) and global positioning systems (GPS) are typical forerunners of this trend. However, it must be remembered that such schemes will work optimally only when there is a large degree of uniformity between all the different spacecraft and earth station systems operating within the spread spectrum band.

REPORT 396-5*

MAINTENANCE TELEMETERING, TRACKING AND TELECOMMAND FOR DEVELOPMENTAL AND OPERATIONAL SATELLITES

Possibilities of frequency sharing between earth-satellite telemetering or telecommand links and terrestrial services

(Question 18/2)

(1966-1970-1974-1978-1982-1986)

1. Introduction

1.1 The functions of maintenance telemetering, tracking and telecommand are frequently carried out in bands which are allocated for the main operations of the service concerned. On the other hand, the World Administrative Radio Conference, Geneva, 1979, allocated several specific bands for various maintenance functions, some with the general designation "Space operation" and some specified for a particular service and/or a particular function. In many instances, whether or not the bands are specially designated, the maintenance functions are performed at frequencies which are shared with other services, notably terrestrial fixed and mobile services, and this Report considers in general terms the interference problems which might arise. Since the potential interference is largely independent of frequency, calculations have been made for representative frequencies, 400 MHz and 4 GHz (Annex II), with some additional calculations pertaining to sharing with land mobile services (Annex III) and comments on problems at VHF (Annex IV). The equipment reliability aspects of a unified system of maintenance telemetering and telecommunications are discussed in Annex V. Annex VI deals with questions arising in the neighbourhood of 2 GHz.

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* This Report should be brought to the attention of Study Groups 1, 4, 5, 7, 8, 9, 10 and 11.

1.2 Estimates have been made of the interference problems that can arise with co-channel working of various systems: co-channel working here implies the operation of two systems at frequencies which are near enough for the spectrum of the transmission of one system to overlap the whole or part of the receiving bandwidth of the other system. Such overlapping of frequencies must be contemplated, since there seems little likelihood of interleaving satellite services, channel by channel, with existing services. Since the magnitude of interference is usually a function of the particular relationship between the frequencies of the two systems involved, an endeavour is made in each assessment to consider the worst case. A comprehensive treatment of the interference would require detailed statistical analyses of the percentages of time that the interference occurs. The present discussion is, however, concerned primarily with relative levels of interference in the various cases, to determine whether there is an *a priori* basis for sharing.

1.3 The possibilities of interference with respect to the following services and systems have been examined:

- earth-satellite telemetering;
- earth-satellite telecommand;
- communication-satellite service;
- line-of-sight radio-relay systems;
- frequency-modulation broadcasting;
- television broadcasting;
- land mobile services;
- aeronautical mobile service;
- tropospheric-scatter systems;
- ground-radar systems.

2. The assessments involved

2.1 There are four typical modes of interference involved:

2.1.1 Interference between satellite-borne transmitters and satellite-borne receivers.

2.1.2 Interference between satellite-borne transmitters and ground receivers.

2.1.3 Interference between ground transmitters and satellite-borne receivers.

2.1.4 Interference between ground transmitters and ground receivers.

Note. – In this Report, the term "ground station" refers to either terrestrial or earth stations.

2.2 Interference of the first type can be considered without the need for calculation. In any case, it would not seem wise to permit frequencies to be transmitted by satellites which are the same as those which have to be received, for other services, by other satellites. Unless specific cases only are concerned, the possibility must always be considered of the transmitting and receiving satellites reaching quite close spacings as their relative motions continue. Thus, such sharing should not be proposed in any general allocation of bands. However, under certain conditions it may be possible for frequency sharing of the first type to be successfully realized.

2.3 Interference between satellite-borne transmitters and ground receivers or vice-versa, can be quantitatively assessed. Assumptions must, however, be made as regards frequency, transmitter power, receiver sensitivity and susceptibility to interference, antenna gains inside and outside their beams (if beamed) and also as regards the altitudes of the satellites involved.

3. Calculation of interference between satellite-borne transmitters and ground stations

3.1 Consider interference from a satellite transmitter to a ground receiver. If the interfering transmitter power within the input bandwidth of the receiver is P_T (dBW), the transmitter antenna gain G_T (dB), the free-space basic transmission loss L (dB) and the receiver antenna gain G_R (dB), then the level of the interference entering the receiver is:

$$P_T + G_T - L + G_R \qquad \text{dBW}$$

The maximum permissible level of interference (P_I) within the receiver input bandwidth can be expressed as follows:

$$P_I = X - Y$$

where:

X: minimum permissible median level (dBW) of the wanted signal at the input to the receiver which may experience interference,

and Y: required protection ratio (dB), i.e. the minimum permissible ratio of wanted-to-interfering signal powers at the receiver input and within the receiver input bandwidth.

The values of Y are derived so as to give a prescribed minimum acceptable signal-to-interference ratio at the system output.

An "interference safety margin" M can now be defined by the equation:

$$M = P_I - (P_T + G_T - L + G_R) \qquad \text{dB} \tag{1}$$

L is calculated for the range over which interference takes place with the assumed satellite orbit; if the value of L is assumed to be varied until $M = 0$, then a minimum safe slant-range can be determined. For satellites at less range than this there will be significant interference.

The above equation for interference safety margin is evidently applicable to interference from ground to satellite or vice-versa.

4. Calculation of interference between ground stations

4.1 Equation (1) is valid for interference between the earth stations for satellite systems and those for terrestrial services, if L is now taken as the tropospheric basic transmission loss. In this case, however, it is more useful to determine the safe spacing of the ground stations, for which $M = 0$. From equation (1) it follows that, if L_0 is the basic transmission loss for which $M = 0$:

$$L_0 = P_T + G_T + G_R - P_I \qquad \text{dB} \tag{2}$$

From calculated values of L_0, safe spacings can be determined by the use of the tropospheric propagation data given in Report 239. The present calculations are based on 1% propagation data, but in evolving specific sharing criteria, more detailed considerations would need to be given to the percentage time to be adopted and other factors would need to be taken into account.

4.2 In the conclusions reached in regard to such spacings, it has been taken that, where the safe spacing is of the order of 500 km or more, frequency sharing is not likely to be generally practicable. Where more practicable spacings are effective, these may be still further reduced if natural screening by hills, etc., can be exploited: such reduction will, however, make aircraft-reflected interference relatively more important; for the cases where frequency sharing seems possible, the effect of aircraft-reflected interference has been estimated.

5. General parameters of the telemetering and telecommand systems involved

5.1 Since either telemetering or telecommand is common to all the assessments, much care has been taken to decide upon the most realistic single values possible for the various parameters of these systems; it is inevitable, however, that some practical systems may depart appreciably from the figures given. It is assumed that telemetering and telecommand are pulse-coded systems and that factors X and Y therefore, relate to simple systems of this sort.

5.2 Two classes of telemetering system have been considered, according to the bit rate of the system and the complication of the receiver. The first class of system is representative of relatively low-altitude satellites for developmental purposes; the bit rate may be a few kbit/s with a radiated power of the order of a watt and omnidirectional satellite antennas. It is found in these circumstances that relatively simple receiving equipment will give adequate sensitivity. It is assumed that for a typical system of this sort, the intermediate-frequency bandwidth can be as wide as 100 kHz; this is a compromise value between possible lower values at the lower end of the range of frequencies considered and higher values at the higher end.

The second class of telemetering is representative of operational communication satellites in higher altitude orbits. Although such satellites would have earth-stabilized communication antennas, it is assumed that omnidirectional telemetering and telecommand antennas are a requirement arising from the need to assure these services, even if the satellite should be unstabilized. Only very low bit rates are required in this case and an output bandwidth of about 10 Hz would be adequate. By properly taking advantage of this narrow data bandwidth in the receiving system, the extra attenuation due to the greater range of this second class of satellite can be overcome whilst still retaining modest transmitted power. To do this requires the use of coherent detection systems for bi-phase, phase-modulation or feedback systems for frequency modulation. The intermediate-frequency bandwidth can be quite narrow, of the order of a few kilohertz, but its exact value does not affect the theoretical assessment of thermal noise, since in these systems, the effective input noise bandwidth has a low limit value of about twice the output bandwidth. The value of intermediate-frequency bandwidth does, however, affect the value of the protection ratio Y for noise-like interference: it has, therefore, been necessary to select an intermediate-frequency bandwidth; 10 kHz has been taken as a reasonable and practicable value.

The two telemetering systems outlined above are referred to as "wideband" and "narrow-band" systems respectively, in the assessments which follow.

5.3 For radio-frequency equipment, it is assumed that the earth-station receivers use good parametric amplifiers (not masers), and that ground antennas have apertures such as are provided by paraboloids of up to 4.5 m in diameter; this aperture can provide the gains specified using circularly polarized feed. Similar sizes of ground antennas are assumed for telecommand.

5.4 For telecommand also, "wideband" and "narrow-band" receivers have been considered. However, for this service, the receiver must always be simple and the difference between the two classes depends only on the data-rate assumed and the Doppler effect, according to the orbit. For wideband receivers, the input bandwidth is taken as 100 kHz. This can accommodate considerable Doppler shift as well as a large bit-rate. The narrow-band design is only materially different for a low bit-rate receiver operating at high altitude but at low frequency. For the one case considered, the input bandwidth is taken as 5 kHz.

5.5 The minimum value of wanted-signal X for telemetering, has been taken as 3 dB higher than the threshold value for satisfactory operation determined solely by system noise considerations. For telecommand, X is taken as well above the noise level of a simple receiver; it is assumed that such receivers would employ, in effect, some artificial threshold to combat the effects of noise and interference.

5.6 Protection ratios have been estimated for the typical telemetering and telecommand receivers, in respect of typical types of interference. The resulting values discussed in Annex I differ from those which can be derived from Recommendation 364 and Report 548 applying to links for space research.

5.7 The typical characteristics chosen must not only represent important classes of system, but must also be numerically self-consistent in terms of quantities such as receiver sensitivity and actual received power under representative conditions. By such consistency, it is assured that the interference potentials in both directions are properly related, with the implication that by "trading" transmitter power for receiver sensitivity, within limits, the balance of interference in the two directions can be adjusted for the best compromise. The assumed characteristics of the various systems are given in Table IV of Annex II.

6. Conclusions

6.1 Eleven cases of frequency sharing for telemetering and eleven for telecommand have been considered. These cases, numbered, are listed in Table I, for telemetering, and in Table II, for telecommand; with a brief note in respect of each on the conclusions to be drawn. It has been mentioned in § 2.2 that frequency sharing which involves the use of the same frequency for transmitting in some satellites and receiving in others should not be proposed in any general allocation of bands. However, such sharing situations may be feasible under certain conditions. This applies to telemetering cases 2 and 3 and telecommand cases 2 and 4. Calculations and comments for one important case are given in Annex III.

TABLE I – *Possibilities of sharing between telemetering and other systems*

Telemetering case No.	Other systems considered	Possibility of frequency sharing
1	Other similar satellite telemetering	Limited sharing is possible.
2	Satellite telecommand (systems as described in this Report)	Unlikely to be practicable. Satellites of the two systems may approach.
3	Communication satellite (Earth-to space link)	Unlikely to be practicable. Satellites of the two systems may approach.
4	Communication satellite (space-to-Earth link)	Limited sharing is possible.
5	Line-of-sight radio-relay systems	Limited sharing is possible with acceptable separation distances. There is interference with line-of-sight service in some circumstances.
6	Frequency-modulation broadcasting	Unlikely to be practicable. Severe interference with telemetering reception.
7	Television broadcasting	Unlikely to be practicable. Severe interference with telemetering reception.
8	Land mobile services	Limited sharing is possible.
9	Aeronautical mobile service	Unlikely to be practicable. Severe interference with telemetering reception can be produced by aircraft emission.
10	Tropospheric-scatter systems	Unlikely to be practicable. Severe interference to the scatter service.
11	Ground radar systems	Unlikely to be practicable. Severe interference to telemetering reception.

TABLE II – *Possibilities of sharing between telecommand and other systems*

Telecommand case No.	Other systems considered	Possibility of frequency sharing
1	Other similar satellite telecommand	Limited sharing is possible.
2	Satellite telemetering (systems as described in this Report)	Unlikely to be practicable. Satellites of the two systems may approach.
3	Communication satellite (Earth-to-space link)	Appropriate frequency separation will be needed to avoid interference to reception in the communication satellite.
4	Communication satellite (space-to-Earth link)	Unlikely to be practicable. Satellites of the two systems may approach.
5	Line-of-sight radio-relay systems	Limited sharing is possible with reasonable separation distances between stations. There is interference to telecommand in some circumstances.
6	Frequency-modulation broadcasting	Unlikely to be practicable. Severe interference to telecommand.
7	Television broadcasting	Unlikely to be practicable. Severe interference to telecommand.
8	Land-mobile services	Limited sharing is possible but interference to telecommand can occur in some circumstances.
9	Aeronautical mobile service	Unlikely to be practicable. Ground station of the aeronautical service can interfere with telecommand. Telecommand can produce severe interference in aircraft receivers.
10	Tropospheric-scatter systems	Unlikely to be practicable. Severe interference to telecommand.
11	Ground radar systems	Unlikely to be practicable. Severe interference to telecommand.

Problems at VHF are discussed in Annex IV. Questions arising in the neighbourhood of 2 GHz are examined in Annex VI.

Maintenance telemetering, tracking and telecommand in frequency bands in which space-to-space communications are permitted are discussed in Report 548. As can be seen from Tables I and II, frequency sharing between maintenance telemetering and telecommand, on the one hand, and the majority of terrestrial services, on the other, is difficult, and can be accomplished on only a limited basis. Also, considering the inefficiency of using separate transmitters for the sole purpose of telemetering and telecommand when other receiving and transmitting systems working in operational bands are used for satellite communications or data transmission purposes, it would appear practical, whenever possible, to carry out maintenance functions in the operational bands allocated to the service concerned. Nevertheless, there will continue to be requirements for space operations in specially designated bands, especially at frequencies of the order of 2 GHz and below, where relatively inexpensive techniques can be adopted.

A discussion on the reliability provided by a unified system as typified by that used in the Apollo Manned Space Programme is presented in Annex V.

ANNEX I

FACTORS *X* AND *Y* FOR TELEMETERING AND TELECOMMAND RECEIVERS

1. The most likely systems to be encountered for telemetering and telecommand are simple pulse-code modulation (PCM) systems; frequency modulation (FM) or bi-phase phase-modulation (PM) is assumed, the modulation waveform being rounded pulses.

The types of interference considered are:

- noise-like interference, such as may arise when a part of a wideband transmission falls in the comparatively narrow band of the telemetering or telecommand receiver, or when many unrelated narrow-band transmissions combine to give interference of fairly uniform power spectrum;
- CW-type interference, e.g. carriers and sub-carriers of other transmissions;
- interference from narrow-band AM and FM transmissions.

2. Minimum permissible signal at receiver input, *X*

2.1 In all PCM systems, the decision circuit produces a threshold, above which increasing noise inputs rapidly give intolerable noise or error rate. This threshold corresponds to a signal-to-noise ratio in the input to the decision circuit of about 12 dB. (In an FM system there will be a similar threshold at the input to the discriminator.) For telemetering, the minimum permissible level of wanted signal at the receiver input X (dBW) is here taken as 15 dB above the thermal noise, to allow for the presence of interference in addition to thermal noise.

2.2 For telecommand, the factor X usually includes a greater margin over noise and interference than for telemetering. This follows from the greater importance usually attached to reliability of telecommand as compared to telemetering and also the greater possibility of providing increased transmitter powers in the case of telecommand. Thus, the philosophy in telecommand is to use receivers which are intentionally less sensitive than signal-to-noise design would dictate; in effect, an artificial threshold is produced somewhere in the receiving chain, which eliminates the effects of wanted signals or interference below a prescribed level. The level at which such a threshold is set is arbitrary, but a typical procedure would be to add an allowance of 6 to 12 dB to the minimum signal, which would be considered appropriate to telemetering. Thus, the value of X for telecommand would be about 15 + 6 to 15 + 12 dB above thermal noise. In this Report, the mean of these values is taken so that the minimum permissible signal level X for telecommand is 24 dB above the thermal noise level.

3. Protection ratio, Y

3.1 A PCM system will fail in the presence of noise-like interference when the ratio of signal-to-thermal noise plus noise-like interference reaches the threshold value of 12 dB. As thermal noise has been set at 15 dB below signal (see § 2.1 of this Annex) it follows from this limiting condition, that the ratio of permissible signal-to-noise-like interference is also 15 dB. Coherent systems for bi-phase PM or frequency-modulation feedback (FMFB) systems cause this threshold to be effective, in the limit, only over a radio-frequency bandwidth equal to twice the post-detector bandwidth. Thus, in the narrow-band telemetering system employing the above techniques, as the output bandwidth is 10 Hz, the 15 dB criterion has only to apply to any 20 Hz of the input bandwidth, assuming that the major part of the wanted signal power is in its carrier. If the input bandwidth is, say, 10 kHz, then the noise in it will be 27 dB greater than that which provides threshold. The value of Y for noise-like interference is therefore given by $15 - 27 = -12$ dB.

3.2 CW, narrow-band FM or narrow-band AM interference, with the receivers considered here, can be estimated by considering the interference as a vector which combines with the wanted-signal vector to phase- or frequency-modulate it. Any wanted modulation of the signal vector is completely distorted when the interference vector is about the same magnitude; any further increase of interference then "captures" the receiver. For the telemetering cases for which the simultaneous effects of noise and CW-type interference on the decision circuit have been estimated, the value of the protection ratio Y has been found to be about 14 dB. For the narrow-band receiver, this form of interference is confined to that in a very narrow frequency band near the wanted carrier; CW-type interference outside these limits, but within the intermediate-frequency band, can only interfere by capture effects, for which the factor Y can be assumed to lie between 0 dB and the above value of 14 dB. For narrow-band AM interference, allowance must be made for the fact that the critical level may be reached on the peaks of the modulated wave. Values of Y for AM interference are therefore taken as 6 dB greater than those for CW or narrow-band FM interference. The various values of the protection ratio Y are collected in Table III.

TABLE III

Type of interference	Protection ratio Y (dB)		
	Telemetering		Telecommand
	Wideband	Narrow-band	Wideband or narrow-band
Noise-like	15	−12	15
CW-type or narrow-band frequency-modulation	14	14	14
Narrow-band amplitude-modulation	20	20	20

3.3 The protection ratios for telemetering tabulated above are different from the values which can be derived from Recommendation 364 and Report 548. For noise-like interference in a wideband receiver, it will be noted that the permissible interference level quoted, −15 dB relative to the signal level, is equal to the noise value in the whole input band, not −6 dB relative to the thermal-noise level as advocated in Recommendation 364. The difference arises because the designs given here specifically allow increased transmitter power to enable the assumed signal-to-interference and thermal-noise ratio to be achieved (see § 2.1 of this Annex).

For CW-type interference, the protection ratio is 14 dB for the typical PCM system that has been evaluated, so that the permitted CW interference is +1 dB relative to the input noise which is effective in producing output noise (this effective noise is that of the full input bandwidth for the wideband receiver, but only that of 20 Hz of the input bandwidth for this particular narrow-band design described).

4. Shielding effects due to the ionosphere

Long-term observations of the field produced on the Earth by a CW transmission from a geostationary satellite in the 136 MHz band have shown that short breakdowns of field strength may happen occasionally. Even apart from the cases of auroral blackout known to occur near the auroral zones, such breakdowns have been found to occur at mid-latitudes more than 10 times per month; each of these lasting between 20 s and 1 min [CCIR, 1966-69]. The values of X and Y given in Annex I do not take account of such very rare particular conditions.

REFERENCES

CCIR Documents

[1966-69]: IV/75 (Federal Republic of Germany).

ANNEX II

TELEMETERING AND TELECOMMAND SYSTEMS, DESIGN VALUES ASSUMED

Table IV gives summarized calculations for the various telemetering and telecommand systems considered. The aim is to show, for each case, a set of compatible characteristics with, however, a general safety factor included. It is considered that a target value for this factor of safety should be 3 dB for telemetering and 10 dB for telecommand. The higher value for telecommand is because of the greater importance attached to the achievement of maximum reliability in this service. Calculations have been made, as appropriate, at one or both of two typical frequencies, which have been taken as 400 MHz and 4 GHz.

ANNEX III

TYPICAL INTERFERENCE CALCULATIONS AND DISCUSSION

All the cases referred to in Table I have been calculated. In the interests of brevity, only the tabulated calculations and the discussion for the case of interference with respect to the land-mobile service (case 8), are given in Tables V and VI of this Annex.

The following abbreviations have been used:

TM : Telemetering
TC : Telecommand
NB : Narrow-band
WB : Wideband
L of S : Line-of-sight
A/C : Aircraft.

TABLE IV – *Characteristics of telemetering and telecommand systems*

Service	Altitude (km)	Maximum slant-range (km)	Frequency (GHz)	Receiving system: System WB or NB (1)	Receiving system: Bandwidth (Hz) Pre-detector	Receiving system: Bandwidth (Hz) Post-detector	Receiving system: Factor X (dBW)	Receiving system: Antenna gain G_R (dB)	Transmitting system: Radiated power P_T (dBW)	Transmitting system: Antenna gain G_T (dB)	Attenuation L (dB): Zenith	Attenuation L (dB): Max. slant-range	Received power $P_R = P_T + G_T + G_R - L$ (dBW)	System safety factor (dB) (2)
Tele-metering	500	2600	0·4	WB	10^5	Up to the order of 10^5	−137 (3)	20 (4)	0 (5)	0	139	153	−133	+4
	10 000	15 000	0·4	NB	10^4	10	−174	20	−10	0	164	168	−158	+16 (6)
			4	NB	10^4	10	−177	40 (4)	−10	0	184	188	−158	+19 (6)
Tele-command	500	2600	0·4	WB	10^5	Up to the order of 10^5	−122	0 (5)	20	20 (4)	139	153	−113	+9
	10 000	15 000	0·4	NB	5×10^3	Up to the order of 5×10^3	−135	0	23	20	164	168	−125	+10
			4	WB	10^5	Up to the order of 10^5	−120	0	37	40 (4)	184	188	−111	+9

(1) The systems are classed as wideband (WB) or narrow-band (NB) as explained in §§ 5.2 and 5.4 of this Report.

(2) Safety factors are estimated for maximum slant-range.

(3) In estimating factor X for telemetering a total input temperature of 460 K is assumed at 400 MHz, of which 280 K is due to galactic noise; at 4 GHz, the total temperature has been taken as 220 K of which 40 K is galactic. Factor X is then taken as 15 dB above the noise value produced, at the appropriate temperature, in the radio-frequency band which is effective for noise calculations (only 20 Hz for the narrow-band case). For telecommand, a noise factor of 8 dB has been assumed at 400 MHz and 10 dB at 4 GHz. As discussed in § 2 of Annex I, the minimum permissible signal levels have been taken as 24 dB above these noise values.

(4) Antenna gains of 20 dB at 400 MHz and 40 dB at 4 GHz have been assumed. These correspond to a paraboloid of 4.5 m diameter with circularly polarized feed. The beamwidth is 12° at 400 MHz and 1.2° at 4 GHz.

(5) It is assumed that the satellite antennas are omnidirectional.

(6) These safety factors are unnecessarily great although P_T has been reduced to a practical low limit. However, for a synchronous satellite, the attenuation for maximum slant-range is 9 dB greater so that factor X is more nearly of the order required. Therefore, the low values of factor X are retained. However, for satellites at 10 000 km altitude it would seem reasonable to permit interference inputs say 10 dB greater than would follow from these values of factor X: this point is given attention in particular cases in the Tables which follow.

TABLE V * – *Telemetering – Case 8*

Interference between telemetering and land mobile service

Case No.	Type of interference		Altitude	Frequency (GHz)	Y (dB)	X (dB)	Permitted level of interference P_I (dB)	P_T (dB)	G_T (dB)	G_R (dB)	L (dB)	Interference level produced $P_T+G_T+G_R-L$ (dB)	Interference margin of safety M (dB)
TM 8 *(a)*	*AM land mobile service*												
	TM transmitter to receiver of mobile service	Satellite at zenith	Low	0·4	14	−116	−130	0	0	−3	139	−142	+12
		Satellite at horizon			14	−116	−130	0	0	+2	153	−151	+21
		Satellite at zenith	High	0·4	14	−116	−130	−10	0	−3	164	−177	+47
		Satellite at horizon			14	−116	−130	−10	0	+2	168	−176	+46
	FM land mobile service												
	TM transmitter to receiver of mobile service	Satellite at zenith	Low	0·4	10	−130	−140	0	0	−3	139	−142	+2
		Satellite at horizon			10	−130	−140	0	0	+2	153	−151	+11

* *Notes* to this Table appear at the end of Table VI.

TABLE V *(continued)* – *Telemetering – Case 8 (continued)*
Interference between telemetering and land-mobile service

Case No.	Type of interference		Frequency (GHz)	Y (dB)	X (dB)	P_T (dB)	G_T (dB)	G_R (dB)	Required L_0 (dB)	Safe spacing (km) Overland	Safe spacing (km) Oversea
TM 8 *(b)*	*AM land-mobile service*										
	Mobile ground transmitter to TM receiver (WB)	In TM beam	0·4	20	−137	20 (1)	+2	20	199	420	500
		Out of TM beam		20	−137	20 (1)	+2	0	179	250	500
	Mobile ground transmitter to TM receiver (NB)	In TM beam	0·4	20	−174	20 (1)	+2	20	236	> 500	> 500
		Out of TM beam		20	−174	20 (1)	+2	0	216	> 500	> 500
	FM land-mobile service										
	Mobile ground transmitter to TM receiver (WB)	In TM beam	0·4	14	−137	+20	+2	20	193	360	> 500
		Out of TM beam		14	−137	+20	+2	0	173	200	> 500
	Mobile ground transmitter to TM receiver (NB)	In TM beam	0·4	14	−174	+20	+2	20	230	> 500	> 500
		Out of TM beam		14	−174	+20	+2	20	210	> 500	> 500

(1) 20 dBW is taken as the possible maximum value for the base station of a mobile service.

TABLE VI* – *Telecommand – Case 8*

Interference between telecommand and land-mobile service

Case No.	Type of interference		Frequency (GHz)	Y (dB)	X (dB)	P_T (dB)	G_T (dB)	G_R (dB)	Required L_0 (dB)	Safe spacing (km)	
										Overland	Oversea
TC 8 *(a)*	*AM land mobile service*										
	TC transmitter to receiver of mobile service	In TC beam	0·4	14	−116	23	20	2	175	230	> 500
		Out of TC beam		14	−116	23	0	2	155	100	> 500
	FM land mobile service										
	TC transmitter to receiver of mobile service	In TC beam	0·4	10	−130	23	20	2	185	280	> 500
		Out of TC beam		10	−130	23	0	2	165	120	> 500

* *Notes* to this Table appear at the end of this Table.

TABLE VI *(continued)* – *Telecommand – Case 8 (continued)*

Case No.	Type of interference		Altitude	Frequency (GHz)	Y (dB)	X (dB)	Permitted level of interference P_I (dB)	P_T (dB)	G_T (dB)	G_R (dB)	L (dB)	Interference level produced $P_T+G_T+G_R-L$ (dB)	Interference margin of safety M (dB)
TC 8 *(b)*	*AM land-mobile service*												
	Mobile or base transmitter to TC receiver (WB) in satellite	Satellite at zenith	Low	0·4	20	−122	−142	20 (1)	−3	0	139	−122	−20
		Satellite at horizon			20	−122	−142	20 (1)	+2	0	153	−131	−11
	Mobile or base transmitter to TC receiver (NB) in satellite	Satellite at zenith	High	0·4	20	−135	−155	20 (1)	−3	0	164	−147	−8
		Satellite at horizon			20	−135	−155	20 (1)	+2	0	168	−146	−9
	FM land-mobile service												
	Mobile or base transmitter to TC receiver (WB) in satellite	Satellite at zenith	Low	0·4	14	−122	−136	20	−3	0	139	−122	−14
		Satellite at horizon			14	−122	−136	20	2	0	153	−131	−5
	Mobile or base transmitter to TC receiver (NB) in satellite	Satellite at zenith	High	0·4	14	−135	−149	20	−3	0	164	−147	−2
		Satellite at horizon			14	−135	−149	20	2	0	168	−146	−3

(1) 20 dBW is taken as the possible maximum value for the base station of a mobile service.

Notes to Table V

Note 1. – The values shown in the Table are those for mobile or base stations of the land-mobile service.

Note 2. – The interference from the telemetering transmitter of a low- or high-altitude satellite when above the horizon would be acceptable in AM and FM mobile services. The interference produced in single-channel FM fixed services would also be acceptable.

Note 3. – Interference with a wideband telemetering receiver, out of its beam, would be acceptable if the receiver were spaced (overland) at 200 km from an FM mobile or base transmitter, or 250 km from an AM transmitter. For a narrow-band telemetering receiver, these spacings would become greater than 500 km. FM fixed service transmitters would give the same order of interference as the mobile services.

Note 4. – Interference with a wideband telemetering receiver, in the beam, would be acceptable if the spacings were 360 km (FM) and 420 km (AM). The corresponding spacing for an FM fixed service transmitter is of the same order. With a narrow-band telemetering receiver, the spacings to permit tolerable in-beam interference, would be impracticably great.

Note 5. – For interference to narrow-band telemetering receivers, except where the satellite is synchronous, some 10 dB increase of interference input could be permitted with consequent decrease of safe spacings.

Note 6. – In any specific case of interference from mobile or fixed services, the possibility of simultaneous interference from a number of transmitters must be estimated.

Note 7. – Aircraft would not reflect significant interference in any of the cases.

Notes to Table VI

Note 1. – The values shown in the Table are those for mobile or base stations of the land-mobile service.

Note 2. – Interference from the telecommand transmitter, out of its beam, would be tolerable if the mobile or base station receiver were spaced from the telecommand transmitter by an overland distance of 120 km for FM mobile services and by 100 km for AM services. The corresponding spacing for FM fixed service receivers is of the same order. The interference from telecommand is, in any case, likely to be of short duration.

Note 3. – Interference from the telecommand transmitter, in its beam, would be tolerable if the spacings were 280 km and 230 km for FM and AM services respectively. The corresponding spacings for FM fixed service receivers are of the same order.

Note 4. – As regards interference to the telecommand receiver in the satellite, the practicability of frequency sharing will also depend on the number of mobile or base stations within the coverage area of the satellite, which may contribute to the total interference power received. The value shown above for a single transmitter will thus in practice be exceeded. Comparisons between Tables III and VI show that there would be possibilities of sharing if telecommand transmitter powers were increased and telecommand transmitters made correspondingly less sensitive. The possibilities of sharing are greater for high altitude satellites.

ANNEX IV

SOME CONSIDERATIONS FOR FREQUENCY SHARING AT VHF

1. Frequency sharing in the 136 to 138 MHz band

Because the potential interference problems are largely independent of frequency over a fairly broad frequency range, sample calculations are presented for only two frequencies, 400 MHz and 4 GHz, in Annexes II and III. Sharing problems in the 136 to 137 and 137 to 138 MHz bands are basically as discussed in those Annexes, but the following differences may be significant with regard to interference to a terrestrial service by a satellite transmitter.

– The receivers of the terrestrial systems in the 136 MHz range will be more sensitive than those in the 400 MHz range.
– It is common practice to use the 136 to 138 MHz band for transmitting signals for range and range rate measurements.

Based upon characteristics of frequency-modulation receivers operating in this frequency range, the sensitivity of a typical receiver is approximately −145 dBW. This value of sensitivity does not consider the ambient noise level in which the receiver is operating. A measure of the degradation to system sensitivity by external noise at 160 MHz has been provided [Deitz *et al.*, 1966]. Based upon this data, a minimum usable receiver input of −140 dBW is indicated in the presence of the average ambient noise level at 160 MHz. Assuming that the noise levels at 136 MHz are basically the same as at 160 MHz, this would suggest that the factor X (which is defined as the minimum permissible median level of the wanted signal at the input to the receiver: see § 2, Annex I) should be −140 dBW for systems in the 136 to 138 MHz band as opposed to the −130 dBW used for the 400 MHz example (see Table V, Annex III). This would reduce the interference margin of safety by 10 dB at 136 MHz as compared to 400 MHz and basically indicates that sharing is somewhat more difficult at the lower frequencies.

The range and range rate system commonly used in the 136 to 138 MHz band is described elsewhere [Coates, 1969]. The system uses a tone ranging technique with transmission to the satellite at a nominal frequency of 148 MHz and retransmission from the satellite in the 136 to 138 MHz band. With regard to the interference potential of the signal, it generally has less transmitted power than has a common telemetry signal. However, the power spectrum is such that a significant amount of power is concentrated in the carrier and in discrete sidebands [Coates, 1969]. Therefore, it can be a more serious source of interference than normal telemetry.

The problem of interference from terrestrial transmitters to the telemetry receivers at 136 to 138 MHz is covered in other parts of this Report, where consideration is given to the propagation characteristics at the lower frequencies. Again, sharing will be more difficult at 136 to 138 MHz since coordination distance will be somewhat larger than at 400 MHz because of the lower propagation losses.

2. Interference between space telecommand links and terrestrial services in the 148 to 149.9 MHz band

The sharing problems between telecommand links and terrestrial services have been discussed earlier in this Report and particularly in Annex II. The basic approach to sharing as established in the Report is applicable to the band 148 to 149.9 MHz. Since this band is at times used for the up link for range and range rate measurements, consideration should be given to the unique spectral characteristics of the ranging signal and the necessary protection requirements of this type of signal as opposed to normal command up links in determining coordination distances and up-link interference margins.

Within the last few years, data have been obtained on interference from terrestrial transmitters to satellite command receivers in this band. In NASA [1969] several cases of interference to satellite command receivers are described and techniques for solving the problems are discussed.

A possible modulation scheme for minimizing the interference effects in this band is a digital spread-spectrum pseudo-noise approach [Heffernan and Gilchriest, 1969]. In addition to anti-radio-frequency interference properties or narrow-band interference rejection capabilities of pseudo-noise receivers, the transmitted spread-spectrum signal would be less objectionable than standard command signals in terms of interference to terrestrial receivers. Implementation of a pseudo-noise system would require a contiguous band of frequencies of approximately 2 MHz, such as 148 to 149.9 MHz. However, due to extensive use of this band by other services, utilization of tracking and telecommand facilities employing pseudo-noise techniques may be difficult.

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ANNEX V

THE RELIABILITY OF A UNIFIED SYSTEM FOR MAINTENANCE TELEMETRY AND TELECOMMUNICATIONS

1. Introduction

A unified system unites all the space system functions into one system which uses a single antenna, transmitter, power amplifier, frequency and receiver. An example of this is the "Unified S-Band system" initiated with the Apollo Manned Space Programme [Varson, 1965]. The earlier Gemini Space Programme employed a system in which space operations and communications were handled separately with frequencies for command and telemetry in the UHF region. Due to the limited potential of telemetry and telecommand to share terrestrial services, as shown in this Report, integration of space operations with communications links is the important, if not the only, viable alternative. The purpose of this Annex is to demonstrate that the reliability of space system radio communications is improved by utilization of the unified systems approach.

2. The basis of system reliability

It is assumed here, that space operations and communications are in the same band; that the system reliability depends solely on that of the equipment, and that any failures have random causes. The unified system modulation hardware is no more complex than the individual systems were, if viewed collectively. The data processed is the same, and therefore, the modulation requirements are no greater. Accordingly, there is no corresponding detrimental effect on equipment reliability as demonstrated by the successful utilization of the unified methods in several systems including the Apollo Project.

A final area of consideration is regarding system redundancy capability. Figure 1 shows an example of each of the two systems. In the multi-system network (System I), telemetry and communications use separate antennas, transmitters, power amplifiers and receivers with the whole electronic system represented by a box in the Figure. In the unified system, (System II) telemetry and communications, whether multiplexed or not, use one antenna, transmitter, receiver, power amplifier, etc. Backup electronic systems are indicated with primes.

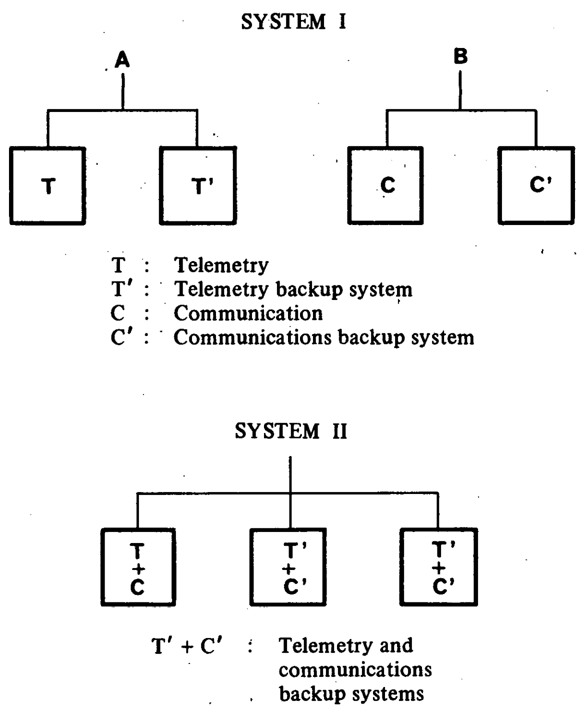

FIGURE 1 – *Examples of the multi-system (I) and the unified system (II)*

3. The probability of the working of the two systems

The probability of System I being in workable order is as follows:

$$P_{\mathrm{I}} = (1 - p^2) \times (1 - p^2) = 1 - 2p^2 + p^4 \tag{3}$$

where p is the probability of failure of any electronic system and $(1 - p^2)$ is the probability of subsystem A or B being in workable order. This is assuming that subsystems A and B are mutually independent. Failure of A or B, however, results in a total considered failure of System I.

If the probability of failure is assumed to be the same for all equipment in the two systems, then the probability of System II being in workable order is as follows:

$$P_{\mathrm{II}} = 1 - p^3 \tag{4}$$

Within its design lifetime, probability of failure p for an antenna system is expected to be small, most likely less than 5%. For values of p less than 5% Table VII shows the reliability of the two systems.

TABLE VII – *The reliability of the two systems*

Probability of any individual electronic system failure, p	System I reliability, P_{I}	System II reliability P_{II}
1%	99.98%	99.99%
3%	99.82%	99.99%
5%	99.50%	99.98%

The reliability of the transmission or reception is assured by redundancy of the equipment. According to this standard and as demonstrated above, the unified system provides greater reliability with less equipment. The discrepancy in the reliability between the two systems increases with increasing probability *(p)* of the failure of the components of the system. The unified system provides the same overall reliability, with a 5% probability of individual electronic system failure, that the multi-system provides, with only a 1% probability of individual electronic system failure.

4. Summary and conclusions

The Apollo Programme among others has operated successfully and reliably utilizing the unified S-band system. In this case, the unified system is theoretically more reliable and has proved so in practice, in addition to relieving the weight problem on the spacecraft by the reduction of equipment. It is efficient to use proven techniques and equipment in order to minimize development and to afford the highest probability of success.

REFERENCES

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ANNEX VI

POSSIBILITIES OF FREQUENCY SHARING BETWEEN THE SPACE OPERATION SERVICE AND THE FIXED SERVICE (LINE-OF-SIGHT RADIO-RELAY SYSTEMS) IN THE NEIGHBOURHOOD OF 2 GHz

1. Introduction

The characteristics of the fixed service and the space operation service in the neighbourhood of 2 GHz are reviewed. There follows a study of interference between terrestrial stations and a satellite, and then between a terrestrial station and an earth station.

The following calculation method relating to the study of interference between a terrestrial station and an earth station does not replace the method given in Appendix 28 to the Radio Regulations. It is not intended to be used in evaluating coordination distances. It allows the *a priori* evaluation of an order of magnitude for acceptable separation distances between an earth station and a terrestrial station, on the basis of a number of parameters. For this purpose, the calculation of the attenuation over the interference path is based not on the worst case but on an average case, with reference exclusively to diffraction caused by an obstacle situated between the two stations. The separation distance thus calculated gives a realistic idea of practical sharing possibilities between the space service and the terrestrial service.

2. Technical characteristics

2.1 *Characteristics of the space systems in question*

2.1.1 *Orbits*

A large number of space, scientific or applications missions use earth satellites:

- either in orbits close to the Earth (these are often circular at altitudes between 300 and 1200 km);
- or in the geostationary-satellite orbit;
- or in highly eccentric orbits (with apogees up to 200 000 km).

In addition, geostationary satellites are placed in position after having been placed in eccentric orbits (apogee altitude: 36 000 km).

2.1.2 *Frequencies*

Space operation systems may use up links carrying telecommand and tracking signals in the 2025-2110 MHz band and down links carrying telemetering and tracking signals in the 2200-2290 MHz band. The powers emitted by the satellite or earth stations should be within the regulatory limits.

2.1.3 *Bandwidths*

The following bandwidths are used:

- earth station: 250 kHz for transmitting and receiving;
- space station: 500 kHz for receiving, on the assumption that there is no automatic frequency control device to compensate the Doppler effect and oscillator drift, and 250 kHz for transmitting.

2.1.4 *Antennas*

A standard type of earth station antenna is used, with a diameter of 9 m. It is assumed that the antenna's radiation diagram is in conformity with that given in Report 391 (see Fig. 2).

2.1.5 *Operational limits*

The use of the earth station, both for transmitting and for receiving, is limited to elevation angles more than 5° above the local horizontal plane. This limit is, however, increased to 10° in the case of telecommand links for highly eccentric satellites in the neighbourhood of the apogee and in the case of geostationary satellites.

The technical characteristics of space links adopted in this study are given in Table VIII.

TABLE VIII — *Characteristics of space links*

		Low-altitude circular-orbit satellites			Geostationary satellites	Highly eccentric elliptical orbit satellites	
		300 km	800 km	1200 km		200 000 km	300 km
$-20 \log \frac{4\pi d}{\lambda}$	At an elevation angle of 5°	– 163 dB	– 168 dB	– 170 dB	– 191.5 dB	– 205 dB	– 163 dB
	At the zenith	– 149 dB	– 157 dB	– 161 dB	– 190.5 dB	– 205 dB	– 149 dB
Earth station	G_{max}	43 dB	43 dB	43 dB	43 dB	43 dB	43 dB
	Polarization	circular	circular	circular	circular	circular	circular
	TCTP	500 W	500 W	500 W	500 W	1.5 kW at 10°	500 W
	T_r	300 K	300 K	300 K	300 K	150 K	300 K
	P_i	– 126 dBm	– 126 dBm	– 126 dBm	– 126 dBm	– 129 dBm	– 126 dBm
	E.i.r.p.	52 dB (W/4 kHz)	52 dB (W/4 kHz)	52 dB (W/4 kHz)	52 dB (W/4 kHz)	56 dB (W/4 kHz)	52 dB (W/4 kHz)
	$B_r = B_t$	250 kHz	250 kHz	250 kHz	250 kHz	250 kHz	250 kHz
Space station	G	– 5 dB	0 dB	0 dB	0 dB	10 dB	– 5 dB
	Polarization	circular	circular	circular	circular	circular	circular
	TMTP	0.3 W	1 W	1 W	2.5 W	6 W	0.3 W
	T_r	800 K	800 K	800 K	800 K	800 K	800 K
	Y	20 dB	20 dB	20 dB	20 dB	20 dB	20 dB
	Pfd 5°	– 163 dB(W/(m^2. 4 kHz))	– 158 dB(W/(m^2. 4 kHz))	– 160.5 dB(W/(m^2. 4 kHz))	– 177 dB(W/(m^2. 4 kHz))	– 177 dB(W/(m^2. 4 kHz))	– 163 dB(W/(m^2. 4 kHz))
	Pfd zenith	– 149 dB(W/(m^2. 4 kHz))	– 147 dB(W/(m^2. 4 kHz))	– 150.5 dB(W/(m^2. 4 kHz))	– 176 dB(W/(m^2. 4 kHz))	– 177 dB(W/(m^2. 4 kHz))	– 149 dB(W/(m^2. 4 kHz))
	B_t	250 kHz	250 kHz	250 kHz	250 kHz	250 kHz	250 kHz
	B_r	500 kHz	500 kHz	500 kHz	500 kHz	500 kHz	500 kHz

G_{max}: axial gain

TMTP: telemetering transmitting power

TCTP: telecommand transmitting power

B_r: receiver bandwidth

B_t: transmitting bandwidth

T_r: equivalent noise temperature

P_i: permissible interference power

Y: protection ratio

2.2 *Characteristics of terrestrial systems*

To take account of the great variety of systems in use or planned in the near future, two representative examples have been adopted, called "type 1 stations" and "type 2 stations" (see Table IX).

For both type 1 and type 2 stations, antennas have been adopted with diameters of about 3 m but with different configurations, with radiation diagrams in conformity with Report 391 (see Fig. 3).

TABLE IX — *Characteristics of radio-relay systems*

	Type 1 station	Type 2 station
Frequency band	2–2.3 GHz	2–2.3 GHz
Axial gain	34.8 dB	36 dB
Polarization	linear	linear
Transmitted power	24 dBm (20 dBm on the carrier)	43 dBm
Reference bandwidth	(not applicable to this study)	4 kHz
Permissible interference power	–97 dBm	–118 dBm (in 4 kHz)
Modulation	digital	analogue

3. Study of interference

Four cases of interference may be encountered:

– satellite receives interference from the terrestrial station and vice versa;

– earth station receives interference from the terrestrial station and vice versa (Fig. 4).

Generally speaking, a link without interference satisfies the relation:

$$P_i - \left[P_e + G_e + 10 \log \frac{\Delta F_r}{\Delta F_e} - 20 \log \frac{4\pi d}{\lambda} + G_r - D_p - A_b - D_f - A_h(\varepsilon) \right] \geqslant 0 \qquad (5)$$

where:

P_i : permissible interference level (dBm),

P_e : transmitted power (dBm),

G_e : transmitting antenna gain in the direction in question (dBi),

$\Delta F_r / \Delta F_e$: receiving/transmitting bandwidth ratio. If it is above 1, the value of 1 is to be used,

G_r : receiving antenna gain in the direction in question (dBi),

D_p : polarization losses (dB),

A_b : receiver connection losses (3 dB),

D_f : frequency decoupling (see below),

$A_h(\varepsilon)$: losses due to relief (see below).

– *Frequency decoupling: D_f*

Contingent attenuation (dB) due to the difference between the space link frequency and the nearest frequencies of those planned in the arrangement of fixed service radio channels.

– *Losses due to relief (site shielding): $A_h(\varepsilon)$*

An attenuation factor (dB) due to the horizon angle of deviation (ε) in accordance with Report 724 (Geneva, 1982):

$$A_h(\varepsilon) = 20 \log (1 + 4.5 f^{1/2} \varepsilon) + f^{1/3} \varepsilon \text{ with } f \text{(GHz) and } \varepsilon \text{ (degrees)} \qquad (6)$$

This factor only comes into play in the case of interference between the earth station and the terrestrial station.

All calculations are made for $f = 2200$ MHz.

3.1 *Satellite receives interference from the terrestrial station and vice versa*

– By way of example, a study was made of the most unfavourable case corresponding to a satellite in circular orbit at an altitude of 300 km.

– In applying the general formula, use is made of the following numerical values:

D_p = 3 dB,

D_f = 0 dB (because it will be impossible to guarantee frequency decoupling between a moving satellite and all the terrestrial stations that the satellite may "see" at any time),

A_h = 0 dB,

A_b = 3 dB.

3.1.1 *Earth-to-space link*

First of all, the interference level produced by a single radio-relay transmitter is examined. Two cases are considered:

(a) an average situation in which the satellite is outside the main lobe of the radio-relay antenna at an oblique distance of 600 km. In this case the transmit gain of the radio-relay antenna toward the satellite is 0 dB and the space loss is −155 dB.

(b) a particular situation in which the satellite is at the horizon and in the main lobe of the terrestrial station antenna. In this case the transmit gain is the maximum gain and the space loss is −165 dB.

For a type 1 terrestrial station the most unfavourable case is carrier interference. Here:

P_e = 20 dBm

and $\Delta F_r/\Delta F_e > 1$, this ratio is therefore replaced by 1.

For a type 2 terrestrial station, the transmitted power is:

P_e = 43 dBm.

Since various cases are possible for ΔF_e, consideration is again given to the cases where $\Delta F_r/\Delta F_e > 1$, which are the most unfavourable cases; this ratio is therefore once more replaced by 1.

The accumulated effect of a large number of radio-relay transmitters is then added. In order to estimate the total number of radio-relay systems in line-of-sight of the satellite, a density of 5 transmitters per earth surface area 10 000 km² is assumed. Six thousand transmitters are found in line-of-sight for an altitude of 300 km.

To estimate the total number of transmitters in situation *(b)*, account is taken of the main-lobe beamwidth, estimated at 3.6°. First of all a calculation is made of the width of the annular strip of land within which the satellite is seen at an angle of elevation of between 0° and 1.8°. It is deduced that this belt comprises 1200 transmitters. On the assumption that the pointing azimuths of the antennas in the 1200 interfering stations are equally spread out over 360°, 1% of them, i.e. 12 stations, will see the satellite in their 3.6° wide main lobe.

Finally, the permissible interference level is determined by calculating the power of the received wanted signal at the limit of the earth station's range, that is to say at an angle of elevation of 5°, i.e. at 1500 km; 20 dB, the value Y in dB adopted for the protection ratio, being subtracted.

$$P_i = P_r - Y \tag{7}$$

$$P_i \text{ (dBm)} = -20 \text{ dB} + P_r(1500) \text{ dBm}$$

where:

$$P_r = P_e + G_e - 20 \log \frac{4\pi d}{\lambda} + G_r - A_b$$

$$P_r \text{ (dBm)} = 57 + 43 - 163 - 5 - 3 = -71 \text{ dBm}$$

$$P_i = -91 \text{ dBm}$$

The results are given in Table X.

Table X shows that with type 1 stations interference is less than the permissible level. It would be possible:

– either to tolerate interference from 30 times more stations;

– or reduce the power of the telecommand transmitter.

TABLE X — *Satellite receiving interference from the terrestrial stations*

Type of interfering terrestrial stations	Position of satellite in relation to interfering station	Power of interference received from a single interfering station (dBm)	Number of stations	Power of interference received from all stations (dBm)	
Type 1 terrestrial station	Average case In the main lobe	– 146 – 121	6000 12	– 108 – 110	– 106
Type 2 terrestrial station	Average case In the main lobe	– 123 – 97	6000 12	– 85 – 86	– 82

Note. — Permissible interference power = – 91 dBm.

With type 2 stations the permissible level is exceeded by 9 dB. Here it would be possible:

- either to tolerate the interference from 8 times fewer stations;
- or multiply the e.i.r.p. of the telecommand transmitter by 8.

These results relate to a spacecraft at an altitude of 300 km. At higher altitudes it can be established that the results would be more favourable.

3.1.2 *Space-to-Earth link*

The space operation system must comply with the power flux-density limits given in Recommendation 358, i.e. in any 4 kHz band:

-154 dB(W/m^2) for angles of arrival between 0° and 5° above the horizontal plane;

$-154 + 0.5 (\delta - 5)$ dB(W/m^2) for angles of arrival δ (in degrees) between 5° and 25° above the horizontal plane;

-144 dB(W/m^2) for angles of arrival between 25° and 90° above the horizontal plane.

3.2 *Earth station receiving interference from the terrestrial station and vice versa*

3.2.1 *Calculation hypotheses*

An attempt has been made to estimate what would be, in practice, the order of magnitude of the separation distances d associated with those cases for which limited sharing is indicated in Tables I and II of this Report, i.e., distances at which an earth station could operate in relation to an existing radio-relay network after all cases of coordination had been satisfactorily settled. The characteristics adopted for this calculation are given in Figs. 5 to 8. So as to allow for practical orders of magnitude, account was taken for calculation purposes of the following favourable factors:

- the earth station is assumed to be placed in a hollow: the elevation angle ε of the physical horizon – varying between 0.5° and 4° – has been taken as a secondary variable. The earth station is assumed not to operate at angles of elevation below 5°;
- in the case of non-geostationary satellites, 10 dB may be deducted in order to take into account the variety of the angular positions occupied by the satellites in the line of sight from the earth station (Report 382);
- in the case of geostationary satellites, the earth station is assumed to be pointed at a fixed elevation angle;
- it is also always assumed that the direction of the radio-relay system does not coincide with the straight line joining the terrestrial station to the earth station. As a principal variable, an offset angle θ has been assumed between these two directions, varying between 5° and a value corresponding to a limit gain of -10 dBi (see Fig. 4) (Report 391);
- we have allowed for an additional attenuation of D_f by assuming interleaved frequency assignments for the two services: since it involves bandwidths which are usually less than 1 MHz, the space operation service may choose frequency assignments halfway between two adjacent channels in the plan for the radio-relay systems.

According to the values obtained for the variable d, and according to the density of the existing or planned radio-relay network, this method gives an *a priori* idea of the chances of all the cases of coordination being successfully settled. This means that the concept of separation distance, as calculated above, provides an *a priori* estimate of the possibility of frequency-sharing between terrestrial and earth stations.

In cases where coordination seems *a priori* difficult, it may be useful to consider other favourable factors which have not been taken into account in the analysis described above:

- the position envisaged for an earth station is not usually critical and may be moved several hundred kilometres to facilitate coordination;
- if difficult cases of coordination remain in one or two particular azimuths measured from the earth station, it might be possible in these azimuths to raise the normal lower limit of operation of the earth station above a 5° elevation angle;
- the reduction of 10 dB indicated in the second point above is to take account of an angular statistical factor. But earth stations of the space operation service usually do not work on a permanent basis; in particular, the telecommand of a low orbit satellite (altitude less than a few thousand kilometres) lasts about 1 min, four times a day. In this case, account may be taken of a time statistical factor.

3.2.2 *Example of calculation*

On the basis of the points made above, the separation distances d have been determined in the form of charts as a function of the two variables θ and ε.

Four cases, shown in Figs. 5 and 8, have been taken as examples.

Details of the calculations for Figs. 5 and 7 are given below:

(a) Interference caused to an earth station by a type 1 terrestrial station (Fig. 5):

From general formula (5), we derive the relationship:

$$G_e(\theta) \leqslant P_i - P_e - G_r - 10 \log \frac{\Delta F_r}{\Delta F_e} + 20 \log \frac{4\pi d}{\lambda} + D_p + A_b + A_h + D_f \tag{8}$$

This gives:

P_e = 20 dBm

P_i = −126 dBm

D_p = 0 dB

A_b = 3 dB

D_f = 22 dB

G_r: to take account of the diversity in the angular positions occupied by the earth station tracking a satellite above an angle of elevation of 5°, we take the value at $5 - \varepsilon$ from Fig. 2, less 10 dB.

$$10 \log \frac{\Delta F_r}{\Delta F_e} = 0$$

Thus

$$G_e(\theta) \leqslant -121 - (G_r - 10) + A_h(\varepsilon) + 20 \log \frac{4\pi d}{\lambda} \tag{9}$$

TABLE XI

	ε	A_h (1°)	G_r (5–ε)	$20 \log \frac{4\pi d}{\lambda}$	$G_e(\theta) \leqslant$
Point ① d = 20 km	1°	19.1 dB	18.7 dB	126 dB	+ 15.4 dB
Point ② d = 50 km	1°	19.1 dB	18.7 dB	134 dB	+ 23.4 dB

(b) Interference caused to a type 1 terrestrial station by an earth station (Fig. 7).

From the general formula, we derive the relationship:

$$G_r(\theta) \leqslant P_i - P_e - G_e - 10 \log \frac{\Delta F_r}{\Delta F_e} + 20 \log \left(\frac{4\pi d}{\lambda}\right) + D_p + A_b + A_h + D_f \qquad (10)$$

This gives:

$P_e = 57$ dBm

$P_i = -97$ dBm

$10 \log \frac{\Delta F_r}{\Delta F_e} = 0$

$L_p = 3$ dB

$A_b = 3$ dB

$D_f = 12.5$ dB

G_e: it is assumed that the earth station is fixed at an angle of elevation of 10°. Therefore we take G_e at $(10 - \varepsilon)$ read on Fig. 2.

Thus

$$G_r(\theta) \leqslant -135{,}5 - G_e + 20 \log \frac{4\pi d}{\lambda} + A_h(\varepsilon) \qquad (11)$$

TABLE XII

	ε	A_h (2°)	G_e (10–ε)	$20 \log \frac{4\pi d}{\lambda}$	$G_r(\theta) \leqslant$
Point ① d = 20 km	2°	25.7 dB	11.2 dB	126 dB	+ 5.0 dB
Point ② d = 50 km	2°	25.7 dB	11.2 dB	134 dB	+ 13.0 dB

4. Conclusion

4.1 It will be remembered that the protection of terrestrial stations against interference from space stations is assured by compliance with the power flux-density limit laid down in Recommendation 358. The study also shows that the interference caused to space stations by terrestrial stations can be kept below the permissible level if, in the case of radio-relay systems with high e.i.r.p., the e.i.r.p. of the telecommand earth stations is increased (see § 3.1.1).

4.2 Before undertaking the coordination procedure described in Appendix 28 of the Radio Regulations, it is often necessary to make a rapid analysis of the practical conditions for the siting of the earth station in an existing radio-relay network. This analysis can be carried out by the graphical method referred to in § 3.2 by which the best sites for the earth station in relation to those of the radio-relay system terrestrial stations can be provisionally determined.

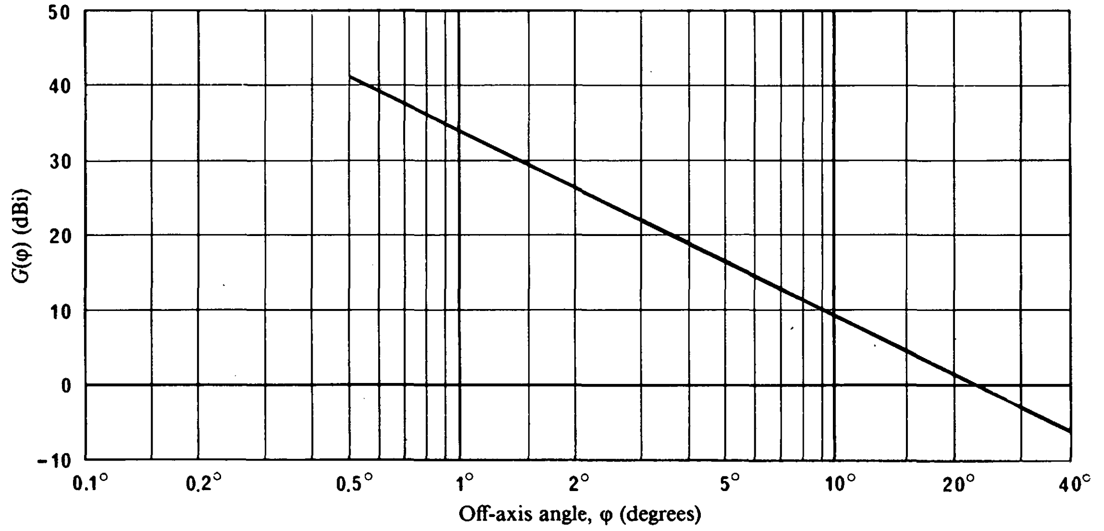

FIGURE 2 — *Radiation diagram of the earth station antenna*

$G(\varphi)$: gain over isotropic $= 52 - 10 \log \dfrac{D}{\lambda} - 25 \log \varphi$

outside the main lobe, i.e. beyond the – 3 dB points

Other characteristics:

— parabolic antenna of 9 m diameter

— carrier frequency: 2200 MHz

— – 3 dB beamwidth = 1°

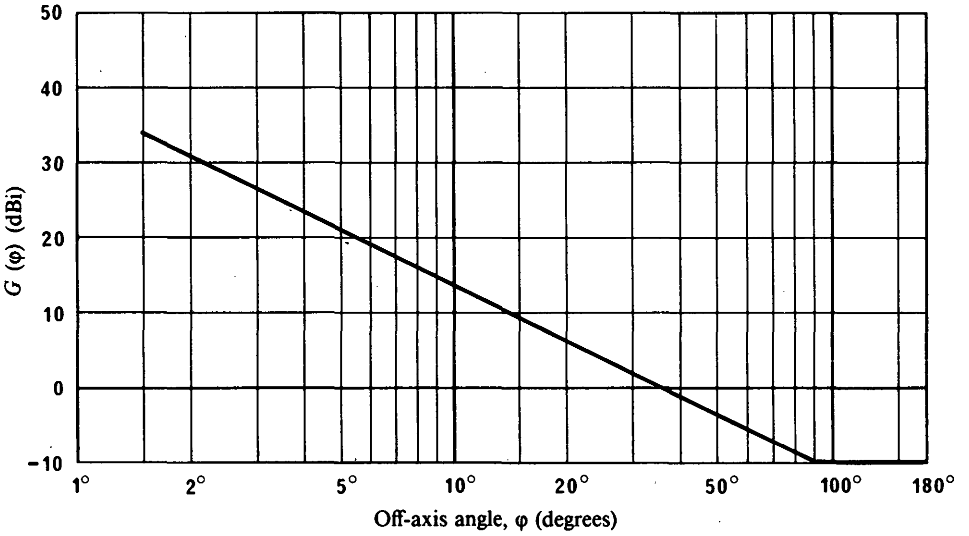

FIGURE 3 — *Radiation diagram of the terrestrial station antenna*

$G(\varphi)$: gain over isotropic $= 52 - 10 \log \dfrac{D}{\lambda} - 25 \log \varphi$

outside main lobe i.e. beyond the – 3 dB points

Other characteristics:

— parabolic antenna of 3 m diameter

— carrier frequency: 2200 MHz

— – 3 dB beamwidth: 3.2°

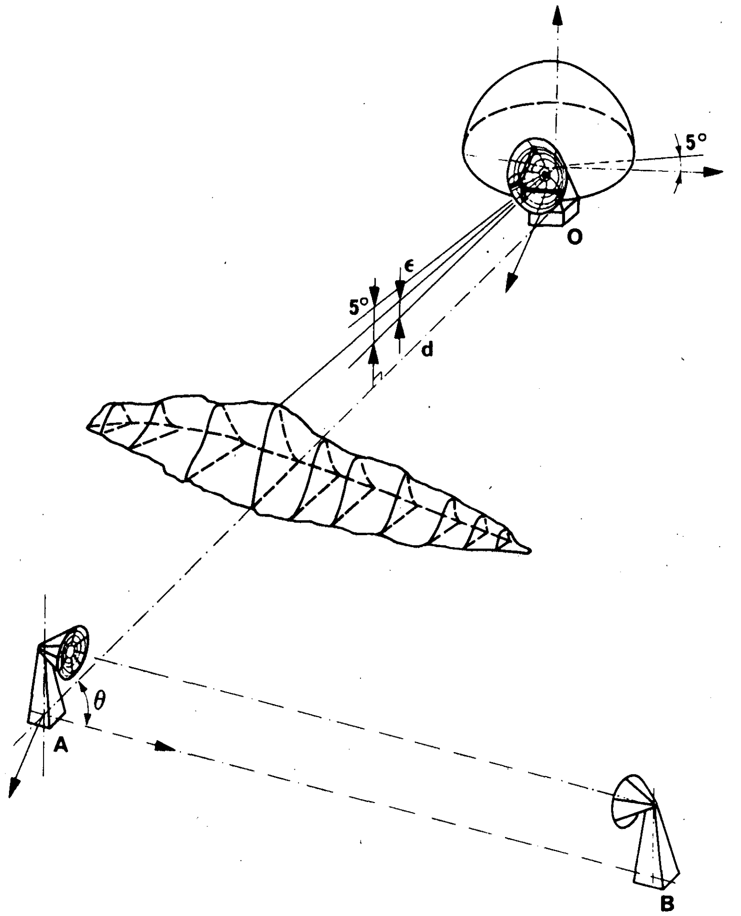

FIGURE 4 — *Position of the terrestrial stations in relation to the earth station for the study of interference*

d: distance OA

ε: geographical protection angle

O: earth station

AB: line-of-sight radio-relay link

θ: offset angle

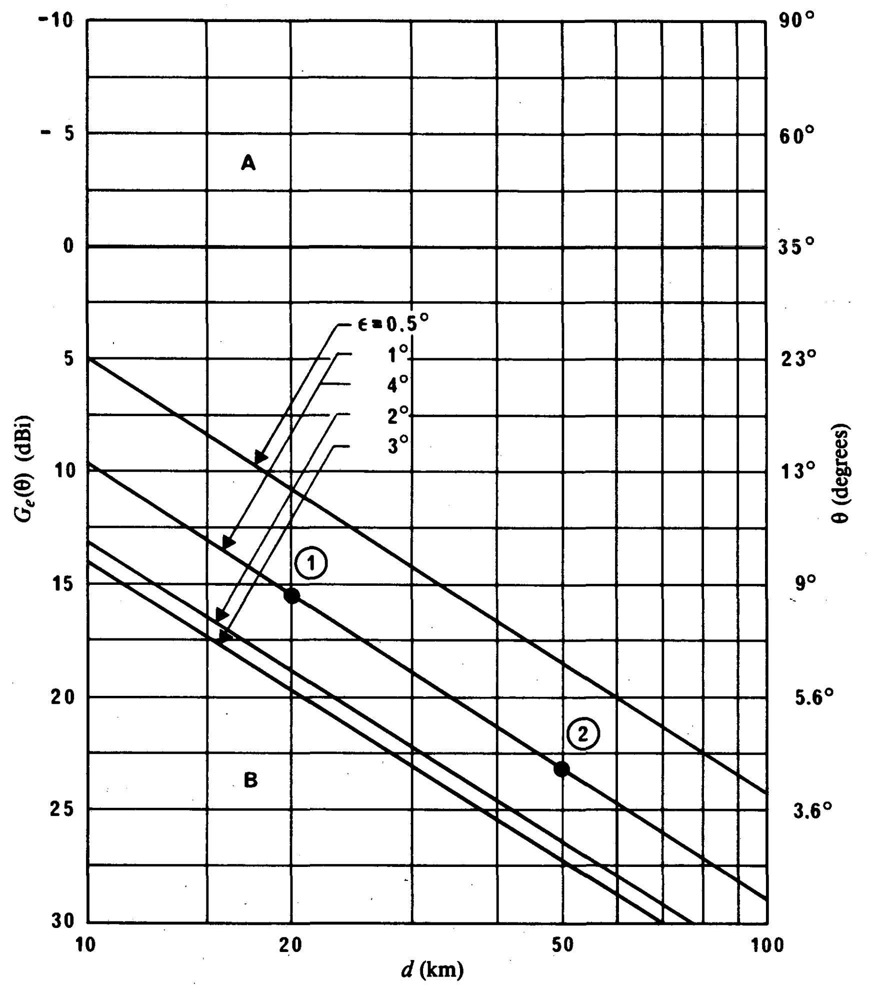

FIGURE 5 — *Earth station receiving interference from a type 1 terrestrial station*

d: distance separating the earth station from the terrestrial station

$G_e(\theta)$: antenna gain of the terrestrial station in the direction of the earth station

θ: offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station

ε: elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station is assumed to receive the emission from a *non-geostationary* satellite and to operate at an elevation angle of over 5°.

A: area of improbable interference

B: area of probable interference

D_f: 22 dB corresponding to the use of an interleaved frequency in the plan for the type 1 radio-relay system

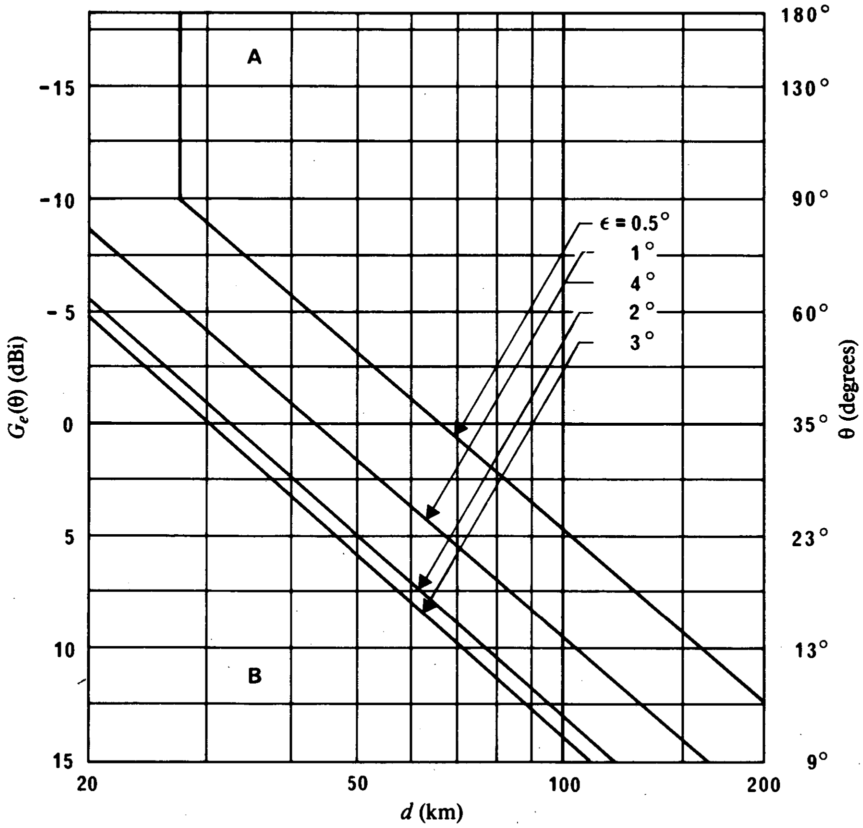

FIGURE 6 — *Earth station receiving interference from a type 2 terrestrial station*

d:	distance separating the earth station from the terrestrial station
$G_e(\theta)$:	antenna gain of the terrestrial station in the direction of the earth station
θ:	offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station
ε:	elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station is assumed to receive the emission from a *non-geostationary* satellite and to operate at an elevation angle of over 5°.

A:	area of improbable interference
B:	area of probable interference

This diagram has been obtained in the special case of a frequency decoupling of D_f = 22 dB.

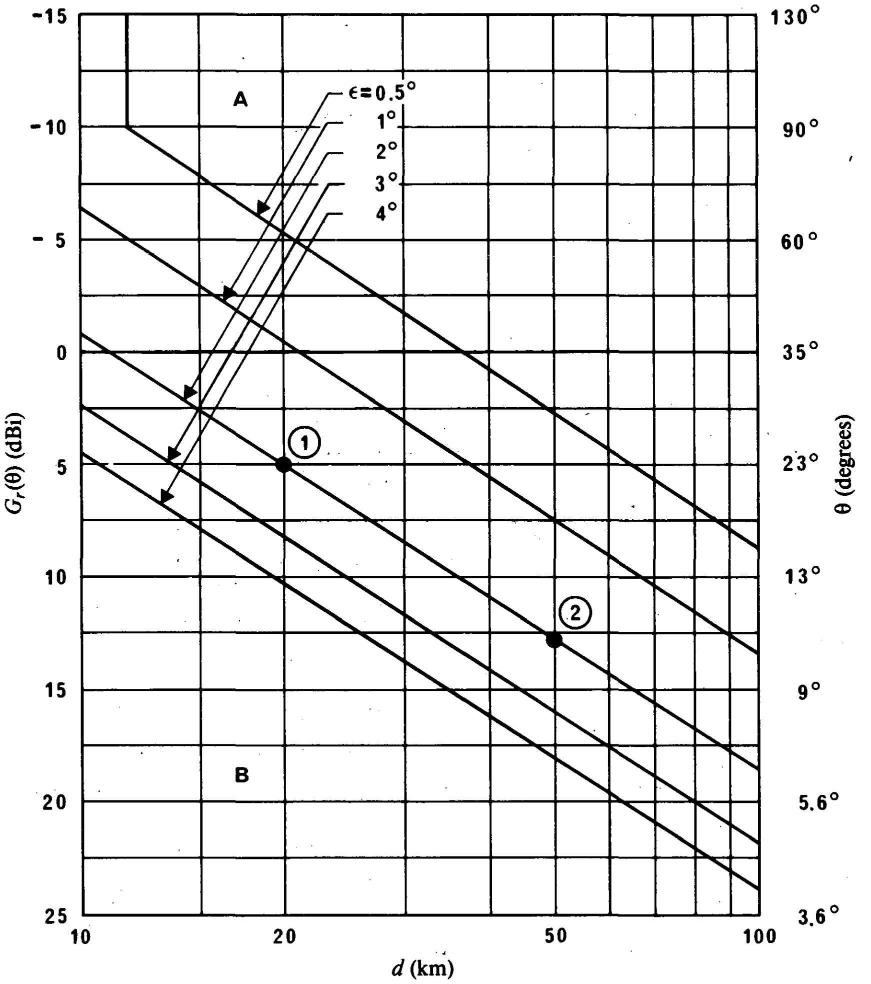

FIGURE 7 — *Type 1 terrestrial station receiving interference from an earth station*

d: distance separating the earth station from the terrestrial station

$G_r(\theta)$: antenna gain of the terrestrial station in the direction of the earth station

θ: offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station

ε: elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station antenna is assumed to be transmitting at an elevation angle of 10° in the direction of a *geostationary* satellite and the transmission power is taken at 500 W.

A: area of improbable interference

B: area of probable interference

D_f: 12.5 dB corresponding to the use of an offset frequency in the plan for the type 1 radio-relay system

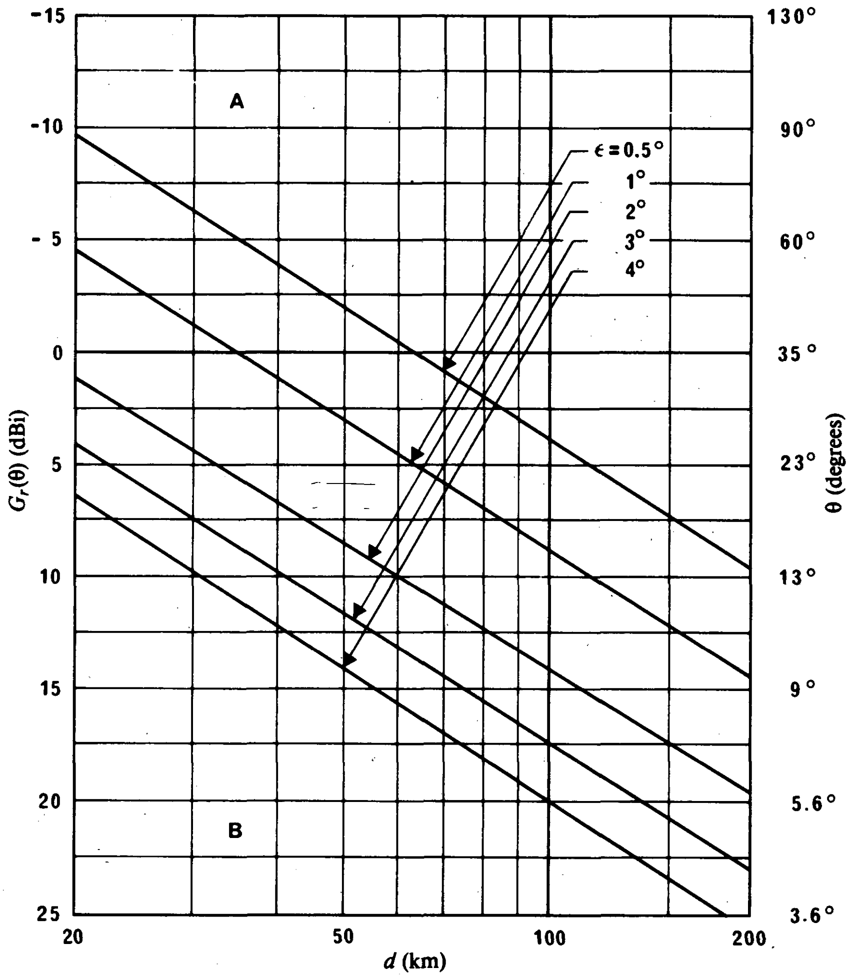

FIGURE 8 — *Type 2 terrestrial station receiving interference from an earth station*

d: distance separating the earth station from the terrestrial station

$G_r(\theta)$: antenna gain of the terrestrial station in the direction of the earth station

θ: offset angle between the direction of the radio-relay link and the straight line joining the terrestrial station to the earth station

ε: elevation angle of the physical horizon of the earth station in the direction of the terrestrial station

The earth station is assumed to be transmitting at an elevation angle of 10° in the direction of a *geostationary* satellite and the transmission power is taken at 500 W.

A: area of improbable interference

B: area of probable interference

This figure has been obtained in the special case of a frequency decoupling of D_f = 12.5 dB.

RECOMMENDATION 363-3 *

SPACE OPERATION SYSTEMS

Frequencies, bandwidths and protection criteria

(Question 18/2)

(1963–1974–1982–1986)

The CCIR,

CONSIDERING

(a) that the frequencies technically suitable for maintenance telemetering, tracking and telecommand of developmental and operational radionavigation, meteorological, communication, earth exploration and broadcasting satellites lie in the range from 100 MHz to 30 GHz;

(b) that the integration of maintenance telemetering, tracking and telecommand links with data transmission and communication systems may have advantages which include, among others, efficient use of the spectrum particularly for the on-station operational phase of geostationary satellites;

(c) that the validity of this approach has been demonstrated in some operational systems;

(d) that satellite safety nonetheless requires wide-coverage antenna radiation to maintain links during specific phases of launch and orbit transfer or in cases of momentary loss of attitude, and that wide-coverage radiation is difficult to obtain at frequencies above 8 GHz;

(e) that, in the case of broadcasting satellites, the World Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service, Geneva, 1977 (WARC-BS-77) planned the use of the bands 11.7 to 12.5 GHz in Region 1 and 11.7 to 12.2 GHz in Region 3 by allotting channels to the administrations in those Regions for satellite broadcasting, that no specific allotments were made for maintenance telemetering, tracking and telecommand (although the WARC-BS-77 reserved guardbands at the edges of both bands) and that consequently it may be difficult to use these bands also for maintenance telemetering, tracking or telecommand. (Some potential difficulties involved in this particular implementation of the space operation function are discussed in Report 1076.) The Regional Administrative Radio Conference for the Planning of the Broadcasting-Satellite Service in Region 2 (RARC SAT-83) specified that space operation systems could be used in the allotted guardbands of 12 MHz at each end of the 12.2 to 12.7 GHz and 17.3 to 17.8 GHz bands for Region 2;

(f) that, in most cases, the necessary bandwidths for space operations are determined by the transmission of ranging signals;

(g) that the e.i.r.p. of space station transmitters is limited, so that earth receiving stations must operate at maximum sensitivity;

(h) that the e.i.r.p. of earth-station transmitters can be increased within the limits defined in the Radio Regulations to give an acceptable protection ratio at space station receiver inputs,

UNANIMOUSLY RECOMMENDS

1. that bands of frequencies below 1 GHz are technically suitable for use for some types of maintenance telemetering, tracking and telecommand of developmental and operational low-orbit (for example, below 2000 km) satellites;

2. that the preferred bands of frequencies for maintenance telemetering, precision tracking and telecommand should be between 1 and 8 GHz;

3. that bands of frequencies above about 10 GHz are technically suitable for use for maintenance telemetering, tracking and telecommand during the re-entry of satellites into the atmosphere of the Earth (see Report 222);

* This Recommendation should be brought to the attention of Study Groups 4, 8, 9, 10 and 11.

4. that, for satellite systems such as those used for meteorological, radionavigation, communication, earth exploration and broadcasting purposes, and taking account of requirements for reliability and economical use of the frequency spectrum and for the safety of spacecraft in all phases of operation, frequencies within the mission bands used for data transmission or communications should be preferred for use for maintenance telemetering, tracking and telecommand, where practicable. Where this is not practicable, frequencies in the bands specifically allocated to the space operation service should be used;

5. that the special needs for maintenance telemetering, tracking and telecommand should be considered in the planning of frequencies for the broadcasting-satellite service and for the associated feeder links;

6. that the necessary bandwidths should usually lie between 200 kHz and 1 MHz with classical modulation methods;

7. that the protection criteria for earth-station receivers should be as follows: for frequencies above 1 GHz, total interference power in each band 1 kHz wide must not exceed −184 dBW at the receiver input for more than 1% of the time each day; for frequencies below 1 GHz, this value is increased by 20 dB per decreasing frequency decade;

8. that the protection criteria for spacecraft receivers should be as follows: the ratio of signal power to total interference power in each band 1 kHz wide must not fall below 20 dB for more than 1% of the time, each day;

9. that these criteria are insufficient to guarantee the safety of spacecraft in certain brief critical phases, such as launching and that the administrations concerned should be invited to make any necesssary provisions to guarantee the safety of spacecraft during such brief critical phases.

REPORT 678

TECHNICAL FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE OPERATION SERVICE AND THE SPACE RESEARCH SERVICE IN THE 1 TO 10 GHz BAND

(Question 1/2)

(1978)

1. Introduction

The Space Operation Service, within which the vital satellite functions – maintenance, telemetry, telecommand and tracking – can be performed, will assume growing importance as satellite systems in many services move to frequency bands beyond 15 GHz and as increasing use is made of high-gain spot-beam antennas for the illumination of rather limited service areas. Thus, satellite systems using the geostationary orbit will run into more and more difficulties, particularly during the injection and transfer orbit phase, when relying on the service frequency bands for their maintenance telemetry, telecommand and tracking transmissions. The antenna systems, which frequently have only high-gain spot-beams will, in many cases, not be adequate to provide the required coverage. One way to overcome this problem would be to use additional satellite equipment, operating at lower frequencies, and having the required antenna characteristics and link performance. This equipment would logically operate in the bands of the Space Operation Service.

The purpose of this Report is to demonstrate the technical feasibility of frequency sharing between the Space Operation and Space Research Service. If frequency sharing is proved to be feasible, it should be possible to make certain bands already allocated to the Space Research Service available also to the Space Operation Service. In this way the utilization of the spectrum can be made more efficient without adversely affecting the interests of the Space Research Service.

Finally, the sharing of the same frequency bands by the Space Operation Service and Space Research Service, together in some cases, with the joint use of the same earth station sites, would considerably ease the task of coordination with other frequency users (mostly terrestrial) sharing the same band: once the earth station site has been coordinated in a particular frequency band for the Space Research Service, it would be automatically coordinated for the Space Operation Service.

2. Sharing analysis

The sharing analysis is limited to the 1 to 10 GHz band: below 1 GHz the feasibility of sharing between the Space Research Service and Space Operation Service is well established and certain bands are allocated simultaneously to the two Services; above 10 GHz, problems similar to those outlined in the Introduction will occur, hampering the reliable performance of maintenance, telemetry, telecommand and tracking. Quasi-omnidirectional or hemispherical coverage antennae with an acceptable gain make considerable technological demands at frequencies above 10 GHz. At the same time, propagation conditions – particularly in areas of low geographical latitude – require considerable additional safety margins for a reliable link performance.

TABLE I – *Typical system parameters (at 2 GHz)*

Mode	System parameters	Space research		Space operation (up to geostationary altitude)
		Near-Earth	Deep-space	
Reception at earth station	Telemetry bandwidth	10 kHz – 30 MHz	1 Hz – 4 MHz	100 kHz
	Tracking bandwidth	400 kHz – 1 MHz	1 Hz – 4 MHz	400 kHz
	G/T earth station	20–35 dB(K^{-1})	37–60 dB(K^{-1})	≈ 20 dB(K^{-1})
Transmission from earth station	Telecommand bandwidth	100 kHz – 1 MHz	1 Hz – 3 MHz	100 kHz
	Tracking bandwidth	400 kHz – 1 MHz	1 Hz – 3 MHz	400 kHz
	e.i.r.p. earth station	60 – 90 dBW	75 – 116 dBW	≈ 65 dBW

2.1 *1 to 6 GHz band*

The analysis of this band will be based on typical equipment (existing or planned) in the 2 GHz band. Table I provides a comparison of the system parameters of the Space Research Service (for near-Earth satellites and deep-space probes) and of the Space Operation Service.

The system parameters of satellites in the Space Research Service (near-Earth) and the Space Operation Service are very similar, the Space Operation Service usually occupying the lower part of the performance range. The latter fact substantiates the statement made in the Introduction concerning the coordination with other services (terrestrial) sharing the band. Finally, the standards used for maintenance, telemetry, telecommand and tracking, are identical or very similar. The Space Research Service (near-Earth) and the Space Operation Service are thus mutually compatible and can consequently share the same bands.

As for the frequency sharing between the Space Research Service (deep-space) and the Space Operation Service, the results of Report 685 are directly applicable, i.e. sharing is not feasible in this case.

Interference situations between satellites operating in the Space Research Service (near-Earth) and the Space Operation Service occur relatively rarely and are generally of short duration. This is explained, in particular, by the fact that the majority of research satellites use low orbital altitudes (up to 2000 km). Typical interference durations of less than 1 minute would be encountered between a low-orbiting satellite and a satellite at geostationary altitude for a pass through the centre of the antenna beam with both satellites operating at the same frequency. Consequently, interference periods can be kept to well below 0.1% of the time, which is acceptable for both Services. Interference situations can be further reduced by conscientious frequency assignments based on frequency coordination between spacecraft operators, where possible even ahead of the advance publication (see No. 1042 of the Radio Regulations).

2.2 *6 to 10 GHz band*

The sharing situation in the 6 to 10 GHz range is virtually the same as in the 1 to 6 GHz range: system parameters of the Space Research Service (near-Earth) and the Space Operation Service are very similar (see Table II) and standards used for maintenance, telemetry, telecommand and tracking are identical or very similar, which renders the Services mutually compatible. Sharing should thus be feasible between the Space Research Service (near-Earth) and the Space Operation Service; it is not feasible in the case of the Space Research Service (deep-space).

From a technological point of view, sharing in the 6 to 10 GHz band is far less attractive than in the 1 to 6 GHz band, the main reasons being that towards the upper end of the 6 to 10 GHz range antenna technology for quasi-isotropic or hemispheric coverage becomes more difficult, while at the same time propagation conditions are inferior to those in the 1 to 6 GHz band – particularly the lower part thereof.

TABLE II – *Typical system parameters (at 8 GHz)*

Mode	System parameters	Space research		Space operation (up to geostationary altitude)
		Near-Earth	Deep-space	
Reception at earth station	Telemetry bandwidth	100 kHz – 30 MHz	1 Hz – 4 MHz	100 kHz
	Tracking bandwidth	100 kHz – 2 MHz	1 Hz – 40 MHz	500 kHz
	G/T earth station	25 – 45 dB(K^{-1})	≈ 58 dB(K^{-1})	26 – 30 dB(K^{-1})
Transmission from earth station	Telecommand bandwidth	100 kHz	1 Hz – 3 MHz	100 kHz
	Tracking bandwidth	100 kHz – 2 MHz	1 Hz – 40 MHz	500 kHz
	e.i.r.p. earth station	70 – 90 dBW	110 – 120 dBW	75 dBW

3. Conclusions

Sharing between the Space Research Service (near-Earth) and the Space Operation Service should be feasible in the 1 to 10 GHz band. For technological and propagation reasons the lower part of the band is more attractive than the upper part. Sharing between the Space Research Service (deep-space) and the Space Operation Service is not feasible.

Interference situations within the shared bands can be kept at an insignificant level provided that frequency assignments are made conscientiously within the framework of Article 11 of the Radio Regulations.

SECTION 2D: DATA RELAY SATELLITES

Recommendations and Reports

REPORT 848-1

CHARACTERISTICS OF DATA RELAY SATELLITE SYSTEMS IN BANDS 9 AND 10

(Question 11/2)

(1982–1986)

1. System concepts of data relay satellites (DRS)

A data relay satellite is a satellite used to relay data between space stations, which are generally in low circular orbit, and earth stations.

The purpose of this Report is to present a general description of telecommunication links between earth stations and near-Earth orbiting space stations, which use one or more geostationary satellites as intermediate relays. Descriptions of experiments conducted to validate the feasibility of this type of telecommunication link are contained in Report 537 (Kyoto, 1978). Reference to Reports 846 and 847 should be made for more detailed information relating to sharing and compatibility with other services and to sharing within the space research service.

Annex I contains the technical parameters of a developed DRS system. Annex II provides a description of an operational data relay satellite system. The concept of a future data relay satellite system is discussed in Annex III.

An example of a current data relay satellite system is the Tracking and Data Relay Satellite System (TDRSS) being constructed by the United States. This section presents a brief description of this system and its capabilities.

At present, the United States makes use of a world-wide network of earth stations to receive telemetered data from spacecraft-borne instrumentation. These data, once received by the earth station network, are routed by various means to central data processing sites within the United States. In addition to receiving the scientific data from spacecraft, the Earth-based network must transmit commands to the spacecraft and annotate the received data with auxiliary information such as the spacecraft to earth station range and rates of change of range and the data time-of-arrival. Also, a portion of the overall data network provides a pre-launch checkout capability to ensure that the spacecraft are fully operational prior to launch.

The principal purpose of the TDRS system is to improve the efficiency and reduce the cost of returning spacecraft-gathered scientific data to Earth. In addition, real time coverage of low-orbit satellites can be provided on a near global basis, as compared to the current network of United States earth stations which can support a given space research mission for only about 15% of the time due to visibility constraints. Once launched and in operation, the TDRS system will be capable of supporting numerous spacecraft simultaneously with a system comprised of two geostationary satellites, separated by 130° longitude, and a single earth station located at White Sands, New Mexico. Not only will the TDRSS replace some 10 of 13 existing earth stations which comprise the United States near-Earth data collection network, but it will provide increased capability for obtaining data from low altitude, Earth-orbiting spacecraft.

To fulfil the functions performed by the current earth station network, the TDRS will make use of a number of different types of communications links. Briefly, the TDR satellite will:

- relay low and medium data rate communications from a relatively large number of low-orbit spacecraft to the TDRS earth station;
- relay commands from the TDRS earth station to low-orbit spacecraft;
- relay high data rate communications from a few low-orbit spacecraft to the TDRS earth station;
- relay relatively high data rate communications from the TDRS earth station to a few low-orbit spacecraft including manned spacecraft;
- provide for the gathering of ranging information about the low-orbit spacecraft;
- transfer time information to the low-orbit spacecraft;

– provide for the pre-launch testing of the scientific spacecraft's communication systems;
– communicate directly with the earth station for command and control purposes.

These communication links are described in greater detail in Annex II.

In order to fulfil all of these functions with efficient spectrum use, the TDRS will make use of a number of different frequency reuse techniques. These techniques include code division, multiplexing, polarization diversity, multi-beam antennas and, of course, operational time scheduling.

2. Preferred frequency bands

As indicated in Report 537 (Kyoto, 1978) the frequencies which would normally be used for direct communication between the user spacecraft and the earth stations will, instead, be used between the user spacecraft and the data relay satellite. Technically preferred frequencies for user spacecraft are discussed in Report 548.

In the current TDRS system, the communication links between the earth station and the data relay satellite operate in band 10 and the space-to-space links operate in bands 9 and 10.

3. Conclusions

A data relay satellite system reduces the number of earth stations required to track low-orbit spacecraft. An example of a current DRS system is the Tracking and Data Relay Satellite System being constructed in the United States. This system utilizes two geostationary relay satellites. Communication links between the earth station and the relay satellite are multiplexed and operate in band 10. The space-to-space links operate in bands 9 and 10 and involve both low and high data rate transmissions.

ANNEX I

DATA RELAY SATELLITE (DRS) SYSTEM PARAMETERS

Table I gives the technical parameters of a DRS system developed in the United States of America. This Table is extracted from Report 537 (Kyoto, 1978).

TABLE I

	Forward link			Return link		
	Earth station to relay	Relay to user spacecraft		User spacecraft to relay		Relay to earth station
Frequency band	Band 10	Band 9	Band 10	Band 9	Band 10	Band 10
Radio-frequency bandwidth (MHz)	330	10	50	10	225	500
Data rate (Mbit/s)	[1]	0·1	Up to 50	1	Up to 225	[2]
Earth station						
e.i.r.p. (dB(W/Hz))	4					
Relay satellite						
Receive antenna gain (dB)	50			36	50	
Receive system noise temperature (K)	2300			720	2300	
e.i.r.p. (dB(W/Hz))		−28	−26			−26
User receive system noise temperature (K)		800	2050			
User e.i.r.p. (dB(W/Hz))				−51 [3]	−49 [3] to −28	
Earth station receive system noise temperature (K)						420

[1] Composite of all signals sent to user spacecraft.
[2] Composite of all signals received from user spacecraft.
[3] Actual value dependent upon user satellite altitude.

ANNEX II

DESCRIPTION OF A DATA RELAY SATELLITE SYSTEM

1. TDRS low and medium data-rate communications (band 9)

The data rates produced by the majority of scientific spacecraft are modest, generally ranging from about 1 to 250 kbit/s. The TDRS system will be capable of relaying data from up to 20 low-orbit spacecraft simultaneously to the TDRS ground station. The TDRS sub-system which performs this function, operates on frequency of 2287.5 MHz. The capability of receiving up to 20 co-frequency data streams, each originating from a separate spacecraft, is obtained through the use of code division multiplexing techniques, and the use of a multi-beam phased array antenna on board the TDRS. At the low-orbit spacecraft, the scientific data along with pseudo noise (PN) code are modulated onto the transmitted carrier frequency. This signal is received by a 30 element array antenna on board a TDRS satellite. The information received by each of the 30 antenna elements is isolated, using frequency division multiplex techniques, translated to 13.5 GHz, and retransmitted to the TDRS earth station. After reception at the earth station, the data streams from all 30 antenna elements are demultiplexed, each data stream delayed slightly in phase, and then recombined. Delaying the phase of the signal received by each element of TDRS antenna array creates a synthetic phased array beam. The phase delay introduced into each of the 30 received data streams from the desired satellite is adjusted to maximize the signal based upon the predicted satellite position which, in effect, "aims" this synthesized beam at the low-orbit spacecraft. As the low-orbit spacecraft moves in orbit, the phase delays introduced into the 30 antenna element signals are changed to keep the synthesized beam "tracking" the spacecraft.

After the synthesized beam has been formed, the enhanced signal is processed to remove the PN code modulation. This processing further enhances the data signal while simultaneously suppressing interference and signal components from the other 19 scientific satellites being received on the same centre frequency.

As implemented, the limitation on the total number of scientific spacecraft which may simultaneously use this TDRS "multiple access" (MA) system is based upon the number of MA processing computers available at the TDRS ground station. In the US system, 20 such computers will be employed, thereby limiting the number of multiple access user satellites to 20, regardless of the actual number of TDRS satellites in orbit.

In addition to receiving data from low-orbit spacecraft, the multiple access system is capable of relaying commands from the TDRS earth stations to the low-orbit spacecraft. Seventeen of the 30 elements in the phased array antenna contain programmable phase shifters. These elements, under control of the TDRS earth station, can be used to form a single phased array transmit beam which can be directed at a scientific spacecraft. The multiple access command information is transmitted from the earth station to a TDRS satellite on 14.8 GHz, where it is frequency-shifted to 2106.4 MHz, and retransmitted to the low-orbit spacecraft. In order to ensure that only one of the low-orbit spacecraft responds to the multiple access commands, the command information is modulated on a PN data stream. The transponders in the low-orbit spacecraft will only respond to a single unique PN code. The use of the PN modulation also spreads the command signal energy over a 6.2 MHz bandwidth. This spectrum spreading technique reduces the power flux-density at the surface of the Earth, while simultaneously allowing the low-orbit satellite to receive command information with a usable signal strength.

Each TDRS phased array antenna is capable of forming only one transmit beam at a time, therefore the number of multiple access command links corresponds to the number of operational TDRS satellites.

2. TDRS high data-rate communications (bands 9 and 10)

In order to provide for the relay of high data rate telemetry to and from the scientific spacecraft, each TDRS satellite is equipped with two 4.9 m steerable parabolic reflector antennas. Each of these antennas will be used to track a low-orbit satellite and relay communications between the low-orbit satellite and the TDRS earth station. The antennas are equipped with dual feeds capable of operating in either band 9 or band 10. An additional 2 m antenna, operating only in band 10, relays data to and from the TDRS satellite and the TDRS earth station. For high data rate applications the TDRS satellites operate as simple frequency translating repeaters. The band designation, "band 10 or band 9" refers to the frequency band in which the TDRS to low-orbit spacecraft communications takes place.

2.1 *Band 9 high data-rate communication*

The TDRS band 9 high data rate communication system (also termed the "S-band" single access or SSA system) will transmit from the geostationary TDRS satellite to the low-orbit spacecraft in the 2025-2110 MHz frequency band. This system has a usable bandwidth of 20 MHz; however, for most applications the relayed signal will be a 6.2 MHz PN coded PSK signal. The maximum usable data rate using the PN coded signal is 1 Mbit/s. The 20 MHz TDRS system bandwidth will allow for high data rate communication using non-PN coded PSK modulation should this capability be required.

The TDRS satellites receive the data, which is to be relayed to the low-orbit spacecraft, from the TDRS earth station, at 14.68 and 14.72 GHz.

The low-orbit spacecraft-to-TDRS communications will take place in the 2200-2290 MHz frequency band. The low-orbit spacecraft will transmit on a 10 MHz wide channel within this frequency range, and will usually use PN coded 6.2 MHz bandwidths. The maximum information data rate with PN coding is about 1 Mbit/s although up to 5 Mbit/s can be relayed by the TDRS system if non-PN coded transmissions are used.

Within the TDRS satellite the two band 9 high data rate channels are up-converted to band 10 for transmission to the TDRS earth station. These space-to-Earth links are implemented at 13.768 and 13.698 GHz respectively.

2.2 *Band 10 high data-rate communication*

The band 10 high data rate communications system (also termed "K-band single access or KSA system") transmits from the TDRS to the low-orbit spacecraft on 13.775 GHz.

While the system is capable of relaying up to 25 Mbit/s of FSK modulated data, the usual transmitted signal will consist of up to 1 Mbit/s of information on a 6.2 MHz PN modulated data stream. The actual maximum information data rate will depend upon the gain and receiver noise temperature of the low-orbit spacecraft. The corresponding Earth-to-TDRS links, for this service, will be implemented at 14.625 and 15.2 GHz.

A single channel is available for receiving high data rate transmissions from low-orbit spacecraft. This channel has a bandwidth of 225 MHz, and is received at the TDRS satellite on a centre frequency of 15.0 GHz. When two low-orbit spacecraft are simultaneously transmitting to the TDRS on this frequency band, one of the transmissions will use left-hand circular polarization and the other right-hand circular polarization. The resulting polarization discrimination, in conjunction with the TDRS antenna discrimination, is sufficient to separate the two signals. The two signals are relayed to the TDRS earth station on 13.53 and 13.93 GHz respectively.

3. Ranging operations in the TDRS system

Information concerning the orbital parameters of scientific spacecraft is of extreme importance to the completion of the spacecraft mission. For this reason two types of ranging operations will take place with the TDRS system. The first type of operation yields information on the overall communication path length between the TDRS earth station and the low-orbit spacecraft. However, since this operation is relayed through the TDRS geostationary satellite, any change in the position of the TDRS satellite itself will affect the measured distance to the low-orbit spacecraft during ranging operations. The second ranging operation (termed bilateration ranging) is designed to supply precise information on location of the TDRS satellites so that movement of the TDRS satellite can be taken into account when determining the position of the low-orbit spacecraft.

Both types of ranging operations are carried out in a similar fashion, and are based upon determining the time a signal takes to go from the TDRS earth station, through the TDRS satellite, to a low-orbit spacecraft transponder and then return to the earth station. The range from the TDRS earth station through the TDRS satellite to the low-orbit spacecraft transponder is of the order of 70 000 km. A signal transmitted by the earth station, transponded and then received by the earth station will take about half a second to make the round trip. By precisely measuring the signal round trip time and accounting for the equipment time delay and other known factors, the range to the low-orbit spacecraft transponder can be determined to an accuracy of several tens of metres. As mentioned above, this ranging system can be used two ways:

– if the transponder is placed at a known position on the surface of the Earth, then the location of the TDRS can be determined (actually several measurements using different locations on the surface of the Earth are required to yield an accurate location of the TDRS satellite);

– if the transponder is on board a low-orbit spacecraft, and if several measurements of range and range rate are made, the orbital motions of the scientific spacecraft can be accurately determined.

This ranging system is implemented in the TDRS system, by modulating a long sequence PN ranging code in quadrature with the standard information bearing PN signal. This ranging code can be used in conjunction with either the low data rate or high data rate system.

The bilateration system, used to determine the position of the TDRS satellite, will operate using the low-data rate band 9 system. The bilateration earth terminals will receive on 2106.4 MHz and transmit on 2287.5 MHz, using a 6.2 MHz and a 5 MHz bandwidth respectively. These terminals will use 23 dB gain antennas and have an e.i.r.p. of 35 dBW.

4. Time transfer

Once the range to a particular TDRS user transponder has been determined, as discussed in § 3, the time a signal takes to go from the TDRS earth station to the transponder is known. With this information it is possible to transmit precise time information for use at the transponder. By using this technique, both scientific spacecraft and selected Earth-based facilities may be supplied with very accurate time information. The details of the actual technique used to transfer time information via the TDRS system have been defined and the system will use the standard low-data rate TDRS link. The time transfer system is compatible with the bilateration earth terminals and the low-orbit spacecraft low-data rate transponders.

5. Simulation and spacecraft testing

Before a spacecraft is launched, all of its operating systems must be fully tested. In order to test the communication systems of spacecraft prior to launch, spacecraft simulation stations located at the launch sites will be connected to a simulator terminal, via a hard-wired connection, and the entire spacecraft, TDRS satellite and TDRS earth station system will be tested.

Two other simulation-terminals will be used to test portions of communications systems. These terminals are located at the US Goddard Space Flight Center and at the TDRS earth station.

6. TDRS command and control links

The TDRS system uses two independent command and telemetry systems, an operational system operating in band 10, and an emergency back-up system which operates in band 9. The operational command and telemetry system utilizes the 18 m antenna at the TDRS ground station and operates with 80.3 dBW of e.i.r.p. The TDRS telemetry is transmitted to the TDRS earth station at 13.731 GHz, and the commands are transmitted from the earth station at 14.786 GHz.

The emergency command and telemetry system is designed to operate automatically if a TDRS satellite loses attitude control. The telemetry system, transmitting via an omnidirectional antenna on the TDRS, operates on 2210 MHz. The corresponding emergency command system operates on 2036 MHz.

In addition, a highly stable 15.15 GHz "pilot tone" is transmitted from the TDRS ground station to the TDRS satellites. This tone is used on board the satellite as a frequency reference to ensure that the various frequency translation operations are carried out in a precise manner.

ANNEX III

A DESCRIPTION OF THE TRACKING AND DATA ACQUISITION SYSTEM (TDAS)

1. Introduction

Conceptual studies are currently under way in the United States of America to define a follow-on system to the tracking and data relay satellite (TDRS) system. The system is referred to as the tracking and data acquisition system (TDAS). The TDRS provides the means by which scientific research data from earth satellites will be relayed from the spacecraft to Earth. The TDAS will provide similar service in the post-2000 era and incorporate a number of technical improvements to satisfy more effectively future requirements such as higher data rates. The following sections discuss the current conceptual design of the TDAS using the TDRSS as a baseline reference point. An important aspect of the TDAS design concept is to maintain the capability of operating with user spacecraft that currently interface with the TDRS system.

2. System characteristics

The TDAS, like the TDRS system on which it is based, involves several communications links in its design. These include the ground-to-TDAS links, links to user spacecraft from TDAS geostationary satellites, referred to as forward links, and return links from the user spacecraft to the TDAS satellites. In addition, two types of service are offered: single access and multiple access. The single access service utilizes a single access antenna on the TDAS satellites which, over a given time-frame, is dedicated to one user using a high data rate. The multiple-access service involves a separate phased array antenna on the TDAS satellites which serves up to 20 low data rate users simultaneously.

Table I summarizes the TDAS goals and possible technical means of achieving them. These are discussed further in the following sections.

TABLE I – *TDAS goals and corresponding system improvements* *

Goals	Possible implementation
Improve multiple access service over current TDRS design	3 dB improvement on return link (user spacecraft-to-TDAS) Two multiple-access forward links (TDAS-to-user)
Provide increased number of high data rate accesses	60 GHz single-access channels utilizing 3 to 5 parabolic antennas
Allow users to receive mission data and control experiments at 5 locations in the United States of America	Multi-beam space-to-Earth link and on-board switch
Provide increased visibility and reduce number of ground antennas	60 GHz or laser inter-satellite cross-links between TDAS
Provide ultra-high data rate accesses (> 300 Mbit/s)	Laser single-access channels between TDAS and user spacecraft
Provide user TTC data directly to mission centres	On-board multiple access beam forming

* These improvements are relative to the existing TDRS system.

2.1 *Multiple access*

It has been recognized in the preliminary design of the TDAS satellites that an increase in the receive gain (by 3 dB) on the return link (the multiple-access user spacecraft to the TDAS satellites) would permit use of the relay service with lower powered user spacecraft. Alternatively, the higher receive gain associated with the TDAS multiple-access link would be beneficial in accommodating higher data rates. This increased gain can be achieved via a 60 element phased array (in contrast to the current TDRS 30 element array). Additionally, consideration is being given to on-board beam-forming for the TDAS as opposed to the TDRS ground-based approach. Another proposed change over the TDRS design is the capability of addressing two user spacecraft simultaneously in the forward link (TDAS satellite-to-user spacecraft) as compared to one such link on TDRS.

2.2 *High data rate access*

A new system characteristic involving single-access service operated at 60 GHz, may be implemented to accommodate the expected increase in the number of high data rate users. An array of between 3 and 5 parabolic antennas is suggested for up to 5 independent return links at 50-300 Mbit/s each. The five discrete antennas would each be capable of tracking low orbit user spacecraft. It would be essential that the TDAS satellite attitude control accuracy be sufficient to allow precise pointing and tracking. In order to achieve the necessary accuracy, the antennas must be symmetrically placed on the TDAS satellites and gimballed. Closed loop tracking would also be required.

2.3 *Multiple earth-station facility*

A significant proposed change to the TDRS system would be a multi-beam down link facility provided by a parabolic antenna with multiple feeds. This system would allow electrically steerable spot beams to deliver user data to any number of desired earth-station locations. The design of the on-board switch necessary to interconnect the various links is currently under consideration and will be largely determined by the other TDAS design options selected.

2.4 *System configuration via inter-satellite laser links*

The initial design concept includes the potential use of laser cross-links between TDAS spacecraft. This would result in a gain in flexibility with regard to their placement and can result in a more nearly optimum visibility coverage of user spacecraft. With the inter-satellite link, only one of the two or three TDAS satellites is required to be within view of the United States of America. The main disadvantage of such a system arrangement is that the down link data rate would be the limiting factor in the total system capacity. Of the laser systems being considered for a TDAS inter-satellite link, the prime candidate is Gallium Arsenide (GaAs).

2.5 *Provision for ultra-high data rate users*

A laser system has been proposed to provide a single-access service between a TDAS satellite and a user spacecraft operating at ultra-high data rates. The advantages are in large bandwidths accommodating high data rates, and narrow beamwidth implying high gain.

3. Preferred frequency bands

The technically preferred frequency bands for the TDAS will be primarily determined by the amount of data which must be transferred between the user spacecraft and Earth through TDAS. The high anticipated data rate requirements are based upon the expected development of future sophisticated sensors imaging the Earth at very high resolution, using multiple frequency bands and with high dynamic range.

In addition to requiring wideband communication, the TDAS choice of preferred frequency bands will be strongly affected by the effects of weather on the space-to-Earth links and by technology and pointing requirements for space-to-space links.

3.1 *Earth-to-space links*

From a technical standpoint, preferred frequency bands for TDAS Earth-to-space links would be below 10 GHz. However, no allocation exists with sufficient bandwidth to support the large anticipated data transfer requirements of TDAS and it appears that this region of spectrum will be heavily used over the next 20 years. Consequently, investigations were made as to the applicability of frequencies in the 10-30 GHz range and 30-300 GHz range, and perhaps laser frequencies to the support of TDAS Earth-to-space links.

The adverse effect of the troposphere on link performance is experienced to varying degrees in the use of all three of the above spectral regions. The effects include gaseous absorption, and rain and cloud cover attenuation, particularly in optical frequency ranges. In addition, all three spectral regions were studied in terms of technology requirements to support these links, i.e. receiver, transmitter and tracking and antenna pointing capabilities. The last requirement is particularly critical in the case of laser communication where antenna beamwidths of the order of 1 arc second will be required.

Preliminary results from the initial conceptual studies indicate that, in view of the attenuation aspects associated with laser frequencies and apparent technology availability in the TDAS time-frame, preferred frequencies for the Earth-to-space links are near 14 GHz, allowing compatibility with the existing TDRS system, and with the fixed-satellite bands near 20 and 30 GHz. This spectral region offers 1 GHz bandwidth with a primary status for all TDAS Earth-to-space services and freedom from aeronautical-mobile users. The fixed-satellite bands at 90/80 GHz present an alternative to the 30/20 GHz bands but require much larger margins ($\gg$ 10 dB additional margin for typical ground sites) to achieve equivalent link performance in the presence of rain.

3.2 *Space-to-space links*

The TDAS will require space-to-space links between user spacecraft and a TDAS geostationary satellite and also space-to-space links between TDAS satellites themselves.

Since the adverse effects of the atmosphere do not constrain the preferred frequency bands for these links, there is more freedom in their selection. The critical factors include satellite platform stability and pointing accuracy, antenna size limitations, prime power generation capabilities, TDAS switching networks and multi-beam forming capability to service several scientific satellites simultaneously.

The potential space-to-space links under consideration in the preliminary conceptual design could operate in the frequency ranges as indicated in Table II.

TABLE II

Link	Frequencies
Multiple-access forward link	Upper portion of band 9
Single-access forward link	Near 14 GHz Near 60 GHz Laser frequencies
Multiple-access return link	Upper portion of band 9
Single-access return link	Upper portion of band 9 Near 15 GHz Near 60 GHz Laser frequencies
Inter-satellite link (between TDAS satellites)	Laser frequencies (Near 60 GHz)

Frequencies near 60 GHz and laser frequencies were selected because the high atmospheric attenuation and tropospheric scattering effects at those frequencies protect radio operations on the ground from interference by the space-to-space links. Also, the 60 GHz centre frequency supports large single-channel bandwidths desired by certain Earth observation spacecraft, and required for TDAS cross-links. Furthermore, technology developments to support links at these frequencies currently appear very feasible.

4. Conclusions

A follow-on system to the current tracking and data relay satellite (TDRS) system is being considered in the United States of America and is referred to as the tracking and data acquisition system (TDAS). The broad purpose of the TDAS is to maintain continuity of service to user spacecraft which operate with the current TDRS system while providing a series of potential improvements. Improving the current multiple-access service by an on-board beam forming capability, increasing the number of forward links (TDAS-to-user) to two and a 3 dB improvement of antenna gain on the return link is being considered. To provide an increased number of high data rate accesses, a 60 GHz single access link is suggested involving five 50 cm parabolic antennas. Other potential improvements over the current system include a multi-beam capability on the space-to-Earth link with on-board switching to provide additional flexibility in the system configuration and the potential use of laser links both for between TDAS satellites and between TDAS satellite and user spacecraft to accommodate ultra-high data rate accesses.

Preferred frequencies for the TDAS services include the current TDRS frequencies (near 2 GHz for multiple access, near 2 and near 14 GHz for single access, near 14 GHz for Earth-to-space link), in addition to laser frequencies for use between TDAS spacecraft and between TDAS and user spacecraft, frequencies near 60 GHz for TDAS user links and frequencies near 20 and 30 GHz for Earth-to-space links. These were selected based on such considerations as continuity of the current service, higher data rates in the future and technology availability.

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REPORT 982

DATA RELAY SATELLITES FOR THE EARTH EXPLORATION SATELLITE SERVICE

(Question 11/2)

(1986)

1. Introduction

Future operational Earth exploration satellites (EES) will require data handling systems capable of supporting the combined data rates of multiple high resolution imaging sensors. The attendant data rates from these low-orbit EES satellites will be as high as 600 Mbit/s and will require large bandwidths which are only available at frequencies above 10 GHz. However, pfd and technology constraints above 10 GHz severely limit the usefulness of direct transmission from an EES to an earth station. Due to these constraints and the requirements for world-wide coverage, a synchronous relay satellite will be necessary. The relay satellite will be designed to relay simultaneously 600 Mbit/s data links from two low orbit EES to a single earth station. Each data link will require an 800 MHz transmission bandwidth, for a total bandwidth requirement with guard bands of 1800 MHz.

This Report describes the preferred frequency bands and sharing aspects of a relay satellite capable of simultaneously supporting two future wideband EES satellites and also discusses the technical characteristics of one possible implementation of an operational EES relay satellite.

The telecommunication system required to transfer these large quantities of data can be implemented by the use of two wideband data links and a narrowband command link as shown in Fig. 1. The links required are:

- A space-to-Earth link from the relay satellite to an earth station in the vicinity of a large data processing facility. This segment will resemble a fixed-satellite service down link.
- A space-to-space data link from the low-orbit EES to a geostationary relay satellite. This link may be implemented anywhere in the spectrum where sharing problems are not encountered and where near-future technology can provide a workable system. The region of 25 to 30 GHz appears to be a good choice for this link from both a sharing and technology standpoint.
- In addition, a command relay channel though the relay satellite is required to control the EES. If the command links (earth station-relay satellite and relay satellite-EES) are close enough in frequency to the EES wideband data links, the space-space portion can utilize the high gain pointable antennas required on board the EES and relay satellite spacecraft for data transmission.

2. Relay satellite to Earth data link

Due to the similarity of the relay satellite-to-Earth wideband data link to a fixed-satellite service system, this link might be implemented in the 15 to 20 GHz portion of the spectrum where the required bandwidth of 1800 MHz is available. Table I shows a typical link calculation for a relay satellite earth station down link that yields an overall carrier-to-noise plus interference ratio of 13 dB and a bit-error probability of 10^{-6}.

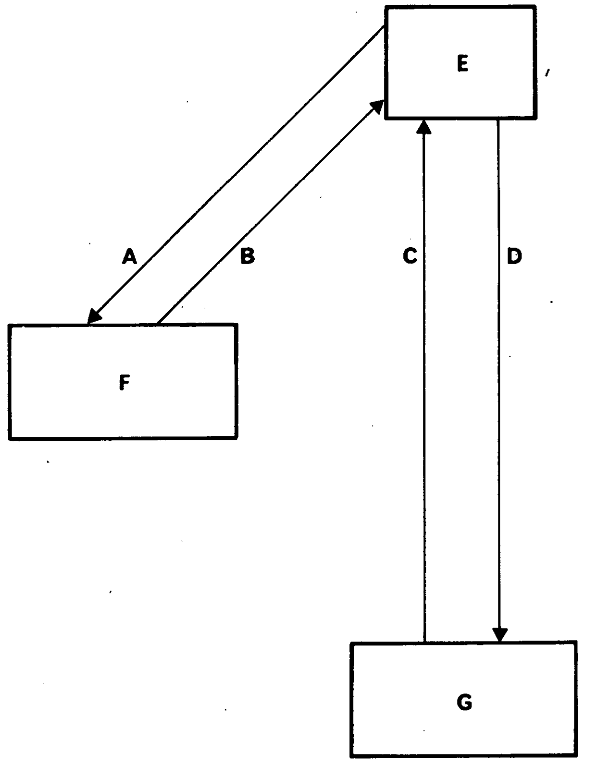

FIGURE 1 – *Operational EES relay satellite data transfer system*

A: Relay satellite to EES telecommand link
B: EES to relay satellite link
C: Earth to relay satellite telecommand link
D: Relay satellite to Earth data link
E: Data relay satellite
F: Earth exploration satellite (EES)
G: Large central data processing facility

TABLE I – *Relay satellite to earth station typical link parameters (near 19 GHz, 800 MHz bandwidth)*

Relay satellite transmit power (dBW)	12.3
Relay satellite transmit gain (dBi) (antenna diameter: 3 m)	52.5
e.i.r.p. (dBW)	64.8
Allowance for spreading loss (40 600 km, 10° elevation) (dB)	–163.2
Bandwidth conversion (MHz/800 MHz) (dB)	–29.0
Atmospheric absorption (dB)	–1.2
Precipitation attenuation (dB)	–5.5
Cloud loss (dB)	–4.0
Miscellaneous losses (dB)	–1.0
Receiver antenna effective area S (12.2 m diameter at 19 GHz) (10 log S)	+18.9
Bandwidth conversion (Hz/MHz) (dB)	–60.0
Received power spectral density (dB(W/Hz))	–180.2
Receiver system noise spectral density (T = 400 K) (dB(W/Hz))	–200.6
C/N down path (dB)	20.4
Margin (dB)	3.0
Required C/N down path (dB)	17.4

3. EES to relay satellite data link

A choice of EES-to-relay satellite up-link parameters will be determined by the available power, the allowable antenna sizes and the pointing capabilities of both the EES and the relay satellite spacecraft.

The relationship between transmitter power, antenna size, and carrier frequency was evaluated to determine the minimum power EES configuration. This analysis assumed a data rate of 600 Mbit/s, a C/N ratio of 14.9 dB and a maximum range from the geostationary orbit to a 5000 km spacecraft of 51 000 km. The following pointing accuracies and minimum beamwidths were assumed:

- EES pointing accuracy = 0.1°
- minimum beamwidth = 0.5°
- relay satellite pointing accuracy = 0.05°
- minimum beamwidth = 0.125°

The analysis determined that an EES having a 100 W transmitter and a 1.5 m antenna would be compatible with the above accuracies if the EES-to-relay satellite link were implemented in the 25 to 29 GHz spectral region. There are several existing frequency bands in this spectral region which are wide enough to support the simultaneous up-link operations from two 600 Mbit/s systems (1800 MHz required bandwidth).

Table II presents the link parameters for an EES-to-relay satellite system operating in the vicinity of 27 GHz. The actual implementation of a system such as this, is dependent upon the technical feasibility of constructing the satellites. The EES must carry a 100 W transponder operating near 27 GHz with a 1.5 m antenna, pointable to 0.1°. The relay satellite will require a 3.0 m antenna, pointable to 0.05°. These characteristics are within the range of technological advances in the foreseeable future.

TABLE II – *EES-to-relay satellite (space-to-space) link parameters*

EES transmit power (dBW)	20.5
EES antenna gain (1.5 m at 27 GHz; beamwidth 0.5°) (dBi)	50.0
Line losses (dB)	–1.0
EES e.i.r.p. (dBW)	69.5
Free space loss (51 000 km at 27 GHz) (dB)	–215.2
Relay satellite antenna gain (3.0 m at 27 GHz; beamwidth 0.26°) (dBi)	56.0
Line losses (dB)	–1.0
DRS received power (dBW)	–90.7
Bandwidth conversion (800 Mbit/s) (dB)	–89.0
Relay satellite received power density (dB(W/Hz))	–179.7
Relay satellite receiver noise density (T = 2500 K) (dB(W/Hz))	–194.6
Received C/N (dB)	14.9

4. Command links

The EES system requires two command links – one from the earth station to the relay satellite and one from the relay satellite to the EES. The required command link data rates and beamwidths are considerably less than that for the high data rate links. The command bandwidth will be of the order of 50 MHz. However, if the command link frequency bands are sufficiently close to the data frequencies, a weight and size reduction can be achieved by using the same antennas for both the relay satellite-EES command link and the EES-relay satellite data link. This consideration underlies the choice of 27.5 to 30 GHz for the command channel, provided the wide band data channel is at 25.25 to 27.5 GHz.

The technical characteristics chosen for the command links are shown in Table III.

TABLE III – *EES command (Earth-to-space and space-to-space) link parameters*

27.5 to 30.0 GHz Earth relay satellite link	
Earth station transmitter power density (dB(W/Hz))	−29.7
Earth station transmitter antenna gain (dBi)	+65
Earth station transmitter e.i.r.p. density (dB(W/Hz))	+21.3
Relay satellite receiver antenna gain (1 m, 28 GHz) (dBi)	55.5
Relay satellite receiver noise temperature (K)	2500
27.5 to 30.0 GHz relay satellite EES link	
Relay satellite transmitter power density (dB(W/Hz))	−64.5
Relay satellite transmitter antenna gain (dBi)	+55.5
Relay satellite transmitter e.i.r.p. density (dB(W/Hz))	−10
EES receiver antenna gain (dBi)	+50
EES receiver noise temperature (K)	2500

5. Sharing analysis

This section analyses sharing for the preferred frequency bands discussed in previous sections of this Report.

5.1 *Relay satellite to Earth data link*

There are two principal elements of the sharing analysis:

- ensuring that the relay satellite meets the existing pfd requirements in the band;
- determining the required angular separation between the relay satellite and a "typical" fixed satellite space station to protect the FSS earth station from interference.

Table IV gives the pfd calculation for the relay satellite-to-Earth data link and indicates that the pfd is 13.4 dB below the existing pfd limit for this band.

To determine the angular separations required between the relay satellite and the fixed satellite, a maximum single entry interference-to-carrier ratio of −35 dB is assumed to protect the fixed satellite system and −30 dB to protect the relay satellite system.

For the fixed-satellite systems described in Report 561, Table I, the carrier pfd on the Earth's surface will be of the order of -125.9 dB(W/(m^2 · MHz)). This value is 3.0 dB above the relay satellite pfd; however, the interference criteria for the EES relay satellite is 5 dB less than for the fixed satellite. Consequently, the separation angle required is about the same for the protection of each system. The required separation angle is approximately 2°, and applies only for co-located earth stations.

TABLE IV – *Calculation of pfd near 20 GHz*

Relay satellite e.i.r.p. (dBW)	64.8
Bandwidth conversion (MHz/800 MHz) (dB)	–29.0
Relay satellite transmit power density (dB(W/MHz))	35.8
Allowance for spreading loss (40 600 km, 10° elevation) (dB)	–163.2
Spectral power flux-density (dB(W/(m^2 · MHz)))	–128.4
Allowable pfd limit (Earth's limb) (dB(W/(m^2 · MHz)))	–115.0
Margin (dB)	–13.4

5.2 *EES to relay satellite data link*

The 25.25 to 27.5 GHz frequency band is allocated to the fixed and mobile services. The closest band, for which a pfd limit has been adopted, is 17.7 to 19.7 GHz band, with a limit of -115 dB(W/(m^2 · MHz)) at the Earth's limb edge, escalating to -105 dB(W/(m^2 · MHz)) at the spacecraft nadir.

The EES system transmits to the relay satellite with an e.i.r.p. of 69.5 dBW, comprised of 50.0 dBi antenna gain, a 20.5 dBW transmit power, and a 1 dB line loss. The emission bandwidth will be 800 MHz. The maximum resultant pfd at the Earth's surface would occur should the EES-to-relay satellite line-of-sight graze the Earth's limb. The slant range for a 1000 km altitude orbit to the limb is approximately 3700 km, yielding a maximum pfd of -97.7 dB(W/(m^2 · MHz)). In order to protect the fixed and mobile services, 17.3 dB of discrimination must be provided by the EES. This discrimination is best accomplished by constraining the EES antenna to point no closer to the Earth's limb than 0.9° (assuming a 50.0 dB antenna gain and a discrimination pattern of $32 - 25 \log \varphi$ (off-axis angle)). This does not impose any operational constraints on an EES system.

In addition to the allocation for the Earth exploration-satellite service (space-to-space) the WARC-79 added up links for the standard frequency and time signal-satellite service in the 25.25 to 27.5 GHz band. Sharing between these two services will be a function of satellite separation angle between the data relay satellite and the standard time and frequency satellite and can be accommodated via coordination according to the Appendix 29 procedure.

The fixed-satellite service has an allocation in a portion of the 25.25 to 27.5 GHz band, specifically 27.0 to 27.5 GHz. Sharing with this service also can be handled according to Appendix 29 procedures.

5.3 *EES earth station – relay satellite link sharing with fixed-satellite service*

The earth station transmission parameters for the relay satellite command link are given in Table III. The transmitted power density is approximately equal to that expected from a fixed service earth station. Assuming that both the relay satellite earth station and the fixed-satellite earth station were in the main beam of a fixed satellite, then a satellite separation of less than 2° is required to protect the fixed satellite with a single entry C/I of 35 dB.

Conversely, taking the relay satellite command link interference criteria as a C/I of 30 dB, the satellite separation must also be of the order of 2° to protect the relay satellite, again assuming that both earth stations are within the relay satellite main beam. The 3 dB beamwidth of the relay satellite antenna is approximately 0.25°, implying that both earth stations must be located within about 125 km of each other for this situation to occur.

5.4 *EES earth station – relay satellite link sharing with fixed and mobile systems*

Sharing between the relay satellite earth station and the fixed and mobile services can be implemented via the procedures of Appendix 28 of the Radio Regulations. Since the transmit power density of the relay satellite earth station is the same as the expected transmit power density of the fixed-satellite service, the resulting coordination contours for the EES relay satellite system should be equal to those of the fixed satellite system.

5.5 *Relay satellite-EES link sharing with fixed and mobile services*

There are currently no power flux-density limits in the 28 GHz region for protection of the fixed and mobile services. If it is assumed that the pfd required to protect the fixed and mobile services can be extrapolated from the limits at 18 GHz, a resulting pfd limit of -111 dB(W/(m$^2 \cdot$ MHz)) at low elevation angles is obtained. The following calculation (Table V) presents the anticipated pfd produced on the Earth from relay satellite emissions arriving at low elevation angles:

TABLE V – *Calculation of pfd near 28 GHz*

Relay satellite transmitter power (dB(W/Hz))	-64.5
Relay satellite antenna gain (dBi)	55.5
Feed loss (dB)	-1
e.i.r.p. (dB(W/Hz))	-10.0
Allowance for spreading loss (to Earth's limb at 41 730 km) (dB)	-163.4
Spectral power flux-density (dB(W/(m$^2 \cdot$ Hz)))	-173.4
or (dB(W/(m$^2 \cdot$ MHz)))	-113.4

This level of pfd is 2 dB below that expected to be required for protection of the fixed and mobile services. Consequently, sharing with the fixed and mobile services is considered feasible.

5.6 *Relay satellite-EES link sharing with fixed-satellite service*

The possibility exists that the relay satellite command link transmissions could enter the receiver of a fixed-satellite service space station. This interference mode can occur only when the line connecting the relay satellite and EES spacecraft is near the Earth's limb and simultaneously near the equator. The magnitude of the power density which will be received by FSS receiver, at any given time, is a function of the instantaneous antenna coupling of the FSS and the relay satellite systems.

Using the relay satellite transmit parameters developed previously, the maximum pfd which can be transmitted across the geostationary-satellite orbit is -179.6 dB(W/(m$^2 \cdot$ Hz)).

Assuming a minimum usable fixed-satellite earth-station elevation angle of 20°, a carrier-to-interference criterion of 35 dB and fixed-satellite receiver noise temperature of 2500 K, results in an interference threshold of -214.6 dB(W/Hz). Therefore, the relay satellite must provide 25 dB antenna pattern discrimination to protect the fixed satellite.

Using the antenna pattern of Report 810 the required 25 dB discrimination is obtained at 1.44 times the relay satellite antenna 3 dB beamwidth or approximately 0.4° from its main beam.

Therefore, in order to provide protection to the fixed-satellite service the relay satellite should be constrained from transmitting whenever the relay satellite-EES line-of-sight is within 0.4° of the geostationary orbit. This corresponds to locations of the EES satellite within 3° latitude of the equator and near the Earth's limb as seen from the relay satellite. This would create two small areas of potential interference of short duration. This can be handled via operational procedures for the EES command system.

On the other hand, the possibility exists that the fixed-satellite earth-station transmissions could enter the command and control receiver on the EES low-orbit satellite. Three potential interfering geometries exist and are illustrated in Fig. 2. Calculations for each case are presented in Table VI and are based on the following system parameters:

– *Fixed-satellite earth station*

Transmit power density	–30 dB(W/Hz)
Gain	60 dBi

– *EES low-orbiting satellite*

Gain	50 dBi
Receiver noise temperature	2500 K
C/N ratio	20 dB
C/I ratio	30 dB.

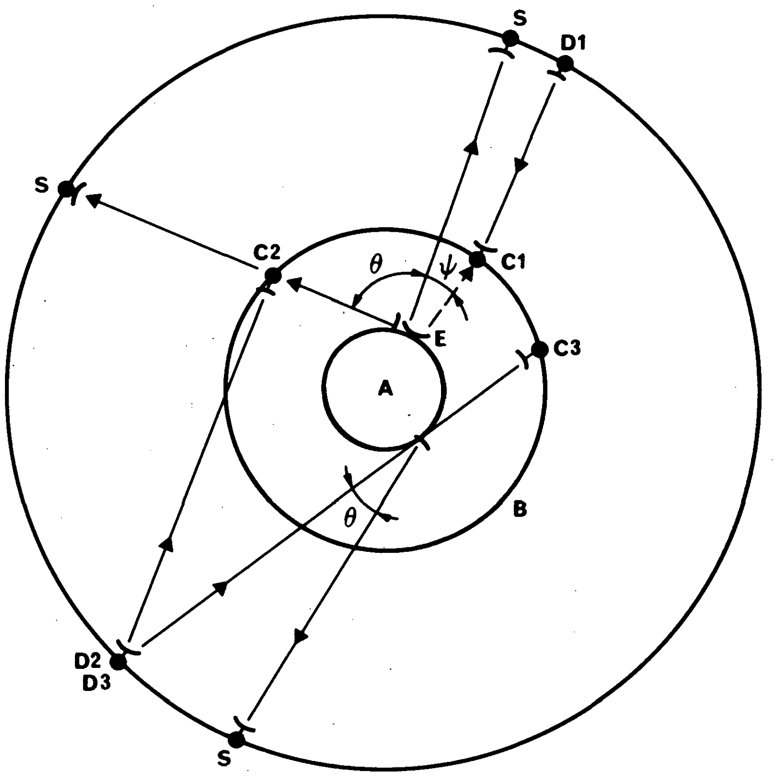

FIGURE 2 – *Interference possibilities into an Earth exploration satellite from an earth station in the fixed-satellite service*

A:	Earth
B:	Earth exploration-satellite orbit
C1, C2 and C3:	Earth exploration satellite (cases 1, 2 and 3)
D1, D2 and D3:	data relay satellite
E:	earth station of fixed-satellite service
S:	space station of fixed-satellite service
θ:	elevation angle
ψ:	off beam angle

Note. – Orbits are not necessarily co-planar. Geometry is shown in 2 dimensions in order to simplify the diagram.

TABLE VI – *Calculation of interference from earth station into EES*

	Case 1	Case 2	Case 3
FSS (1) transmit power (dB (W/Hz))	–30	–30	–30
Gain towards EES (dBi)	60	60	0
Path loss (dB)	–180.4	–192	–192
EES receiver gain towards FSS earth station (dBi)	–10	–10	50
Received interference power density (dB(W/Hz))	–160	–172	–172
Receiver noise power density (dB(W/Hz))	–195	–195	–195
Minimum required *C/N* (dB)	20	20	20
Required *C/I* (dB)	30	30	30
Resulting *C/I* (dB)	–15	–3	–3
Required isolation (dB)	45	33	33
Angle off FSS earth station main beam	± 4.78°	± 1.585°	–
Angle off FSS space station main beam	–	–	4°
FSS elevation angle	–	–	20°
Percentage of time of interference (%)	0.174	0.019	–

(1) FSS : fixed-satellite service.

For cases 1 and 2, interference exists for a small percentage of time. Such interference can be handled, and avoided by operational procedures of the EES command system.

For case 3, the EES command antenna must avoid pointing within 4° of the Earth's horizon as seen from the satellite. This does not constrain the EES service. When the fixed-satellite elevation angles are less than 20°, the EES command antenna would have to point further off the Earth's horizon. These low elevation angle stations would experience greater coordination difficulty.

6. Conclusions

The preferred frequency bands for a relay satellite supporting future wideband Earth exploration satellites have been described. Technical characteristics of one possible implementation of an operational EES relay satellite have been presented.

The preferred frequency bands and constraints which would permit sharing with other services are presented in Table VII. None of the required constraints would materially affect the operational capabilities of an EES system.

TABLE VII – *Preferred frequency bands and constraints for sharing with other services*

Frequency band (GHz)	EES link	Shared service	Sharing constraint
15 to 20 (data link)	Relay satellite-to-earth station	Fixed/Mobile	Existing pfd limits
		Fixed satellite	Standard FSS (1) spacing
25 to 29 (data link)	EES-to-relay satellite	Fixed/Mobile	Pfd limits
25 to 30 (command link)	Earth station-to relay satellite	Standard frequency and time signal-satellite	Appendix 29 to the Radio Regulations
		Fixed satellite	Appendix 29 to the Radio Regulations
		Fixed/Mobile	Appendix 28 to the Radio Regulations
		Fixed satellite	Antipodal transmission constraint (see text)
	Relay satellite-to-EES		May have to restrict command operations over certain limited areas (see text)
		Fixed/Mobile	Appropriate pfd limits

(1) FSS : fixed-satellite service.

REPORT 983

THE MINIMUM LONGITUDE SEPARATION ANGLE NECESSARY TO SHARE FREQUENCIES BETWEEN TWO DATA RELAY SATELLITES

(Question 11/2)

(1986)

1. Introduction

Since the radiply growing space activities require a larger number of data relay satellite (DRS) systems, it seems probable, in the future, that several such systems will be developed separately.

The complexity of a DRS system having multiple space-to-Earth, Earth-to-space amd space-to-space links (see Report 848) makes the problem of developing a generalized DRS-to-DRS sharing model difficult. This Report is an initial attempt to quantify the minimum geostationary longitude separation angle necessary for two DRS systems so that they can share the same frequencies.

A DRS system, as discussed in this Report, consists of a DRS placed in geostationary orbit, one or more user satellites and earth stations. Each earth station has access to each user satellite via the DRS.

The link between an earth station and a DRS is not addressed in this Report. Frequency sharing between a DRS system and other space research systems is discussed in Report 846.

The relationship between a DRS and user satellites is similar to a base station and mobile stations. It is essential that parameters which describe the orbits of the user satellites and the probability of interference be taken into consideration in developing a detailed DRS-to-DRS frequency sharing model which would also include all of the factors providing DRS system-to-system isolation. Some of these factors are inter-system frequency discrimination, modulation/code discrimination, polarization discrimination and antenna side-lobe discrimination. This Report examines only the effect of antenna discrimination to derive an approximate expression for the proportion (P) of service area of a DRS system, over which interference from a second DRS system could be greater than a given threshold.

This expression is a function of the longitudinal separation angle between two DRSs, for given values of DRS and user satellite antenna diameters and for a given value of wanted-to-unwanted signal powers (W/U) at the victim receiver.

2. Development of sharing model

Sections 2.1 to 2.3 discuss the assumptions and approximations used in developing the DRS-to-DRS sharing model. Sections 2.4 and 2.5 develop the sharing expression and necesary definitions of terms used in the sharing expression for the forward (i.e. DSR-to-user satellite) and return (user satellite-to-DRS) links, respectively.

2.1 *Basic assumptions*

The approach used in this Report assumes that the two DRS systems are similar in terms of the DRS antenna diameters, the user satellite antenna diameters and both DRS and user satellite e.i.r.p.s. Additionally it is assumed that the DRS satellites utilize directional antennas. The user satellites may use either directional or omnidirectional antennas. It is further assumed that the user satellite altitudes are much less than that of the geostationary orbit.

2.2 *Antenna radiation patterns*

Directional antennas are used for data relay satellites and for some user satellites. Considering that the radiation pattern of the main lobe and the first side lobe are more important for orbit utilization, the radiation patterns of DRS system satellite directional antennas are defined as the following:

$$G_m - G(\varphi) = 2.5 \times 10^{-3} \left(\frac{D}{\lambda}\varphi\right)^2 \quad \text{dB} \qquad \text{for } 0 \leqslant \varphi \leqslant \frac{89.4\,\lambda}{D}$$

$$G_m - G(\varphi) = 20 \quad \text{dB} \qquad \text{for } \frac{89.4\,\lambda}{D} < \varphi$$

where:

G_m : maximum gain in the main lobe (dBi),

φ : the angle between the axis of the main beam and the direction in question,

$G(\varphi)$: gain at φ degrees,

D : diameter of antenna,

λ : wave length.

The patterns derived from these equations correspond to curves A and B in Fig. 13 of Report 558 (Geneva, 1982). The equations were derived by using the approximation that half of the 3 dB beamwidth of a parabolic antenna can be expressed as $\lambda/D\sqrt{1200}$. For the case of an omnidirectional user satellite antenna, the gain is assumed to be 0 dBi.

2.3 *Ratio of DRS service area to interference area*

As seen from a geostationary DRS, the orbital sphere of a user satellite may appear as a ring (see Fig. 1). The angular width of the highest altitude user satellite is termed, in this Report, the DRS service area, and is assumed to be 2Ω degrees wide. The angular area of this service area will be proportional to $(2\Omega)^2$.

Given that a second DRS system is operating co-frequency with the wanted DRS system, whenever the wanted user satellite and unwanted user satellite approach within some angular distance (ω), the W/U ratio of the wanted system will decrease below some threshold value. If N user satellites are operating within the unwanted DRS system, there will be N independent interference regions within the wanted DRS service area. The sum of the angular area of all of these interference regions will be proportional to $N\omega^2$.

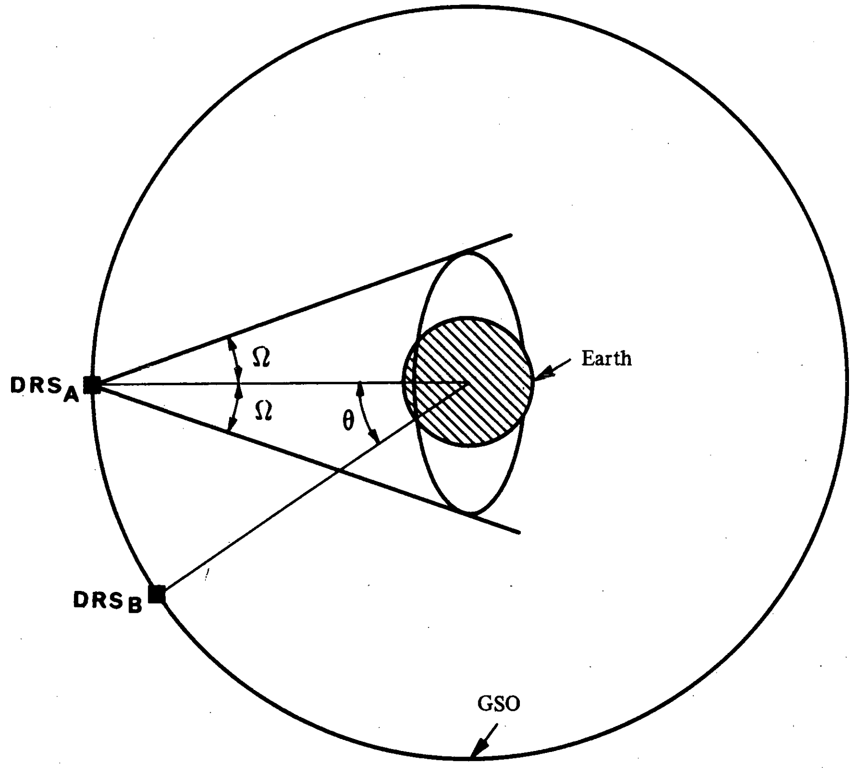

FIGURE 1 – *DRS service area geometry*

θ: longitudinal orbital separation
Ω: conical half angle of service area for the wanted DRS satellite
DRS_A: wanted DRS
DRS_B: unwanted DRS

Assuming that both the wanted and unwanted user satellites may be anywhere within the DRS service area with equal probability, the risk of inter-system interference will be proportional to the ratio of angular areas, or

$$P = \left(\frac{\omega}{\Omega}\right)^2 N \tag{1}$$

In an actual DRS system, the user satellite will not reside at all points in the service area with equal probability. The relationship between the user satellite position for an actual DRS system and the assumption made in this section should be the subject of further study.

2.4 *Forward link*

Because both the wanted and unwanted DRS satellites are assumed to have identical e.i.r.p.s, the W/U ratio measured at the wanted user satellite will be:

$$W/U = \Gamma + \gamma \qquad \text{dB} \tag{2}$$

where:

Γ: off-axis attenuation of the unwanted DRS satellite in the direction of the wanted user satellite (dB),

γ: off-axis attenuation of the wanted user satellite in the direction of the unwanted DRS (dB).

The off-axis attenuation, γ, is defined by the diameter of the user antenna (D_2), frequency and parallax angle α in Fig. 2a. Even if α varies according to its orbit, the minimum value of α is always greater than $\theta/2$ as long as the altitude of the user satellite does not exceed that of the geostationary-satellite orbit, where θ is the longitude separation angle between both data relay satellites. Therefore, the value of γ corresponding to $\theta/2$ is used in this calculation.

The W/U at each satellite receiver is defined as the following:

$$W/U = 2.5 \times 10^{-3} \left(\frac{D_1}{\lambda}\,\omega\right)^2 + 2.5 \times 10^{-3} \left(\frac{D_2}{\lambda}\cdot\frac{\theta}{2}\right)^2 \tag{3}$$

where:

D_1 : diameter of the unwanted data relay satellite antenna,

D_2 : diameter of the wanted user satellite antenna,

λ : wavelength.

The value of ω^2 corresponding to the necessary W/U is derived from equation (3).

$$\omega^2 = \left[\frac{\lambda^2\,[W/U]}{2.5 \times 10^{-3}} - D_2^2\left(\frac{\theta}{2}\right)^2\right]\frac{1}{D_1^2} \tag{4}$$

where:

$[W/U]$: necessary W/U $\qquad [W/U] \leqslant 20$ dB

The approximate proportion P that W/U is less than the necessary W/U is derived from equations (1) and (4).

$$P = \frac{N\omega^2}{\Omega^2} = \frac{N}{\Omega^2\,D_1^2}\left(\frac{\lambda^2\,[W/U]}{2.5 \times 10^{-3}} - \frac{D_2^2\,\theta^2}{4}\right) \tag{5}$$

where:

N: for the forward link case, is equal to the maximum number of unwanted user satellites that can be commanded simultaneously.

2.5 *Return link*

In the return link case, it is assumed that both the wanted and unwanted user satellites have identical e.i.r.p.s. The inter-system discrimination will then be a function of the wanted DRS satellite antenna and the unwanted user satellite antenna (see Fig. 2b). The equations for the return link analysis have the same form as those for the forward link. The symbols, however, have a different meaning as follows:

Γ : off-axis attenuation of the wanted DRS satellite in the direction of the unwanted user satellite;

γ : off-axis attenuation of the unwanted user satellite in the direction of the wanted DRS;

D_1 : diameter of the wanted DRS satellite antenna;

D_2 : diameter of the unwanted user satellite antenna;

N: number of unwanted user satellites that may transmit simultaneously.

3. Example calculation

With the assumption of identical antennas on both the wanted and unwanted DRS systems, the major difference between the expressions developed for the forward and return links is the value of N. Choosing the parameters shown below as examples, Fig. 3 presents the results of applying equation (5) to both the forward and return links of DRS system.

Ω = 20° (8050 km orbital altitude)

λ = 0.15 m (2.0 GHz)

D_1 = 10 m

D_2 = 1 m

$[W/U]$ = 14 dB

N = 3 for the forward link

N = 20 for the return link

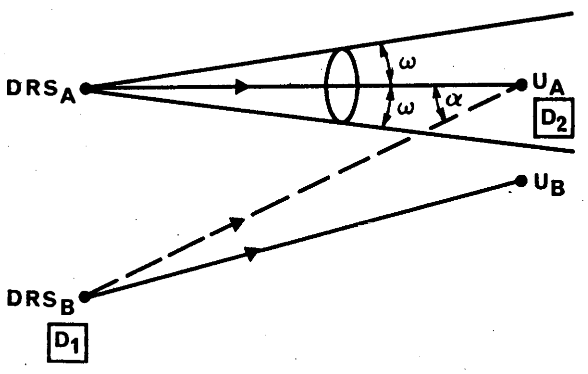

FIGURE 2a – *Forward link*

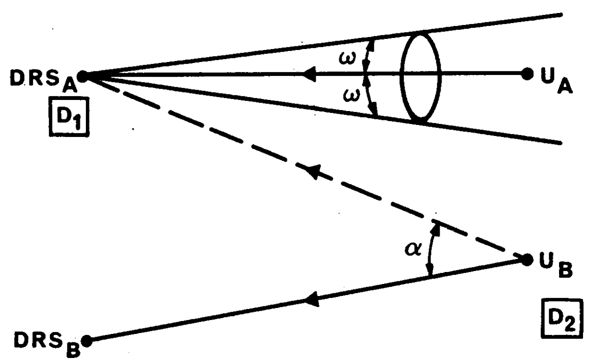

FIGURE 2b – *Return link*

DRS$_A$: wanted DRS
DRS$_B$: unwanted DRS

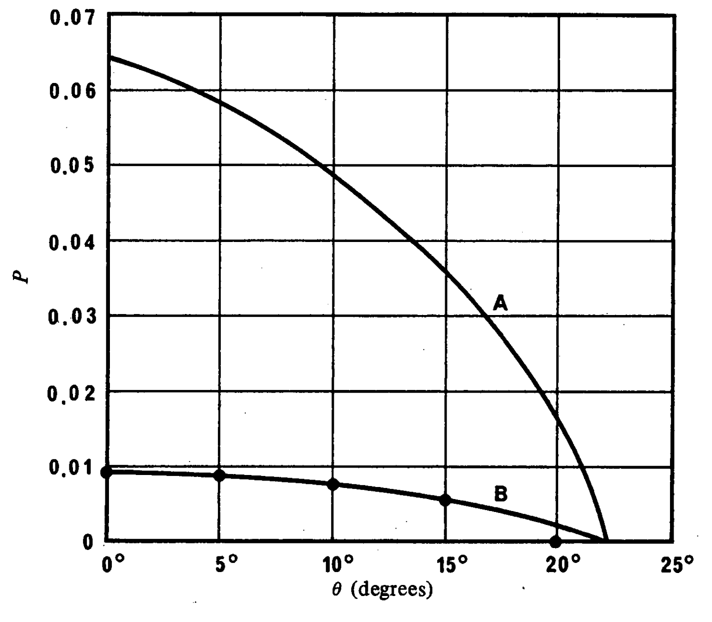

FIGURE 3 – *The relation between P and θ for $[W/U]$ = 14 dB*

Curves A: return link case; N = 20
B: forward link case; N = 3

4. Discussion and conclusions

The DRS and user satellite antenna diameters, D_1 and D_2 respectively, influence the results of applying equation (5) quite differently. The approximate proportion value calculated is directly proportional to $(1/D_1)^2$. The effect of increasing or decreasing D_1 will be to lower or raise the entire curve given in Fig. 3. The effect of changing the value of D_2, on the other hand, will be to change the shape of the curve without changing the $\theta = 0$ value. (Both parameters D_2 and θ have the same effect on the interference.) The value of the curve at $\theta = 0$ is the approximate proportion of interference for DRS systems with omnidirectional user satellite antennas.

The DRS sharing model has shown wanted-to-unwanted signal levels below 14 dB for relatively low percentages of time, less than 1% for forward link and less than 7% for the return link, between two systems operating with a significant number of user satellites in orbits near 8000 km. However, this is a limited model that considers only homogeneous systems operating with the same user altitudes, assuming a constant region of interference and equal probability of a user satellite being anywhere on the orbital sphere. This model, as such, predicts relatively high levels of interference in some cases (i.e. for users in orbits less than about 1000 km). Since, in practice, many widely varying situations may be encountered, a detailed model for DRS systems must take into account several inter-system isolation factors as well as specific orbital dynamics. Some areas that need to be considered are:

- definition of a fixed area about a wanted user satellite within which an unwanted satellite causes interference. The actual area about the wanted user within which an unwanted satellite will cause interference will vary with orbital position and will also vary with each set of orbital parameters considered;
- phasing of satellites in the same orbit;
- Earth blockage effects;
- polarization discrimination;
- coding, modulation and transmissions characteristics.

A more detailed analysis will be required using actual system parameters when determining the minimum longitude separation angle between data relay satellites sharing the same frequency band.

REPORT 846

DATA RELAY SATELLITES *

Sharing with other space research systems near 2 GHz

(Question 11/2)

(1982)

1. Introduction

At present, data telemetered from satellites in the space research service are received directly by earth stations. While it is anticipated that many of these transmissions will, in the future, be routed through a data relay satellite (DRS), some transmissions will still be sent directly to earth stations. Since the satellites using the DRS will share the frequency bands with other space research satellites, the potential for sharing between the two types of service must be investigated. For the purpose of clarity in this Report, satellites directly using earth stations will be referred to as space research satellites and satellites using a DRS will be referred to as DRS user satellites.

For the purpose of this analysis both the space research and DRS user satellites are assumed to be in circular orbits, and the sharing situations involving geostationary satellites and those in highly elliptical orbits and in transfer orbits are not considered.

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* This Report is also of importance to space operations.

2. Forward/up-link interference

The DRS forward link (DRS to user satellite) will share frequency bands with the up link of other space research satellites. Interference may exist if two or more satellites operate co-channel. Typically, space research satellites near 2 GHz use near omnidirectional antennas having a maximum gain ranging up to approximately 6 dBi. The potential for interference with these receivers is largely a function of the relative pfds of the desired and interfering signals, and the periods of time in which the interference can be expected to occur.

2.1 *Interference to other space research service satellites*

The maximum power level of the DRS foward link (space-to-space) is restricted due to the limitation in the Radio Regulations concerning the maximum pfd that can be incident at the Earth's surface. The pfd limit near 2 GHz is -154 dB(W/m^2) in a 4 kHz bandwidth for an angle of incidence less than 5° (No. 747 of the Radio Regulations). This effectively places a limit on the maximum e.i.r.p. of the DRS satellite and determines the maximum pfd incident on a low orbit satellite. The highest pfd that a satellite in a 1000 km orbit could experience due to the DRS emissions is -152 dB(W/m^2) in a 4 kHz bandwidth, occurring when the low-orbit satellite makes its closest approach to the DRS.

Typical earth stations in the space research service in the United States have an antenna gain of 43 dBi, a minimum antenna elevation of 5° and an e.i.r.p. of 31 dBW in 4 kHz. These earth stations would produce a minimum mainbeam pfd at 1000 km altitude satellite of -110 dB(W/m^2). The pfd of this desired signal, when compared to the pfd of the interfering DRS transmission, will result in a carrier-to-interference ratio in the space research satellite receiver of at least 42 dB. This minimum carrier-to-interference ratio would be improved in a non-worst case sharing situation, or if antenna discrimination factors were considered.

2.2 *Interference to DRS user satellites*

The DRS forward link has a bandwidth of 10-20 MHz and a typical data rate of 1000 bit/s. This results in a processing gain of 40 dB or more against an interfering signal. Using the value for the DRS pfd of -154 dB(W/m^2) in 4 kHz, the processing gain, and a required signal-to-noise ratio of 16 dB, a value of -130 dB(W/m^2) in 4 kHz is obtained as the level of interfering signal power flux-density that may cause interference in the receiver of a DRS user. As shown in the previous section, a space research service earth station would produce pfd levels much higher than -130 dB(W/m^2) at a DRS user satellite when the satellite is in the mainbeam of the earth station antenna. This, however, is a relatively rare event, due to the small beamwidth of the 43 dBi earth station antenna and the rapid movement of low-orbit satellites relative to the earth station. The probability of interference occurring can be calculated for the long term.

The power flux-density produced at a DRS user satellite by a transmitting earth station over the long term cannot be adequately described by a single time-independent quantity since a spacecraft in a low altitude earth-orbit "rises" and "sets" on the horizon as seen from a fixed point on the Earth. To a first approximation, the satellite can be envisaged as circulating in a plane which is fixed with respect to inertial space. The rotation of the Earth beneath the spacecraft causes the spacecraft ground track to follow a path which is repeated only after an extended period of time. An individual satellite is visible to a fixed point on the Earth for less than 10% of the time.

The proportion of time that a low-orbit satellite resides in a portion of its orbital sphere may be determined using equations contained in Report 684, "Preliminary Analysis of Low-Orbit Satellite Visibility Statistics". This Report describes a bounding equation which relates the long-term visibility of a circular-orbit satellite to the orbital inclination and the latitude and longitude bounds of a region on the satellite orbital sphere. The problem of expressing the pfd at a DRS user satellite as a statistical time function can then be reduced to determining the pfd with the satellite positioned in the centre of a small region of its orbital sphere, and then determining the proportion of time that the satellite spends in the region. If this procedure is carried out over the entire region of the orbital sphere visible to the earth station antenna, then all of the necessary information is available to properly determine the statistical satellite pfd function.

Figure 1 represents a statistical function of the pfd produced at a DRS user satellite by emissions from a space research earth station. The curve was generated using the earth station characteristics of § 2.1 and assumed a radiation pattern according to Report 391-3 (Kyoto, 1978) ($D/\lambda = 66$). The curve shown is the maximum of curves generated considering various latitudes for the earth station and various altitudes and inclinations for the satellite. As shown in Figure 1 the interfering signal pfd will exceed the -130 dB(W/m^2) level less than 0.03% of the time.

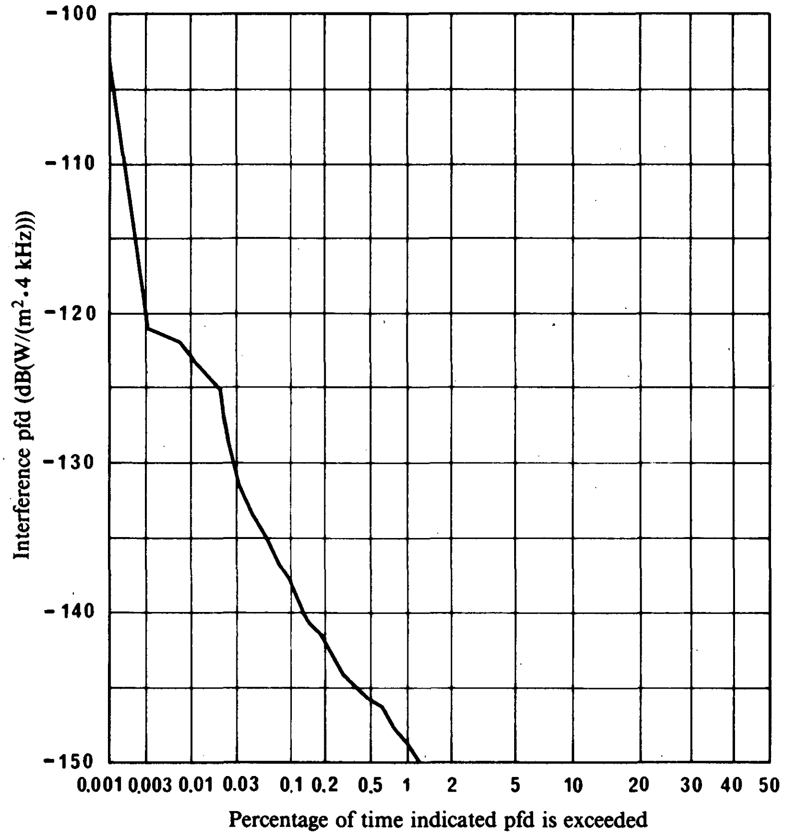

FIGURE 1 — *Statistical pfd function at a DRS user satellite due to space research earth station emissions*

3. Down/return link interference

The DRS return link (space-to-space) (user satellite to DRS) will share frequency bands with the down link of other space research satellites and interference may exist if two or more satellites operate co-channel. The earth station and the DRS each have very high gain antennas, so that the sharing situation is highly dependent on the relative locations and pointing directions of the antennas.

3.1 *Interference caused to space research earth stations*

Transmissions from both space research and DRS user satellites are subject to the Radio Regulations restriction on the maximum pfd incident at the Earth's surface. The pfd produced at the Earth's surface by a DRS user satellite will be no greater than the pfd limit and, because the transmissions are directed towards a geostationary satellite, will generally be considerably lower. Table I provides typical examples for the calculation of interference into a space research earth station from a DRS user satellite. The Table considers two cases, one in which the space research and DRS user satellites are visible to the earth station at a 5° elevation angle, and a second case in which the satellites are visible at higher elevation angles. The earth station antenna radiation pattern was defined in § 2.2. Power flux-density levels in the 1 kHz reference bandwidth were obtained by subtracting 6 dB from the pfd in 4 kHz.

The desired signal pfd levels given in Table I were derived from typical parameters given in Report 396 for earth stations which carry out space operation functions. This analysis shows that there will not be interference when the angle between the space research earth station antenna boresight and the DRS user satellite is greater than 6.3°. Depending upon the design and orientation of the DRS user satellite, this angle could be reduced or eliminated due to factors such as DRS user antenna discrimination and shielding of the antenna by the body of the satellite.

TABLE I — *Determination of required off-axis angle at earth station*

	Case 1	Case 2
Interfering signal (DRS user satellite):		
Satellite elevation angle (degrees)	5	> 25
pfd limit in 4 kHz (dB(W/m^2)) (No. 747 of the Radio Regulations)	– 154	– 144
Resultant pfd level in 1 kHz at earth station (dB(W/m^2))	– 160	– 150
Desired signal (space research satellite):		
Satellite elevation angle (degrees)	5	90
pfd level in 4 kHz (dB(W/m^2))	– 163	– 149
Resultant pfd level in 1 kHz at earth station (dB(W/m^2))	– 169	– 155
C/I of pfd levels in 1 kHz reference bandwidth at earth station (dB)	– 9	– 5
Required protection ratio (*C/I* in dB)	20	20
Required discrimination in earth station antenna (dB)	29	25
Required off-axis angle at earth station to achieve required antenna discrimination (degrees)	6.3	4.4

3.2 *Interference to DRS receivers*

The DRS return link is pseudo-random noise coded so as to provide a processing gain against interfering sources of 17 dB or more, depending upon the rate of data being transmitted. This in itself is sufficient to protect the DRS receiver from harmful interference, since the e.i.r.p. of a potentially interfering space research satellite towards the DRS could not be greater than, and in virtually all cases would be less than, the e.i.r.p. of the DRS user's desired signal.

4. Conclusion

The sharing possibilities between space research satellites using a data relay satellite and other space research systems can be summarized as follows:

– data relay satellite transmitters produce a relatively low pfd in the vicinity of low-orbit satellites and, based on an analysis of satellites in a 1000 km orbit, are not expected to cause interference to the reception of the higher-powered signals from space research earth station transmitters;

– space research service earth stations use high gain antennas and, due to the transient passage of low-orbit satellites, operate only for a fraction of the time. The probability that both the space research earth station and the DRS user satellite are operating in the same area at the same time is small. Interference to the DRS satellite receiver could not occur more than 0.03% of the time;

- the analysis showed that there will not be interference when the angle between the space research earth station antenna boresite and the DRS user satellite is greater than 6.3°. Depending upon the relative elevations of the satellites and the design and orientation of the DRS user satellite, this angle may be reduced or eliminated due to factors such as DRS user antenna discrimination and shielding of the antenna by the body of the satellite. However coordination should be performed for the protection of space research earth stations (Nos. 747 and 750 of the Radio Regulations);
- space research satellites have an e.i.r.p. towards the geostationary arc that is less than the e.i.r.p. of a DRS user towards the arc. Since signal processing of the DRS user produces 17 dB or more of gain against interfering signals, the space research satellites will not produce harmful interference to the DRS receiver.

This Report has only considered potential interference to satellites operating in low-altitude circular orbits. Further studies concerning space research geostationary satellites and those in highly elliptical orbits and in transfer orbits should be considered.

REPORT 847-1 *

DATA RELAY SATELLITES

Sharing with other services in bands 9 and 10

(Question 11/2)

(1982–1986)

1. Introduction

The purpose of this Report is to summarize the results of several studies of the feasibility of frequency sharing between space research systems, using geostationary data relay satellites and other services. A description of a data relay satellite (DRS) system including technical parameters is contained in Report 848. The feasibility of frequency sharing between DRS systems and other systems within the space research service is discussed in Report 846.

Further details relating to the frequency sharing and compatibility studies summarized in this Report may be obtained by consulting the Reports referenced in each of the following sections. The particular problems related to use of the band allocated to the aeronautical radionavigation service near 13 GHz are discussed in Report 690 (Geneva, 1982) and Recommendation 511 (Geneva, 1982).

2. Terrestrial systems in band 9 (Report 537-1 (Kyoto, 1978))

A general method was developed in Report 537-1 (Kyoto, 1978) to determine TDRS system design parameters of interest whereby frequency sharing in band 9 between space research systems using a DRS and terrestrial systems would be feasible. A series of inequalities was derived which would help determine what sets of design parameters allow frequency sharing with any terrestrial service based upon acceptable interference to the TDRS space links.

A graphic translation of these inequalities using typical system parameters (user orbital altitude = 500 km, and in accordance with Tables II and V of Report 537-1 (Kyoto, 1978)) shows where appropriately designed antenna systems permit frequency sharing. The feasibility of sharing is thus dependent upon appropriate combinations of main beam gain and discrimination of the antennas in question. Using the $32 - 25 \log \varphi$ antenna pattern as a first approximation and typical TDRS parameters used in Report 848, an estimate can be obtained in each case indicating when the DRS link in question can expect interference-free operation.

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* This Report should be brought to the attention of Study Groups 4, 8, 9, 10 and 11.

3. **Fixed and mobile services in band 10** (Report 689 (Kyoto, 1978))

The feasibility of frequency sharing between the fixed and mobile services and the TDRSS is discussed in Report 689 (Kyoto, 1978) and summarized in the following sections.

3.1 *Earth station-to-DRS link*

The DRS earth station characteristics are comparable with those expected to be utilized by the fixed-satellite service earth stations in the same frequency range. Hence, the potential for interference from the DRS up link to a fixed and mobile services antenna and the resultant coordination contours should be comparable with those of the fixed-satellite service.

3.2 *DRS transmissions*

In tracking a near-earth user satellite or in transmitting to the earth station in the down link, the DRS may illuminate a terrestrial antenna of the fixed and mobile services. It is recommended that the DRS systems in the space research service can operate near 15 GHz within the following pfd restrictions, which have been determined for transmissions from the fixed-satellite service. The recommended limits, now embodied in the Radio Regulations, for the nearest band where limits apply, are:

$$-148 \quad \text{dB(W/m}^2) \quad \text{for} \quad \delta \leq 5°$$
$$-148 + (\delta - 5)/2 \quad \text{dB(W/m}^2) \quad \text{for} \quad 5° < \delta \leq 25°$$
$$-138 \quad \text{dB(W/m}^2) \quad \text{for} \quad 25° < \delta \leq 90°$$

in any 4 kHz band. δ is the angle of arrival of the signal, measured in degrees above horizontal. For the proposed operational parameters of the DRS, the maximum power flux-density of the RF wave from DRS transmissions at the surface of the Earth would be -152 dB(W/m^2) in the worst 4 kHz band. Hence, no potential for harmful interference to the fixed and mobile services is seen in this case.

3.3 *User satellite-to-DRS link*

Interference to a receiving antenna of the fixed and mobile services is possible when the user satellite is transmitting to the DRS on the return link and the user satellite is on the horizon of the terrestrial station. In order to protect the fixed and mobile services reception, the user satellite must be constrained to operate within the limits of Recommendation 510 by limiting e.i.r.p. and operational pointing directions.

4. **Radiolocation service in the band 13.4 to 14.0 GHz** (Report 691 (Kyoto, 1978))

The summary that follows of the potential for interference from the TDRSS to the radio-location service is taken from Report 691 (Kyoto, 1978) and other sources as cited therein. No radiolocation systems are currently planned in this band, but future systems could be designed to monitor and control airport surface traffic particularly during periods of low visibility. All results of this section are matched to hypothetical, typical radiolocation system parameters.

4.1 *Earth station-to-DRS link*

Whenever a radiolocation antenna is above the DRS earth station horizon, interference at the radiolocation receiver during earth station transmissions to the DRS is possible. The maximum allowable interference spectral power density at a typical radiolocation receiver is assumed to be -203 dB(W/Hz); (see § 4 of Report 691 (Kyoto, 1978)). The two TDR satellites are assumed to be separated by 130° and at an angle of elevation of about 17° above earth station horizontal to achieve maximum signal-to-noise ratio. The DRS earth station is considered to be at 35° N latitude with a transmitting power of -56 dB(W/Hz) and an antenna gain of 60 dBi.

With these suppositions, plus data on the propagation mode and the rain-climate zone type (see Reports 563-1, 564-1 and 569-1 (Kyoto, 1978)), a calculation can be carried out to determine the required separation of the DRS earth station and the radiolocation earth station so as not to exceed -203 dB(W/Hz) in the radiolocation receiver (see Report 382-3 (Kyoto, 1978)). In this case, distances in the 220 to 250 km range provide separations sufficient for interference-free operation of radiolocation equipment, depending on climate/zone assumptions. In cases where the actual separation distance between DRS earth station and the radiolocation receiver is less than the required separation, coordination procedures could be used to determine locations of DRS earth stations where non-interference operations could occur.

4.2 *DRS-to-user satellite link*

A radiolocation site within the DRS horizon may suffer interference from the DRS main beam only if some part of the area within the DRS antenna beam scans across a radiolocation site along a grazing sightline while tracking the user satellite. According to the criteria for unacceptable interference at a radiolocation receiver (assumed in § 4.1), the DRS may produce unacceptably high levels of interference at the radiolocation antenna. Hence, an analysis is undertaken of the relative frequency of occurrence of such levels of interference in a typical, multi-user environment.

The value obtained is for a radiolocation beam scan rate of 135 rpm and 6 user satellites. In this case, the probability of interference from the DRS at the radiolocation antenna being unacceptably high is 1.13×10^{-5}. This is not considered a serious impediment to the operation of a radiolocation service receiver.

4.3 *User satellite-to-DRS link*

A main beam-to-main beam interference path between near-Earth research spacecraft of the space research service (using a DRS) and a radiolocation system exists only if the radiolocation equipment is located within a narrow spherical cap centred at the DRS-user spacecraft horizon along a grazing sightline. For the radiolocation systems to experience main lobe interference, it must be located within this cap while all systems are operating. A typical user spacecraft is assumed to have a spectral e.i.r.p. of -28 dB(W/Hz) producing an interference power of -172 (W/Hz) at the radiolocation receiver. If the radiolocation antenna provides 35 dBi of gain, the receiver will suffer 31 dB of interference power higher than the maximum allowable according to limitations set out in § 4.1.

An analysis on the basis of relative frequency of unacceptable interference to the radiolocation antenna was carried out. User satellite orbital altitudes typically range from 200 km to 1200 km with corresponding main beam-to-main beam coupling times (during a coupled orbit) of 0.46 to 2.2 min. These values lead to a "worst-case" estimate of the probability of occurrence of interference at the radiolocation system of 2.76×10^{-8} (this corresponds to the 1200 km orbit). This probability is not considered an obstacle to adequate radiolocation performance.

5. Feeder links to broadcasting satellites in the 14.5 to 14.8 GHz band

The fixed-satellite service (FSS) and the space research service both have frequency allocations at 14.5-14.8 GHz. However, for territories outside Europe and for Malta, use of the FSS allocation is restricted to feeder links for the broadcasting-satellite service (BSS). In the space research service, this band is used by some DRS systems for Earth-to-space links. Consequently, potential interference exists between the two systems when the earth station of one service illuminates the receiving satellite of the other service. This analysis considers the mutual interference potential between broadcasting and geostationary data relay satellites.

Using typical DRS and BSS parameters (taken from IFRB publications and the Final Acts of the WARC ORB-85), link calculations were performed in the case of DRS up-link interference to BSS feeder links (see Annex I for details). The interference criterion was specified as a minimum C/I ratio of the BSS satellite of 45 dB. Results indicate that this protection ratio can be met with a BSS and DRS satellite spacing of the order of 2° even if the associated earth stations are assumed to be co-located.

A similar analysis was performed in the case of BSS feeder-link interference into DRS up links (see also Annex I). The interference criterion was specified as the ratio of the received interference power to the receiving system noise power. In the case where BSS and DRS satellites are separated by at least 14°, sharing is feasible even if the respective earth stations are co-located. For satellite spacings of less than this amount however, sharing will be feasible provided that the DRS satellite receive antenna has sufficient discrimination towards the BSS feeder-link earth station serving the adjacent BSS satellite. Consequently, care needs to be exercised in the selection of DRS earth-station sites and also in the selection of DRS satellite locations.

6. **Fixed-satellite service near 15 GHz** (Report 686 (Kyoto, 1978))

The sections which follow summarize the feasibility of co-channel operations between the TDRSS and up links of the fixed-satellite services (FSS) from Report 686 (Kyoto, 1978) and other sources cited below.

6.1 *Earth station-to-DRS*

It is possible for an FSS up link to receive interference from DRS earth station transmissions toward the DRS which irradiate a geostationary FSS satellite in a geostationary position near the DRS. According to Appendix 29 to the Radio Regulations (1976), there may be unacceptable interference to a satellite up link if there were a 2% increase in the interference-to-noise ratio in that link due to the incoming interference (in the Radio Regulations of 1982 this number has been changed to 4% which would lessen the sharing constraints). This amounts to a −17 dB ratio of incoming interference-to-noise power ratio at the FSS receiver. The following existing or typical parameters are assumed for the two services: a DRS earth station e.i.r.p. density of 4 dB(W/Hz), an FSS satellite antenna gain of 40 dBi or less depending on off-axis angle (1.5° spot beam), FSS up-link system noise temperature of 1000 K and a total link-to-up-link noise ratio of 5 for the FSS. Under these conditions, an angular separation of 5.7° between the satellites of the two services is required. This requirement can be reduced to 4° by placing the DRS earth station outside the −3 dB contour of the FSS spot beam antenna (approximately 500 to 600 km distance from the FSS earth station). The calculations are based upon antenna radiation reference patterns in Recommendation 465-1 (Kyoto, 1978) for earth stations and Report 558-1 (Kyoto, 1978) for FSS satellite antennas.

6.2 *DRS-to-user satellite*

In tracking the user spacecraft (worst-case assumption of 0° user satellite inclination), DRS transmissions could interfere with FSS satellites operating on geostationary arc segments of width no greater than 2.3° antipodal to the DRS. Given that potentially unacceptable interference is determined as in § 6.1 and again using the satellite antenna reference radiation pattern of Report 558-1 (Kyoto, 1978), an antenna discrimination of 7.6 dB is required at the FSS spacecraft to avoid a 2% increase in the interference-to-noise power ratio in the FSS up link, which would occur for about 10% of the time. The discrimination figure amounts to a needed 1.3° off-beam angle between the DRS transmission and the FSS antenna axis.

In the hypothetical case studied above, wherein the FSS space stations are located antipodal to the DRS satellite and the FSS earth station is located near the equator and near the limb of the earth as seen from the DRS satellite, some constraints may need to be placed on the DRS-to-user operations.

6.3 *User satellite-to-DRS*

As in § 6.1, the FSS satellite is most likely to receive interference from a user spacecraft transmission toward the DRS, when the FSS satellite is located in an adjacent orbital position. Again, as in § 6.1, the criteria for interference to a satellite link can be obtained from Appendix 29 of the Radio Regulations. In this case, the mission spacecraft is assumed to possess a main beam gain of 40 dBi and an orbital altitude of 200 km (to determine the worst-case condition). Using the satellite antenna reference radiation pattern of Report 558-1 (Kyoto, 1978), an angular separation of 2.7° between the geostationary satellites of the two services as viewed from the user satellite is necessary to avoid exceeding the Appendix 29 criterion for interference to the FSS up link. Recalling from § 6.1 that a topocentric angular separation of at least 5.7° between the two geostationary satellites is already required because of DRS earth station emissions intercepting the FSS satellite, the separation required by this interference path is already satisfied. Therefore, the interference caused by mission spacecraft in its return link to the DRS to the FSS up link should not endanger FSS up link performance while sharing frequencies with the TDRSS.

ANNEX I

FREQUENCY SHARING BETWEEN FEEDER LINKS FOR THE BROADCASTING-SATELLITE SERVICE (BSS) AND THE SPACE RESEARCH SERVICE AT 14.5-14.8 GHz

1. Introduction

This Annex evaluates the feasibility of Earth-to-space frequency sharing between typical data relay satellite (DRS) systems in the space research service and feeder links to the broadcasting-satellite systems in the 14.5-14.8 GHz band. The BSS feeder-link operations in this band may be planned for Regions 1 and 3 at the WARC ORB(2). In Region 2, BSS feeder links are planned in the 17.3-18.1 GHz band.

2. Interference analysis

2.1 *Interference from a DRS earth station to a BSS satellite*

The ensuring analysis is based upon typical parameters of BSS and DRS operations. These parameters are:

– *BSS parameters:*

Earth-station antenna gain	57 dB
Maximum e.i.r.p.	82 dBW
RF bandwidth	27 MHz
Required C/I ratio	45 dB

– *DRS parameters:*

Earth-station antenna pattern	$32 - 25 \log \theta$ *
Power spectral density	−62 dB(W/Hz)
Total power in 27 MHz	12.3 dBW

The carrier (C) to interference (I) ratio produced at the BSS satellite can be calculated by comparing the e.i.r.p.s of each system towards the BSS satellite in 27 MHz as follows:

$$C/I = \text{BSS e.i.r.p.} - \text{DRS e.i.r.p.}$$

$$C/I = 82 - (12.3 + 32 - 25 \log \theta)$$

or

$$C/I = 37.7 + 25 \log \theta$$

For a required C/I of 45 dB, the required satellite spacing is calculated as:

$$\theta = \log^{-1} \left(\frac{45 - 37.7}{25} \right)$$

or

$$\theta \approx 2°$$

This calculation assumes co-located earth stations, a worst-case assumption. The value of 2° would be an acceptable angular separation and would indicate feasible operations on this link.

* Where θ is the angular separation between DRS and BSS satellites as seen from DRS earth station.

2.2 *Interference from BSS feeder-link earth station to DRS satellite*

The transmissions of a BSS earth station may also illuminate a receiving antenna of a DRS satellite adjacent to a BSS satellite. Using the parameters described in § 2.1, assuming a DRS satellite receiver noise temperature of 2300 K and a DRS satellite receiver antenna peak gain of 44.5 dBi, the interference to noise ratio produced by a BSS earth station at an adjacent DRS satellite can be calculated as follows:

BSS transmit antenna pattern	$32 - 25 \log \theta$
Power delivered to antenna	25 dBW
Bandwidth conversion	−74.3 dB(Hz/27 MHz)
Spectral distribution factor*	4 dB
Free-space loss	−207.7 dB
DRS satellite peak gain	+44.5 dBi
Interference power spectral density (dB(W/Hz))	$-176.5 - 25 \log \theta$

Therefore:

$$I/N = -176.5 - 25 \log \theta - k - T \qquad \text{dB}$$

$$I/N = 18.5 - 25 \log \theta \qquad \text{dB}$$

where:

k: Boltzmann's constant (equivalent to −228.6 dB(W/(Hz · K)),

T: DRS satellite receiver noise temperature (equivalent to 33.6 dB(K)).

If an allowable I/N ratio at the DRS is taken as −10 dB, then the required spacing θ between BSS and DRS satellites can be calculated by:

$$-10 = 18.5 - 25 \log \theta$$

$$\theta = \log^{-1} (28.5/25)$$

or:

$$\theta = 13.8°$$

This angular spacing is that which would be required if the BSS and DRS earth stations were co-located. If, however, the earth stations are not co-located and therefore additional discrimination toward the unwanted signal can be realized through DRS satellite antenna off-axis pointing, more acceptable satellite spacings can be achieved as shown in Fig. 1. If care in the selection of DRS earth-station sites is exercised, frequency sharing is feasible.

* Spectral distribution factor is defined as the difference between peak (maximum) and average power spectral density of the signal. While the value of 4 dB is used in this calculation, Fig. 1 presents results also for a value of 7 dB.

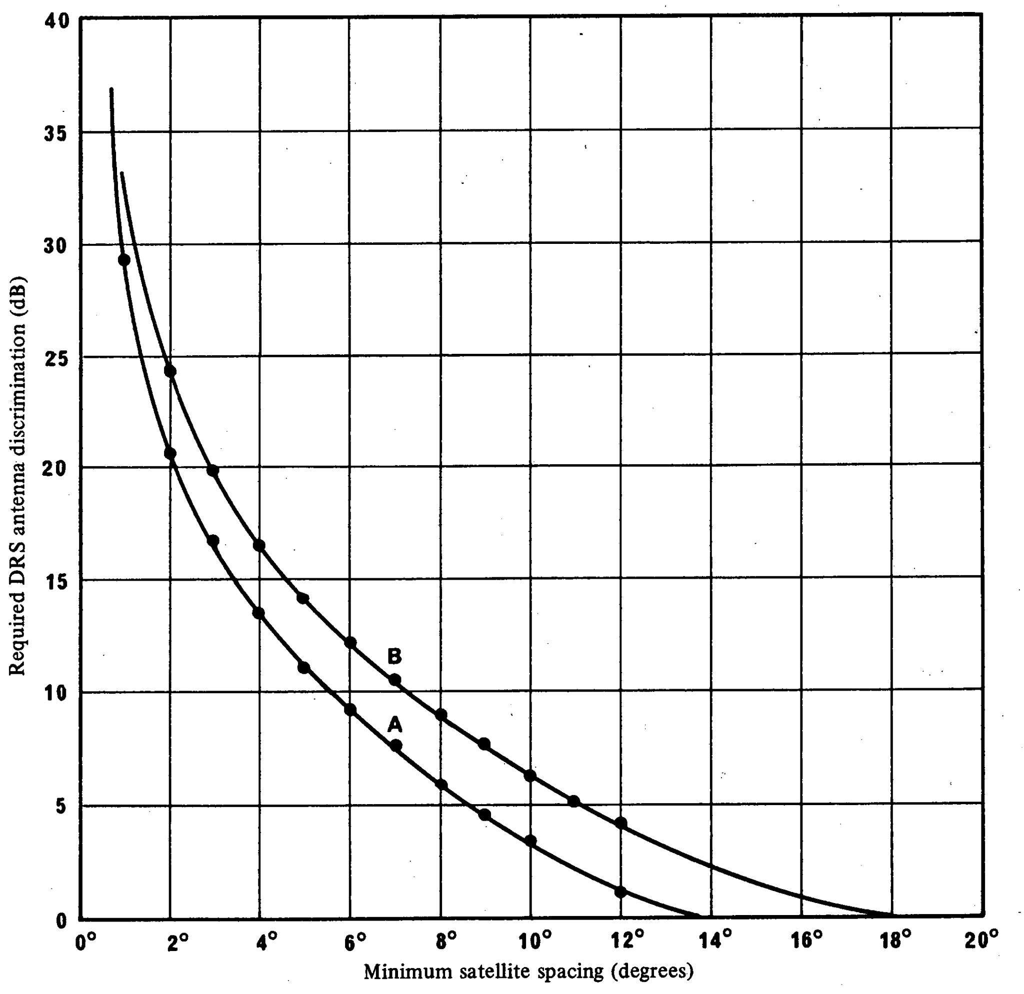

FIGURE 1 – *Minimum allowable satellite spacing as a function of DRS antenna discrimination*

Curves A: spectral distribution factor = 4 dB
B: spectral distribution factor = 7 dB

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RECOMMENDATION 510-1 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE RESEARCH SERVICE AND OTHER SERVICES IN BAND 10

Potential interference from data relay satellite systems

(Question 11/2)

(1978–1982)

The CCIR,

CONSIDERING

(a) that Report 847 refers to the feasibility of frequency sharing within the range 13 to 16 GHz between near-Earth space research applications (transmitters of the data relay satellite system) and other services, namely the fixed and mobile services and radiolocation service;

(b) that, following the provisions of the WARC-79, the space research service may operate on a secondary basis in some of the bands where the above services are primary;

(c) that Report 847 indicates that the data relay satellite transmitters can meet the power flux-density limits given in Recommendation 358 and adopted by the WARC-79 for sharing between the fixed-satellite service and the fixed and mobile services,

UNANIMOUSLY RECOMMENDS

1. that frequency sharing, on a non-interference basis, between transmitters in the space research service and receivers of the fixed and mobile services or the radiolocation service is feasible near 14 and 15 GHz provided that appropriate power flux-density limits are specified for the space research service;

2. that, in frequency bands near 14 and 15 GHz shared between the space research service (data relay satellite systems), and the fixed and mobile services or the radiolocation service, the space research satellites can operate with the following power flux-density limits produced at the surface of the Earth in any 4 kHz band for all conditions and methods of modulation not exceeding:

-148	dB(W/m^2)	for	$0° < \delta \leqslant 5°$
$-148 + (\delta - 5)/2$	dB(W/m^2)	for	$5° < \delta \leqslant 25°$
-138	dB(W/m^2)	for	$25° < \delta \leqslant 90°$

where δ is the angle of arrival of the radio-frequency wave (degrees above the horizontal);

and that these limits relate to the power flux-density and angles of arrival which would be obtained under free-space propagation conditions.

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* This Recommendation should be brought to the attention of Study Groups 8 and 9.

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SECTION 2E: SPACE RESEARCH

Recommendations and Reports

REPORT 548-2

TELECOMMUNICATION REQUIREMENTS FOR MANNED AND UNMANNED NEAR-EARTH SPACE RESEARCH

(Questions 1/2 and 22/2; Study Programme 22B/2)

(1974–1978–1986)

1. Introduction

This Report presents a summary of the telecommunication requirements for near-Earth space research. Such research uses spacecraft or other objects in near-Earth space for scientific or technological research purposes. The discussions provide a foundation for establishing radio-frequency spectrum requirements for the space research service and for frequency sharing between the space research service and other services which are considered in Reports 984 and 985 respectively.

The following concept of near-Earth space research is based on the definition of near-Earth space as:

Near-Earth space:

Space at altitudes above the major portion of the atmosphere of the Earth, but significantly less than the distance to the Moon.

2. General system considerations

2.1 *Types of mission*

The field of space research using near-Earth satellites includes:

- solar/terrestrial physics (ionospheric, magnetospheric, solar wind studies, geomagnetism, etc.);
- cosmic particles and electromagnetic radiation;
- atmospheric physics;
- astronomy, using observations at various frequencies;
- radio propagation;
- geodesy and geodynamics;
- biology, life sciences;
- Earth exploration and meteorology (experimental phases);
- testing of new technology.

2.2 *Mission duration*

The duration of an unmanned mission is determined by the mission objective, and may often be limited by the power and total energy available on the spacecraft. For manned missions, an additional limiting factor is the maximum length of time a human being can safely stay in space. Mission durations may last from a few months to several years for unmanned missions, and from several days to several months for manned missions. For certain manned space research experiments, the human factor that limits its duration can be circumvented by a change of spacecraft personnel.

2.3 *Orbit types*

Near-Earth satellite orbits are classified as either low, geosynchronous or highly elliptical.

2.3.1 *Low orbit*

A low orbit is defined as one in which the apogee and perigee are significantly nearer the Earth than is the geostationary-satellite orbit. A feature of the orbit is that the percentage of time a spacecraft is visible to its earth station or any other fixed terrestrial station, is low. Report 684 discusses the visibility of low-orbit satellites.

2.3.2 *Geosynchronous-satellite orbit*

The period of rotation for a satellite in this orbit is about 23 h 56 min. A particular type of geosynchronous-satellite orbit which is of interest for space research telecommunications is the geostationary satellite-orbit. Two important characteristics of this orbit are:

- the position of a geostationary satellite relative to a point on the Earth is fixed. This implies that visibility is continuous between a geostationary satellite and its associated earth station, and all other stations located in the field of the view of the satellite;
- a geostationary satellite can provide significant coverage to a low-orbit satellite. Inter-satellite links can further permit continuous radio contact between a low-orbit satellite and a single main earth station.

2.3.3 *Highly elliptical orbits*

A characteristic of this type of orbit is that the percentage of time a satellite is visible to its associated earth station can be high. Nearly continuous data transfer to and from the satellite is feasible.

3. Critical communication periods

During each space-research mission, there are certain periods which are critical to the success of the mission. Failure of reliable communications during these critical periods may cause anything from a minor difficulty to the total failure of the mission. Launch, injection and landing (manned) phases are particularly critical periods. For many near-Earth missions which depend on a limited number of tracking facilities, critical periods will generally occur when the spacecraft is within viewing range of the tracking site.

4. Communication requirements

The communication system of any space-research network comprises four basic sub-systems. They are:

- the maintenance telemetry sub-system required for transmitting sensor data regarding the health and condition of the spacecraft or of its human occupants, to Earth;
- the mission telemetry sub-system required for transmitting scientific, engineering, and video data to Earth and for voice communications;
- the command sub-system necessary to provide guidance and control of spacecraft. In the case of a manned spacecraft, the capability of command is not intended to replace control of the spacecraft by its human occupant, but rather to supplement it;
- the tracking sub-system required to provide information regarding the position and velocity of the spacecraft necessary for computing its orbit.

Because of severe limitations on size and weight, many spacecraft combine the tracking, telecommand, telemetering, voice and video systems by integrating the various functions into a single radio system. Such integrated systems consolidate the many various separate transmitters, receivers and antennas by allowing one receiver and one transmitter to perform several functions simultaneously, thus resulting in simplicity, on the spacecraft and on the ground. Additionally, it may provide efficient usage of the spectrum.

Transmission of telecommunication functions may be accomplished by either employing a direct telecommunication link between the spacecraft and earth station, or by an indirect relay satellite link (see Report 537 (Kyoto, 1978)).

For some missions, direct communication links may be adequate to satisfy mission communication requirements. However, for many missions, communication via a geosynchronous relay satellite affords significant benefits to the user community. Some of these benefits, which are a result of the extended coverage provided by relay satellites, are:

- significant increase in real time telemetry;
- reduction or elimination of on-board data storage equipment, e.g. tape recorders;
- real time command control and experiment modification;
- improved scheduling for all uses of the system.

In considering the limitations in the power capabilities of spacecraft, channel coding and modulation techniques reduce the transmitter power while achieving the required bit-error ratio. In certain applications, e.g. relay satellite transmissions, additional burdens such as interference and multipath problems may be placed on the communication system. Since multipath signals are proportional to the transmitted power, the direct signal-to-multipath signal ratio always remains the same, negating an increase in signal power as an option for overcoming the multipath problem. Furthermore, increases in signal power to overcome interference problems are also limited by either spacecraft power capabilities or power flux-density restrictions. For these and other problems associated with relay satellite links, the use of spread spectrum and/or channel coding techniques has been effective.

In the presence of interference, the required energy per information bit may be reduced by increasing the channel bandwidth and either using an appropriate modulation technique (for narrow-band interference) or using channel coding (for wideband interference).

4.1 *Maintenance telemetry sub-system*

The primary purpose for the maintenance sub-system is to ensure the safety of spacecraft personnel and success of the mission, so the communication link should have a capacity large enough to handle all essential information and in the case of propagation through the atmosphere, there should be a link which is independent of weather. Baseband bit error ratio of 1 in 10^5 is the usual requirement for this sub-system.

Data rates during launch and orbit adjustment can be as high as 1 kbit/s, and range from a few bits per second to several thousand bits per second for normal real-time telemetry formats. Special read-outs, such as from computers or tape recorders, are generally at higher rates such as a few hundred kilobits per second.

Power output for maintenance telemetry links ranges from a few milliwatts to several watts. Directional antennas are often used for telemetry links, omnidirectional antennas are primarily used for launch and injection phases, spacecraft rendezvous and emergency situations.

4.2 *Mission telemetry sub-system*

4.2.1 *Telemetry rates*

The volume of mission telemetry data transmitted depends on the types of mission, sophistication of the spacecraft and the available contact hours between transmitting spacecraft and receiving earth station. Real-time telemetry rates may range from several kilobits per second for low data rate spacecraft, to several hundred megabits per second for more sophisticated spacecraft. For data relay satellites, studies have indicated that future systems will need to process data at a rate of gigabits per second. Telemetry rates for stored or computed data, transmitted in the playback or dump mode, are similar to real-time telemetry rates.

4.2.2 *Voice communications*

In manned space flight, voice communication with its inherent flexibility in the transmission of information, is an essential factor in guaranteeing successful missions with maximum safety of the astronaut.

Requiring an information bandwidth of the order of 3 kHz, and a post-detection signal-to-noise ratio of 20 dB, frequency modulated analogue systems can provide reliable and intelligible communication between space and earth stations. However, digital voice encoding techniques such as pulse code modulation (PCM) or adaptive delta modulation (ADM) schemes followed by error correction coding can provide a level of performance which is significantly greater than that practically attainable using analogue systems [Schilling *et al.*, 1978].

4.2.3 *Television*

Requiring an information bandwidth of the order of 4.5 MHz, television signal transmission is generally accomplished by using analogue frequency modulation techniques. Digital systems have not yet been adopted because the required bandwidth is much larger than that required by an analogue system for a desired level of picture quality. However, developments in digital coding techniques have established that significant compression of digital television data can be achieved by using relatively sophisticated source coding algorithms. It is anticipated that video will be transmitted using digital techniques in the near future [Habibi and Batson, 1978].

4.3 *Command sub-system*

A telecommand sub-system, as with the maintenance telemetry sub-system, is of paramount importance to the safety and success of any mission and as such must be particularly reliable under all adverse transmission conditions, e.g., unfavourable weather and radio interference. The problem of interference to telecommand receivers in spacecraft is especially difficult in that the wanted signal is not always present, and the interfering signal must not trigger the telecommand receiver even in the absence of the wanted signal. Required reliability is therefore quite high, with bit error ratios not exceeding 1×10^{-5} for all telecommand links. Additionally, the false command rejection ratio should be at least 1×10^{-8}.

Providing high reliability of telecommand links necessitates the following:

- a weather independent Earth-to-space link;
- high command e.i.r.p. to compensate for the low gain omni-antennas used by the receiving spacecraft during launch and injection phases and during emergencies;
- command encoding to ensure sufficient false command rejection caused by error bursts, fading or spurious signals.

Typical information rates of a command code, range from as low as a few bits per second to about 2 kbit/s for more complex spacecraft. For manned spacecraft, information rates may be as high as 3 kbit/s. The inclusion of a simple parity bit or the use of the complement of the command words are simple error detection methods. More elaborate multi-error correcting codes are also used.

4.4 *Tracking sub-systems*

Reliable radio tracking of spacecraft is one of the basic requirements of any space-research mission. In addition to providing information necessary to determine the location in space of the spacecraft at any instant, tracking is also necessary for evaluation of launch performance, for vernier corrections to trajectories, for determining precise timing for critical manoeuvres such as retrorocket firing and for the transfer of data between earth and space stations. During these times, earth and space-station receivers track the carrier signal with the aid of phase-locked loops and directive antennas. Loss of carrier lock by the phase-locked loops during moments of data transfer may seriously degrade the reliability of the communication link (see Reports 544 and 545 (Geneva, 1982) for a discussion of interference into phase-locked loops).

Standard spacecraft tracking techniques generally involve the determination of one or more of the parameters: range, range-rate and angle data.

Range is determined by measuring the round trip time of a radio signal to and from a spacecraft, range-rate is usually determined by measuring the Doppler-shift in the signal, and angle data is obtained by measuring the angle between the observer's reference plane and the line from a reference point in the plane to the spacecraft. The following techniques are used in the space research service for spacecraft tracking:

- interferometer tracking,
- radar tracking,
- coherent and non-coherent range and range-rate tracking,
- bilateration tracking.

5. Summary

The basic telecommunication requirements for the space research service as outlined in this Report, show that telemetry, tracking and telecommand sub-systems will be required by all space research spacecraft and that voice and video communication are essential to manned missions.

As differing research missions have significantly different requirements, the overall data requirement for an individual mission ranges from a few kilobits per second to many hundreds of megabits per second.

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REPORT 536-3

TELECOMMUNICATION REQUIREMENTS FOR MANNED AND UNMANNED DEEP-SPACE RESEARCH

(Question 21/2)

(1974-1978-1982-1986)

1. Introduction

This Report presents the characteristics of typical United States of America (US) deep-space research missions, the functional and performance requirements for telecommunications needed to conduct deep-space research with spacecraft, and the technical methods and parameters of systems used in connection with such missions. A much more comprehensive treatment of these and related topics may be found in [Yuen, 1983].

Considerations regarding preferred frequency bands for deep-space research can be found in Reports 683 and 849. Interference, protection criteria and sharing are discussed in Report 685.

2. Telecommunication requirements

Deep-space missions require highly reliable communications over long periods of time and great distances. For example, a spacecraft mission to gather specific information at the planet Neptune would take eight years and require telecommunication over a distance of 4×10^9 km. The need for high e.i.r.p. and very sensitive receivers at earth stations is a result of the large communication distances involved in deep-space research.

Continuous usage of deep-space communication bands is a consequence of the several missions now in existence and others being planned. Because many deep-space missions continue for periods of several years, and because there are usually several missions in progress at the same time, there is a corresponding need for communication with several spacecraft at any given time.

In addition, each mission may include more than one spacecraft, so that simultaneous communication with several space stations will be necessary. The US Mars orbiter/lander (Viking) mission was designed for simultaneous operation of two Earth-to-space links and three space-to-Earth links, using a single earth station. Simultaneous co-ordinated communication between a space station and more than one earth station may also be required.

2.1 *Telemetering requirements*

Telemetering is used to transmit both maintenance and scientific information from deep space.

Maintenance telemetering information about the condition of the spacecraft must be received whenever needed to ensure the safety of the spacecraft and success of the mission. This requires a weather independent telecommunications link of sufficient capacity. The propagation properties of the current 2 GHz allocation meet the requirement. Maintenance telemetering data rates are relatively low. For example, the Galileo spacecraft, expected to be launched in 1987, has data rates of 40 and 1200 bit/s for maintenance telemetering.

Science telemetering involves the sending of data from measurements made by the on-board scientific instruments. The scientific data are of two types: imaging (television-like), and non-imaging (general). For example, the imaging experiment on the US 1975 (the dates quoted in this section are launch dates for the space probes) Mars lander (Viking) consisted of two facsimile cameras; non-imaging science experiments were biological, meteorological, seismological, molecular and mineral analysis. Data rates and acceptable error rates may be quite different for the two types of data. Video data rates up to 134 kbit/s have already been used.

Telemetering link capacity has steadily increased with the development of new equipment and techniques. This increase can be used in two ways:

- to gather larger amounts of scientific data about nearby planets, and
- to permit missions to more distant planets.

For a particular telemetering system, the maximum possible data rate is proportional to the inverse square of the communication distance. The same link capability that provides for a Galileo data rate of 134 kbit/s from the vicinity of the planet Jupiter (9.3×10^8 km) would also provide for a data rate of 5 Mbit/s from the vicinity of the planet Venus (1.5×10^8 km). Because higher data rates require wider transmission bandwidths, the ability to effectively utilize the maximum telemetering capability depends in part on the number of simultaneous deep-space missions and the width of allocated bands.

As imaging experiments become more sophisticated, even higher bit rates will be required. This is discussed in § 4.6, including the effect on bandwidth [Davies and Murray, 1971].

An important contribution to telemetering has been the development of coding methods that permit operation with a lower signal to noise ratio [Forney, 1970; Viterbi and Omura, 1979]. The coded signal requires a wider transmission bandwidth. The use of coded telemetering at very high data rates may be limited by allocation width.

2.2 *Telecommand requirements*

Reliability is the principal requirement of a telecommand link. Commands must be received accurately and when needed. For US deep-space missions the telecommand link is required to have a bit error ratio not greater than 1×10^{-5}. Commands must be received successfully, without regard to spacecraft orientation, even when the primary high gain antenna may not be pointed to Earth. For such circumstances, reception using a nearly omni-directional spacecraft antenna is required. Very high e.i.r.p. is needed at earth stations because of low spacecraft antenna gain, and to provide high reliability.

With computers on the spacecraft, automatic sequencing and operation of spacecraft systems is largely predetermined and stored on-board for later execution. For some complicated sequences, automatic operation is a requirement. Telecommand capability is required for in-flight alteration of stored instructions, which may be needed to correct for observed variations or malfunctions of spacecraft behaviour. This is particularly true for missions of long duration, and for those circumstances where sequencing is dependent on the results of earlier spacecraft events. For example, the commands for spacecraft trajectory correction are based on tracking measurements and cannot be predetermined.

Command data rates have been as low as one bit per second, with an increase to a few kilobits per second expected in the future.

The telecommand link must be relatively free from weather effects. Reliable telecommand includes the need for weather independent maintenance telemetering to verify that commands are correctly received and loaded into command memory. The 2 GHz allocations provide weather independence.

2.3 *Tracking requirements*

Tracking provides information used for spacecraft navigation and for radio science studies.

2.3.1 *Navigation*

The basic tracking measurements for navigation are radio-frequency Doppler shift and the round-trip propagation time of a ranging signal. The measurements must be made with a degree of precision that satisfies navigation requirements [Curkendall and Stephensen, 1970]. Measurement accuracy is affected by variations in velocity of propagation, knowledge of station location, timing precision, and electronic circuit delay in earth and space station equipment. Table I lists accuracy specifications for the Viking Mars orbiter/lander and Voyager Jupiter/Saturn flyby missions. Future requirements for longer or more difficult missions require more accurate navigation and tracking [Melbourne, 1976].

TABLE I – *Navigation and tracking accuracy specifications*

Mission (launch date)	Required navigation accuracy (km)	Doppler frequency measurement accuracy (Hz)	Range measurement accuracy (m)	Estimated accuracy of earth station location (m)
Viking Mars Orbiter/Lander (1975)	300 (at Mars)	± 0.003	± 20	± 20
Voyager Jupiter/Saturn flyby (1977)	400 (at Jupiter) 1300 (at Saturn)	± 0.001 ± 0.001	± 4 ± 4	± 2 ± 2
Galileo Jupiter Orbiter (expected 1987)	300 (at Jupiter)	± 0.0005	± 2	± 1

2.3.2 *Radio science*

Spacecraft telecommunication links can also be important to studies of propagation, relativity, celestial mechanics, and gravity [Anderson, 1973; Hennes and Fulmer, 1972; Michael, 1972; Eshleman *et al.*, 1977]. Amplitude, phase, frequency, polarization and delay measurements provide the needed information. The opportunity to make these measurements depends upon the availability of appropriate allocations. Above 1 GHz transmission delay and Faraday rotation (charged particle and magnetic field effects) decrease rapidly with increasing frequency, and thus are best studied with the lower frequencies. The higher frequencies provide relative freedom from these effects and are more suitable for studies of relativity, gravity and celestial mechanics. For these studies, calibration of charged particle effects at the lower frequencies is also needed.

Range measurements with an absolute accuracy of one or two centimetres are required for this fundamental scientific work. This ranging accuracy depends upon wide band codes and the simultaneous use of multiple frequencies for charged-particle calibration.

2.4 *Requirements for manned deep-space missions*

Manned deep-space missions beyond the moon have not yet been flown. The functional requirements of such a mission will be similar in kind to those for unmanned missions. The presence of human occupants in spacecraft will place additional requirements for reliability on the telemetering, telecommand and tracking functions. Given the necessary level of reliability, the significant difference between manned and unmanned missions will be the use of voice and television links for both Earth-to-space and space-to-Earth communication. From a telecommunication standpoint, the effect of this will be an expansion of transmission bandwidth in order to accommodate the video signals. Given the link performance to accomplish the required data transfer rates, telecommunications for manned and unmanned deep-space research are similar enough in concept that separate discussion is generally not required.

3. Technical characteristics

3.1 *Earth stations*

Deep-Space Network (DSN) earth station complexes are located at approximately 120° longitude intervals as shown in Table II. At each complex there is one 64 m diameter antenna, one 34 m antenna, one or more 26 m antennas, high power transmitters with extremely precise frequency control, sensitive phase-locked loop receivers, and associated equipment [Reid *et al.*, 1973]. The DSN is interconnected via terrestrial communication lines and fixed satellite facilities to a control centre in California, USA.

TABLE II – *Location of DSN earth station complexes*

Location	Latitude	Longitude	Height above mean sea level
Goldstone, California (USA)	35°22′ N	115°51′ W	1019 m (3343 ft)
Canberra, Australia	35°28′ S	148°59′ E	818 m (2684 ft)
Madrid, Spain	40°26′ N	4°17′ W	791 m (2595 ft)

Tables IIIa and IIIb list major characteristics of the earth stations.

The system noise temperatures listed in Table IIIa are for the specified conditions. The noise temperature varies with the operating mode, weather conditions and elevation angle. This variation must be included in performance and interference calculations. The noise contribution of the earth station receiver alone is shown in Fig. 1. The curve is based on current US experience in the 2 and 8 GHz bands and estimates of possible implementation at the higher frequencies.

TABLE IIIa – *Characteristics of earth stations with 64 m antennas*

Band (GHz)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)	Receiving system noise temperature (K)	Receiving system noise spectral density (dB(W/Hz))
2.1 Earth-to-space	61	0.15	50 56 (3)	111 117	–	–
2.3 Space-to-Earth	62	0.13	–	–	23 (1) 16 (2)	–215 (1) –217 (2)
7.2 Earth-to-space	71	0.05	43	114	–	–
8.4 Space-to-Earth	72	0.04	–	–	30 (1) (4) 23 (2)	–214 (1) (4) –215 (2)
13.0 Space-to-Earth	75 (4)	0.03	–	–	39 (1) (4) 25 (2) (4)	–213 (1) (4) –215 (2) (4)
17.0 Earth-to-space	76 (4)	0.03	To be determined	To be determined	–	–
32.0 Space-to-Earth	73 (4)	0.04	–	–	75 (1) (4) 53 (2) (4)	–210 (1) (4) –211 (2) (4)
34.5 Earth-to-space	72 (4)	0.04	To be determined	To be determined	–	–

(1) Clear weather, 30° elevation angle, diplex mode for simultaneous reception and transmission.

(2) Clear weather, 30° elevation angle, receive only.

(3) 56 dBW transmitter power use during spacecraft emergencies only.

(4) Preliminary estimate.

TABLE IIIb – *Characteristics of earth stations with 34 m antennas*

Band (GHz)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)	Receiving system noise temperature (K)	Receiving system noise spectral density (dB(W/Hz))
2.1 Earth-to-space	55	0.27	43	98	–	–
2.3 Space-to-Earth	56	0.25	–	–	29(2) 22(1)	–214(2) –215(1)
7.2 Earth-to-space	66	0.08	43	109	–	–
8.4 Space-to-Earth	67	0.07	–	–	26(2)	–214(2)

(1) Clear weather, 30° elevation angle, diplex mode for simultaneous reception and transmission.

(2) Clear weather, 30° elevation angle, receive only.

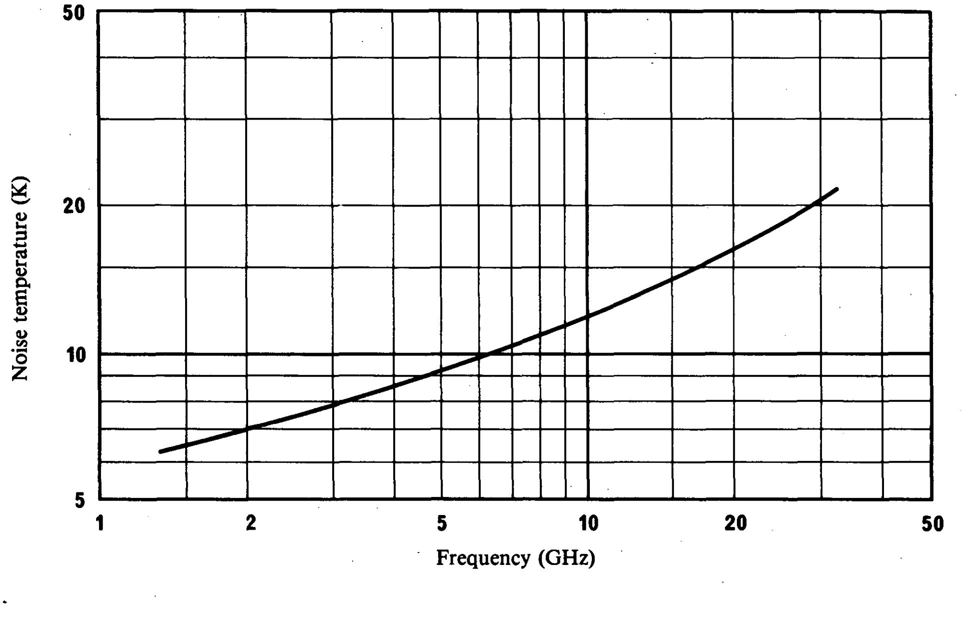

FIGURE 1 – *Noise temperature of earth-station receiving equipment including antenna spillover. Receive-only mode*

The receiving performance of deep-space earth stations is usually specified in terms of the ratio of signal energy per bit to noise spectral density required to give a particular bit error ratio. Another way to show the high performance and sensitivity of these stations is to express the ratio of antenna gain to noise temperature. This ratio, commonly referred to as G/T, is 50 dB at 2.3 GHz, and 58.4 dB at 8.4 GHz. These values may be compared with the lower and typical 41 dB of some fixed satellite earth stations.

3.2 *Space stations*

Spacecraft size and weight is limited by the payload capability of the launch vehicle. The power of the space station transmitter and the size of the antenna are limited in comparison with those parameters at earth stations. The noise temperature of the receiver is higher because a simple uncooled preamplifier is generally used.

The space station has a combined receiver-transmitter, called a transponder, which operates in one of two modes. In the turn-around, (also called two-way) mode, the carrier signal received from an earth station is used to control the oscillator in a phase-locked signal loop. The frequency of this oscillator is then used to control the transmitter frequency of the transponder according to a fixed ratio. In the one-way mode, no signal is received from an earth station, and the transmitter frequency is controlled by a crystal oscillator.

In the two-way mode, the spacecraft transmitted frequency and phase is controlled very precisely because of the extreme accuracy and precision of the signal received from an earth station.

Table IV lists major characteristics of space stations designed for the Galileo mission to Jupiter.

TABLE IV – *Characteristics of United States space station design (Galileo Jupiter Orbiter)*

Space-to-Earth frequency (MHz)	Antenna size (m)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)
2295	3.7	37	2.3	13	50
8425	3.7	48	0.64	13	61

Earth-to-space frequency (MHz)	Antenna size (m)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Receiver noise temperature (K)	Receiver noise spectral density (dB(W/Hz))
2115	3.7	36	2.6	1200	–198
7150	3.7	48	0.64	390	–202

Because of the limited e.i.r.p. of space stations, the earth station must have the most sensitive receiver possible. Receivers with lower sensitivity may be used in space stations as a result of the very high e.i.r.p. of the earth station. Data rate requirements and considerations of size, weight, cost, complexity and reliability determines the receiver noise temperature needed for a particular spacecraft.

The Helios spacecraft of the Federal Republic of Germany had a receiver noise temperature of 600 K at 2.3 GHz. A 7150 MHz receiver being developed for the Galileo mission to Jupiter is expected to have a noise temperature of 390 K.

At the present time, the power of the space station transmitter is limited primarily by the electrical power that can be supplied by the spacecraft, and not by transmitter technology.

4. Deep-space telecommunication methods

Telemetering and telecommand functions for deep-space telecommunications are typically accomplished by transmission of phase modulated carriers [Viterbi, 1966; Lindsey, 1972; Lindsey and Simon, 1973]. Doppler tracking is done by phase coherent detection of the carrier. By adding a ranging signal to the modulation, the ranging function is performed [Edelson, 1972; NASA, 1976].

4.1 *Carrier tracking and Doppler measurement*

As received on Earth, the frequency of a signal transmitted by the spacecraft is modified by the Doppler effect [Curkendall and Stephensen, 1970]. The means to measure the Doppler shift, and hence the velocity of the spacecraft with respect to the earth station, is provided by carrier phase tracking. Earth and space station receivers track the carrier signal with a phase-locked loop. In the two-way transponder mode, the frequency and phase in the space station phase-locked loop are used to develop one or more space-to-Earth frequencies. This provides signals to the earth station that are correlated with the Earth-to-space frequency, enabling precise Doppler measurements to be made.

In the one-way mode, the space-to-Earth frequencies are derived from the oscillator in the transponder, and the Doppler measurement is based on a priori knowledge of the oscillator frequency.

The carrier tracking process also provides the local oscillator signal used to convert the radio frequency to the receiver intermediate frequency.

4.2 *Modulation and demodulation*

The radio links use phase (angle) modulation of the radio frequency carrier. The base-band digital data signal is used to modulate a subcarrier, which in turn phase modulates the radio frequency carrier. A square wave subcarrier is typically used for telemetering; for telecommand the subcarrier may be sinusoidal. The modulation index is adjusted to provide a desired ratio of residual carrier power to data sideband power. This ratio is selected to provide optimum carrier tracking and data detection in the receiver.

RF carrier and data subcarrier demodulation is accomplished by phase-locked loops. Data detection generally uses correlation and matched filter techniques.

Television and voice links for manned missions may use other modulation and demodulation techniques.

4.3 *Coding*

In a digital telecommunication link, error probability can be reduced if the information bandwidth is increased. Coding accomplishes this increases by translating data bits into a larger number of code symbols in a particular way. Some examples of coding types are block and convolutional codes [Forney, 1970; Lindsey and Simon, 1973; Viterbi and Omura, 1979]. After transmission, the original data are recovered by a decoding process that is matched to the code type. The performance advantage of coded transmission is related to the wider bandwidth, and can amount to 3.8 dB (convolutional coding as used in the Voyager Jupiter/Saturn mission, with a maximum bit error ratio of 1×10^{-3}).

4.4 *Multiplexing*

Science and maintenance telemetering may be combined into a single digital data stream by time division multiplexing; or may be on separate subcarriers that are added to provide a composite modulating signal. A ranging signal may also be added in combination with telemetering or telecommand. The amplitude of the different data signals is adjusted to properly divide the transmitter power between the carrier and information sidebands.

4.5 *Ranging*

Ranging is performed from an earth station using the space station transponder in the two-way mode. Ranging modulation on the Earth-to-space signal is recovered in the transponder and used to modulate the space-to-Earth carrier. At the earth station, comparison of the transmitted and received ranging codes yields a transmission delay measurement proportional to range.

A fundamental limitation to ranging precision is the ability to measure time correlation between the transmitted and received codes. The system currently in use employs a highest code frequency of 0.5 MHz. The code period is 2 µs and resolution to 4 ns is readily achieved, assuming sufficient signal-to-noise ratio. This resolution is equivalent to 120 cm in a two-way path length, or 60 cm in range. This meets the current navigation accuracy requirements of Table II.

For the 1 cm accuracy needed for future radio science experiments (§ 2.3.2), a code frequency of at least 30 MHz is required.

4.6 *Bandwidth*

The total bandwidth suitable for deep-space telecommunications is a function of the required data rates, the number of spacecraft in each mission, the number of missions, and the extent to which frequencies may be shared without mutual interference.

4.6.1 *Link bandwidth*

Earth-to-space and space-to-Earth bandwidths are governed by required telemetering data rates [Davies and Murray, 1971] and ranging precision [Couvillon *et al.*, 1970]. By contrast, the telecommand spectrum width is relatively narrow as a result of the relatively low data rate.

To pass a periodic square modulation waveform with no more than 0.3 dB loss, the bandwidth must include the fifth harmonic of the modulating frequency. For the telemetering signal, the radio frequency bandwidth must be wide enough to pass the fifth harmonic of the sub-carrier frequency plus the fifth harmonic of the clock rate (1/2 the bit rate). With present techniques, the sub-carrier frequency must be high enough to provide 1.5 sub-carrier cycles per data bit. The total bandwidth required is therefore:

$$\begin{aligned} BW &= 2[(BR \times 1\tfrac{1}{2} \times 5) + 5 \times \tfrac{1}{2}\, BR] \\ &= 20\ BR \end{aligned} \tag{1}$$

where,

BW: RF bandwidth,

BR: bit rate.

For example, a 1 Mbit/s uncoded data rate requires a 1.5 MHz subcarrier and 20 MHz RF bandwidth.

Figure 2 shows a curve representative of telemetering spectra.

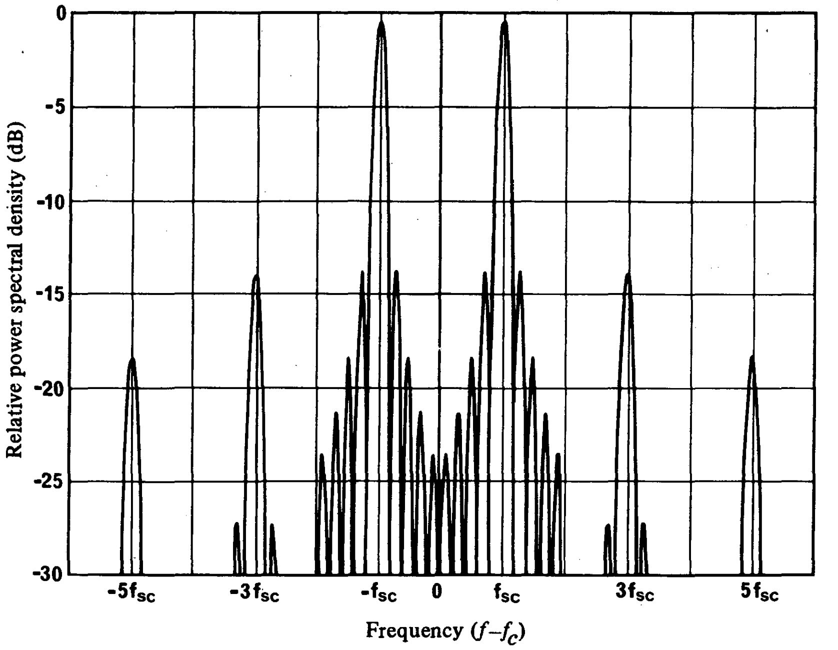

FIGURE 2 – *Telemetering power density spectrum (Space-to-Earth)*

$f - f_c$: Frequency relative to carrier

f_c : Carrier frequency

f_{sc} : Subcarrier frequency

As telemetering data rates increase, the need for a sub-carrier to keep the data power outside the carrier tracking loop bandwidth becomes less important. This is because the carrier loop bandwidth is a relatively smaller fraction of the data spectrum bandwidth. By the use of appropriate coding, data power near the carrier frequency can be minimized so that sub-carriers are not necessary. Elimination of sub-carrier reduces the total bandwidth requirement to:

$$BW = 2[5 \times \tfrac{1}{2} BR] = 5\ BR \tag{2}$$

Direct modulation of the carrier may be used, requiring less bandwidth.

Increased telemetering data rates are expected in the future. For example, the surface imaging radar being developed to study the oceans of the Earth will gather data at 110 Mbit/s. An instrument like this is used for the study of other planets with a corresponding bandwidth requirement for deep-space links.

The current implementation of ranging uses square wave biphase modulation. The bandwidth required for the transmitted ranging signal is determined by the highest code frequency. The spectrum to the fifth harmonic is shown in Fig. 3. A bandwidth equal to six times the code frequency is usually considered acceptable. For some deep-space missions, the maximum bandwidth requirement will be determined by ranging accuracy considerations.

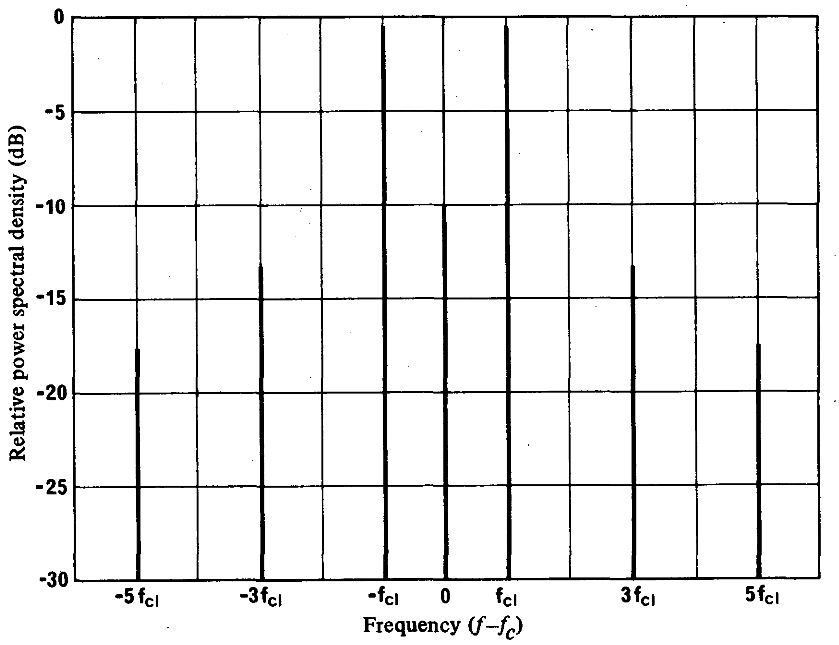

FIGURE 3 – *Ranging power density spectrum (Earth-to-Space)*

$f - f_c$: Frequency relative to carrier

f_c : Carrier frequency

f_{cl} : Ranging clock frequency

Future requirements for very high telemetering and ranging code rates may result in the need for additional reduction of transmitted spectrum bandwidth in order to accommodate one or more spacecraft within a particular band allocation. This is particularly true for the relatively narrow 2 and 8 GHz allocations. Suitable techniques include quadriphase modulation, minimum shift keying utilizing waveforms with reduced harmonic power, and data compression. Some of these techniques impose a penalty in link performance or data quality.

Link bandwidth requirements for deep-space research are based on needed bit rates for the various functions shown in Table V.

The maximum radio frequency bandwidth needed for a particular mission is determined by the total bit rate required to permit simultaneous functions, and by the method of modulation. The ranging function is usually the most significant determinant of the maximum total bit rate. For current implementation, the maximum radio frequency bandwidth for a single unmanned spacecraft is approximately 3 MHz. For the VLBI function (§ 4.8.2), a pair of spectral lines spaced 25 MHz from the carrier frequency will be a part of the transmitted signal. Future requirements for the higher rates shown in Table V will result in required transmission bandwidths up to several hundred Megahertz.

TABLE V – *Required bit rates for a deep-space mission*

Direction and function	Link		
	Weather independent	Normal	High data rate
Earth-to-space			
Telecommand (bit/s)	1–1000	1–1000	1–1000
Computer programming (kbit/s)	1–50	1–100	1–200
Voice (kbit/s)	45	45	45
Television (Mbit/s)	1–4	1–12	6–24
Ranging (Mbit/s)	1	10	100
Space-to-Earth			
Maintenance telemetering (bit/s)	8–500	8–500	8–1000
Scientific data (kbit/s)	0.008–115	1–500	$50–10^4$
Voice (kbit/s)	45	45	45
Television (Mbit/s)	0.2–0.8	2–8	6–24
Ranging (Mbit/s)	1	10	100

4.6.2 *Mission bandwidth*

Some deep-space missions use two or more spacecraft. At some times during the mission, the spacecraft may be simultaneously within the beamwidth of the earth station antenna. A mission where the spacecraft are placed in the orbit around a planet is an important example of this condition. Under these circumstances, the simultaneous operation of the telecommunication links results in a requirement for radio frequency bandwidth sufficient to accommodate the several signals without mutual interference.

Typical mission design, along with consideration of simultaneous function requirements and the possibility of more efficient use of the spectrum, result in the conclusion that expected deep-space missions can be conducted within a total bandwidth of approximately 500 MHz.

4.6.3 *Multiple mission bandwidth*

Several deep-space missions to different parts of the solar system may share the same radio frequencies except during those times when mutual interference results. This interference typically can occur for brief periods when one spacecraft is close to the Earth, resulting in very high signal strength, or when spacecraft from different missions are within the earth station beamwidth. Analysis of current and proposed missions shows that periods of mutual interference are brief enough so that they may be avoided by time-sharing the use of telecommunication links.

The conclusion that 500 MHz bandwidth will accommodate the maximum requirements of future deep-space missions (§ 4.6.2) is also appropriate for a multi-mission environment.

4.6.4 *Link reliability and the utilization of allocated bands*

The foregoing sub-section set forth the maximum bandwidth required for the conduct of deep-space research. Existing allocations near 2 and 8 GHz cannot accommodate these maximum requirements. These allocations do, however, provide an essential capability for deep-space research.

The 10 MHz wide allocations near 2 GHz provide for links that are relatively immune to adverse effects of rain and cloud. Past and currently-planned spacecraft include the equipment needed to make use of these allocations to ensure at least partial mission success in the event of adverse weather that precludes the use of higher frequency bands.

Current missions rely primarily on the 50 MHz wide allocations near 8 GHz to provide the links for normal mission operations. Where maximum possible data rates are not required for a particular mission, these allocations will continue to provide needed deep-space links.

The 500 MHz allocations near 15 and 32 GHz provide for future high performance links that meet the maximum bandwidth requirements specified in the foregoing sub-sections.

4.7 *Antenna gain and pointing*

For the parabolic antennas typically used in space research, the maximum gain is limited by size and by the accuracy with which the surface approaches a true parabola [Ruze, 1966]. The latter limitation places a bound on the maximum frequency that may be effectively used with a particular antenna.

One factor in surface accuracy, common to both Earth and space station antennas, is manufacturing precision.

For earth station antennas, surface deformation is caused by wind and thermal effects. As elevation angle is varied, gravity introduces additional distortion of the surface.

For space station antennas, size is limited by space available in the launch vehicle, and by the state of the art in the construction of unfurlable antennas. Thermal effects cause distortion in space station antenna surfaces.

The maximum usable gain of antennas is limited by the ability to point them accurately. The beamwidth must be adequate to allow for the angular uncertainty in pointing. All the factors that cause distortion of the reflector surface also affect pointing accuracy. The accuracy of the spacecraft attitude control system (often governed by the amount of propellant which can be carried) is a factor in space station antenna pointing.

The precision with which the location of the earth and space stations are known with respect to each other affects the minimum usable beamwidth and the maximum usable gain.

Table VI shows typical limits on antenna performance. Figure 4 shows the gain of the 64 m earth station antennas as a function of frequency and elevation angle.

TABLE VI – *Current limitations on accuracy and maximum antenna gain*

Limiting parameter	Space station antennas		Earth station antennas	
	Typical minimum value of parameter	Maximum gain	Typical minimum value of parameter	Maximum gain
Accuracy of dish surface	0.024 cm r.m.s. on a 3.7 m diameter reflector	66 dB (¹) at 100 GHz	0.12 cm r.m.s. on a 64 m diameter reflector	76 dB (¹) at 20 GHz
Pointing accuracy	$\pm 0.15°$ (3σ)	55 dB (²)	$\pm 0.016°$ (3σ)	75 dB (²)

(¹) Gain at other frequencies will be lower.

(²) Gain of antenna with half-power beamwidth equal to 2 × pointing accuracy (3σ). Beamwidth of antenna with higher gain will be too narrow with respect to the available pointing accuracy.

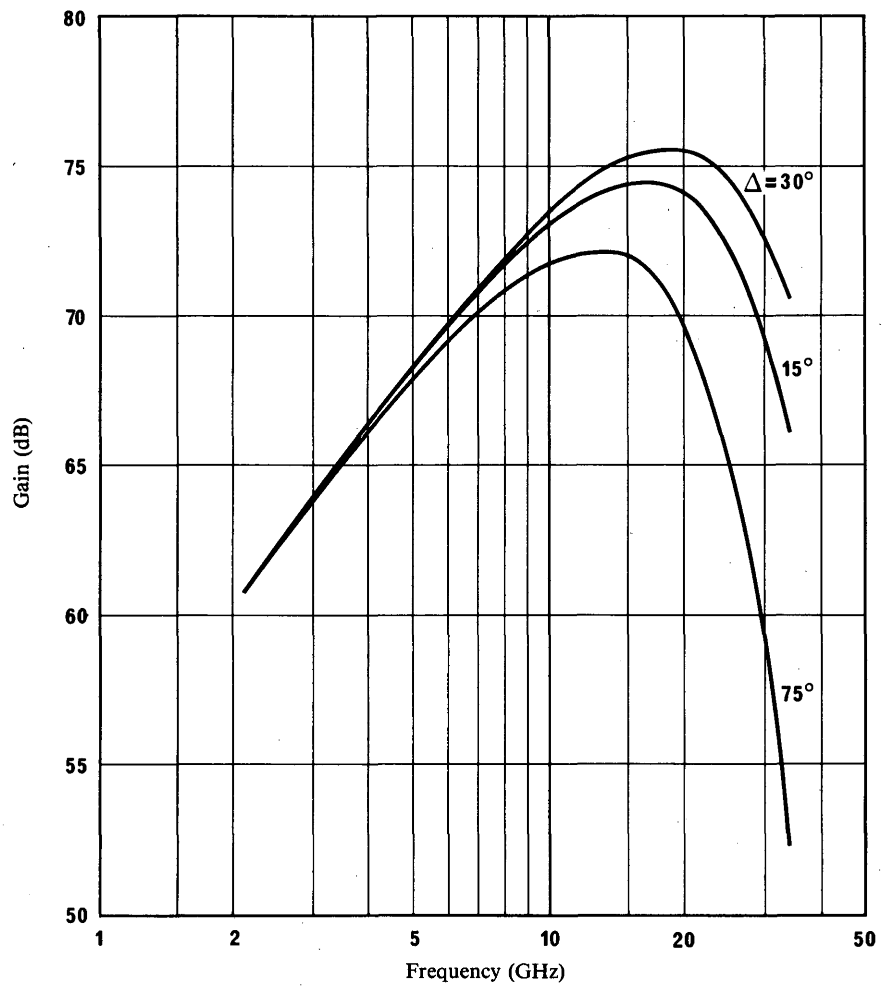

FIGURE 4 – *Gain of 64 m earth station antenna*

Δ: elevation angle of antenna (degrees)

4.8 *Additional radionavigation techniques*

Doppler and ranging measurements provide the basic tracking information needed for navigation. Additional techniques have been developed to enhance navigation accuracy.

4.8.1 *Calibration of the velocity of propagation as affected by charged particles*

Range and Doppler measurements are influenced by variations in the velocity of radio wave propagation caused by free electrons along the transmission path. The electrons exist in varying densities in space and in planetary atmospheres, and are particularly dense near the Sun. Unless accounted for, these variations in propagation velocity can introduce errors in navigation calculations.

The charged particles cause an increase in phase velocity and a decrease in group velocity. By comparing range change with integrated Doppler over a period of time, the charged particle effect may be determined. The effect on propagation velocity is inversely proportional to the square of the radio frequency. This frequency dependence may be used for additional calibration accuracy. Turnaround ranging and Doppler tracking can be performed with simultaneous space-to-Earth signals in two or more separate bands. The charged particle effects in the separate bands are different in magnitude, and this difference is used to improve the calibration.

The charged particle effect is discussed in Reports 683 and 849.

4.8.2 *Very long baseline interferometry (VLBI)*

Accuracy of spacecraft navigation depends upon the precise knowledge of earth station location with respect to the navigation co-ordinate system. A 3 metre error in the assumed station location can result in a 700 kilometre error in the calculated position of a spacecraft at Saturn distance. VLBI provides a means of improving the estimate of station location by using a celestial radio source (quasar) as a signal source at an essentially unchanging point on the celestial sphere [Rogers, 1970]. It is possible to record the quasar signals in such a way as to determine with great accuracy, the difference in time of reception at two widely separated stations. Using a number of measurements the station locations can be determined to a relative accuracy of 50 cm. Frequencies near 2 and 8 GHz are used for VLBI at the present time.

The VLBI technique is also used to measure directly the spacecraft declination angle. Two accurately located earth stations separated by a large north/south distance, measure the range to the spacecraft. The declination can then be calculated with great precision.

A third application of the VLBI method can be used to improve the accuracy of measurement of spacecraft angular position [Reid *et al.*, 1973]. Two earth stations alternately observe a spacecraft signal and a quasar signal. By knowing time, station location, and the effect of Earth rotation on the received signals, the angular position of the spacecraft can be determined with respect to the celestial references. When fully developed the techniques will provide a significant improvement over the current accuracy of 0.01 arc second. The improved accuracy will permit more precise navigation [Swenson and Mathur, 1968; Melbourne and Curkendall, 1977].

5. Performance analysis and design margins

Table VII shows a link budget used for performance analysis. The example given is for high rate telemetering from Jupiter. Similar analysis for telecommand and ranging is done during mission planning. The earth and space station characteristics shown earlier are used as the basis for calculating a performance margin for each telecommunication function.

A most important point in the design of deep-space missions is that the telemetering performance margin is quite small (3.5 dB in the example given). This small margin is a consequence of the need to obtain maximum scientific value from each spacecraft. To design with a 10 dB larger margin of safety would reduce the quantity of telemetered data by a factor of 10. The risk of using a system with small performance margin is its susceptibility to harmful interference, and for bands above 2 GHz, decreased reliability caused by weather effects.

TABLE VII – *Performance budget. Spacecraft-to-Earth from Jupiter*

Mission: Voyager Jupiter/Saturn 1977 Mode: Telemetering, 115.2 kbit/s, coded, 8.45 GHz carrier	
Transmitter parameters	
RF power, (dBW) (21W)	13.2
Circuit loss, (dB)	−0.2
Antenna gain, (dBi) (3.7m)	48.1
Pointing loss, (dB)	−0.2
Path parameters	
Free space loss between isotropic antennas, (dB) 8.45 GHz, 9.3 × 10^8 km	−290.4
Receiver parameters	
Antenna gain, (dBi) (64m, 30° elevation angle)	72.0
Pointing loss, (dB)	−0.3
Weather attenuation, (dB)	−0.1
System noise spectral density, (dBW/Hz) (22.6K)	−215.1
Total power summary	
Link loss, (dB)	−171.1
Received power, $P(T)$, (dBW)	−157.9
Carrier tracking performance (two-way)	
Carrier power/total power, (dB)	−15.4
Received carrier power, (dBW)	−173.3
Carrier threshold noise bandwidth, (B = 10 Hz) (10 log B)	10.0
Noise power, (dBW)	−205.1
Threshold signal/noise, (dB)	20
Threshold carrier power, (dBW)	−185.1
Performance margin, (dB)	11.8
Data detection performance	
Data power/total power, (dB)	−0.3
Data reception and detection losses, (dB)	−0.5
Received data power, (dBW)	−158.7
Noise bandwidth, dB (effective noise bandwidth for matched filter detection of 115.2 kbit/s data)	50.6
Noise power, (dBW)	−164.5
Threshold signal/noise (0.005 bit error rate) (dB)	2.3
Threshold data power, (dBW)	−162.2
Performance margin, (dB)	3.5

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REPORT 984

FREQUENCY BANDS PREFERRED FOR TRANSMISSION TO AND FROM MANNED AND UNMANNED SPACECRAFT FOR NEAR-EARTH SPACE RESEARCH

(Question 22/2; Study Programme 22B/2)

(1986)

1. Introduction

This Report provides the basis for the selection of frequencies for near-Earth space research. Preferred frequencies for use by the space research service for near-Earth missions are presented based upon propagation and technical considerations. The Annex to this Report mentions and discusses propagation factors which affect the transmission of a radio wave and considers other technical aspects relating specifically to the space research service. Preferred frequency bands for passive near-Earth space research are discussed in Report 693.

2. Frequency range

Frequencies for consideration in this analysis range from 100 MHz to 350 GHz. The lower limit is determined by those frequencies at which waves penetrate the ionosphere without important modifications. Although this lower limit is about 30 MHz, factors such as ionospheric disturbances, geographical locations, galactic and man-made noise, mitigate against the use of these low frequencies and place a practical lower limit of about 100 MHz for space research applications (see Report 263). The upper limit of 350 GHz is chosen, as this is above the highest frequency (275 GHz) currently allocated by the ITU.

2.1 *Frequency range division*

Due to atmospheric and precipitation effects, it is convenient to divide the frequency spectrum under consideration into two ranges: 100 MHz-22 GHz, and 22 GHz-350 GHz. Division was chosen at 22 GHz because this frequency is near the first absorption peak of water vapour, and also because it is at the region above which the attenuation due to rain is so high, that, even during periods of low rain rate, trans-atmospheric propagation is not practicable at the low elevation angles employed by the space research service. Precipitation effects in the frequency of range 22-350 GHz are therefore not to be considered as a determininant for preferred frequencies in this Report.

3. Link performance

In the calculation of link performance, use was made of the information and formulae pertaining to atmospheric and precipitation effects given in Reports 563, 564, 670, 719, 720 and 721 (Geneva, 1982). Figures 1 and 2 show total attenuation and sky-noise temperature for an antenna elevation of 5°. A 5° elevation angle has been assumed in this analysis as it is considered to be about the minimum angle that will be required for establishing telecommunications between a space research spacecraft and an earth station. Further, since an earth station will spend considerably more time in communication with a spacecraft at the lower elevation angles than at the higher elevation angles, the 5° earth-station antenna elevation essentially depicts a "worst-case" situation.

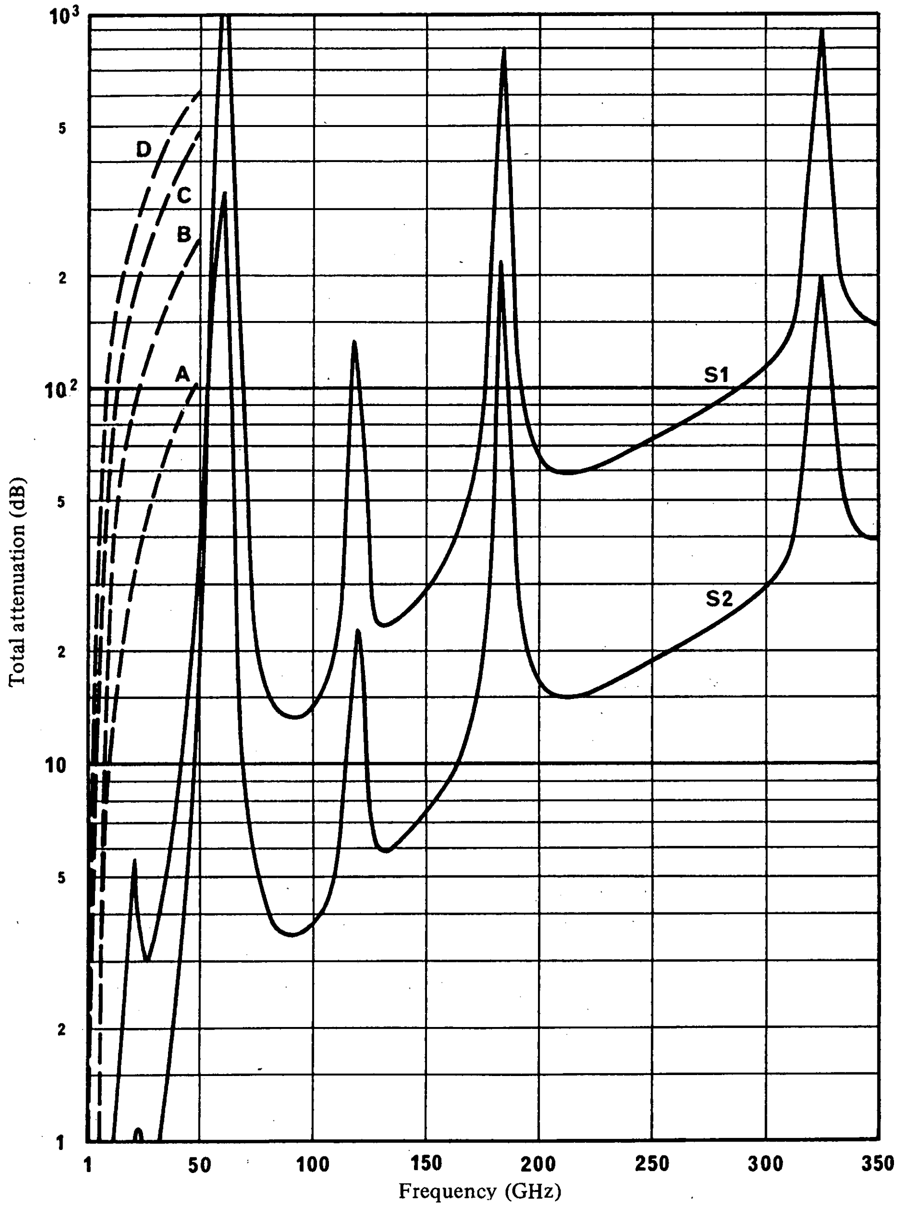


FIGURE 1 – *Total attenuation due to molecular effects and molecular/precipitation effects*

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
} at 5° elevation

S1: clear sky at 5° elevation
S2: clear sky at 20° elevation
} ρ = 7.5 g/m³, temperature = 20 °C

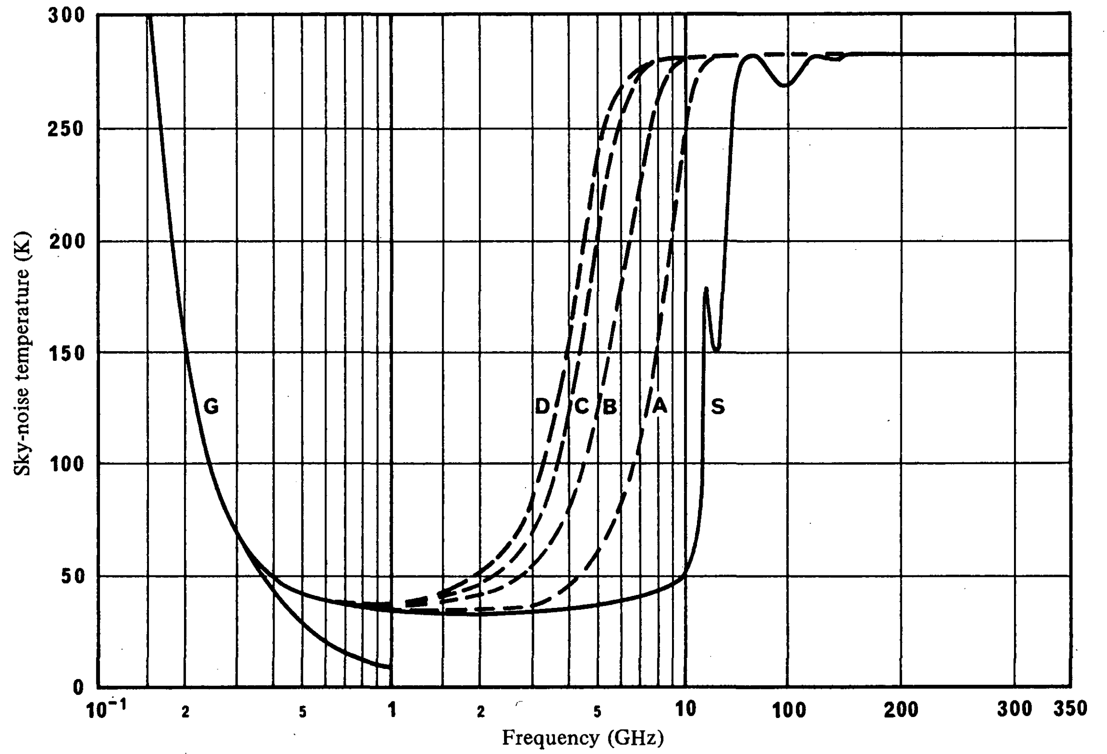


FIGURE 2 – *Sky-noise temperature at 5° elevation*

Curves G: galactic noise
A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky

Assumed system and receiver noise temperatures for space and earth stations are shown in Figs. 3 and 4 respectively. The noise temperatures are depicted as a step function because of the assumption that the receiver noise temperature will not change significantly over its frequency of operation, but rather remain fairly constant over the operating frequency ranges for which it is designed.

Using the above data and the formulae from § 4.1 of Annex I, normalized link performance values were computed for bidirectional propagation through the atmosphere and for the two cases of antenna restrictions (see Annex I, § 4). These normalized link performance values are plotted in Figs. 5 to 8 for the frequency range 0.1-22 GHz, and in Figs. 9 to 12 for the frequency range 22-350 GHz.

4. Discussion

Bandwidths required for near-Earth space research depend on the sophistication and objectives of space missions. The range of typical link bandwidths to meet the diverse requirements of the space research services is discussed in Annex I.

The important features of the link performance curves are the locations of the maxima and the effect of the weather on the optimum frequency range. The optimum frequency range was determined by noting those frequencies on either side of a curve maximum, which correspond to a link performance value of approximately 1 dB below that of the maximum. A decrease of the order of 1 dB below a curve maximum was considered sufficient to represent a relatively flat portion of the curve about its maximum.

In each of the Figs. 5 to 8, a set of parametric curves is shown for precipitation conditions with rain rates of 20, 50, 100 and 140 mm/h and for clear-sky conditions. From these figures, it can be seen that rain has a pronounced effect on the optimum range of frequencies, shortening and shifting the optimum range to lower frequencies for higher rain rates. For countries located in regions of high rain rate (see Report 563 (Geneva, 1982)), the choice of suitable frequencies is critical if they are to maintain a high quality of performance despite adverse weather conditions.

For the frequency range 22-350 GHz, Figs. 9 to 12 show a series of normalized link performance curves for clear-sky conditions only. Figure 1 shows the difference in attenuation for elevation angles of 5° and 20°.

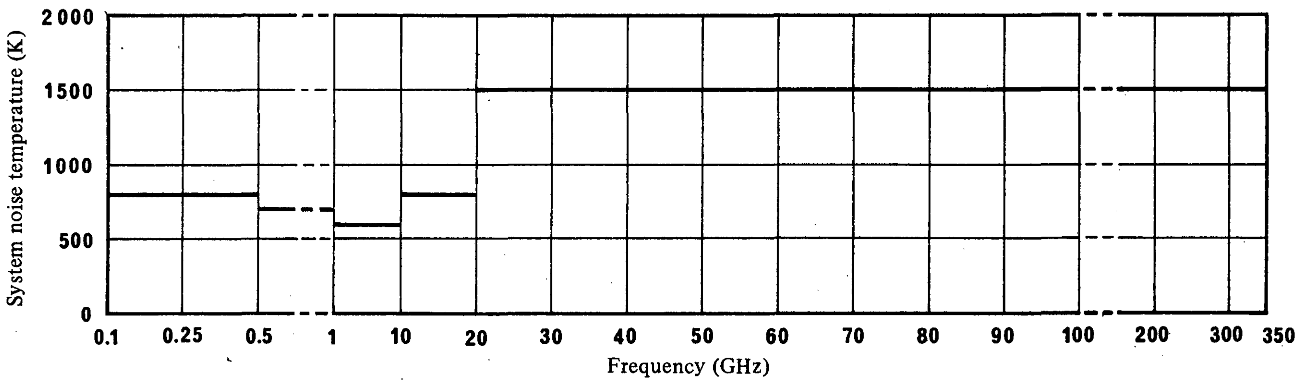


FIGURE 3 – *Assumed satellite system noise temperature*

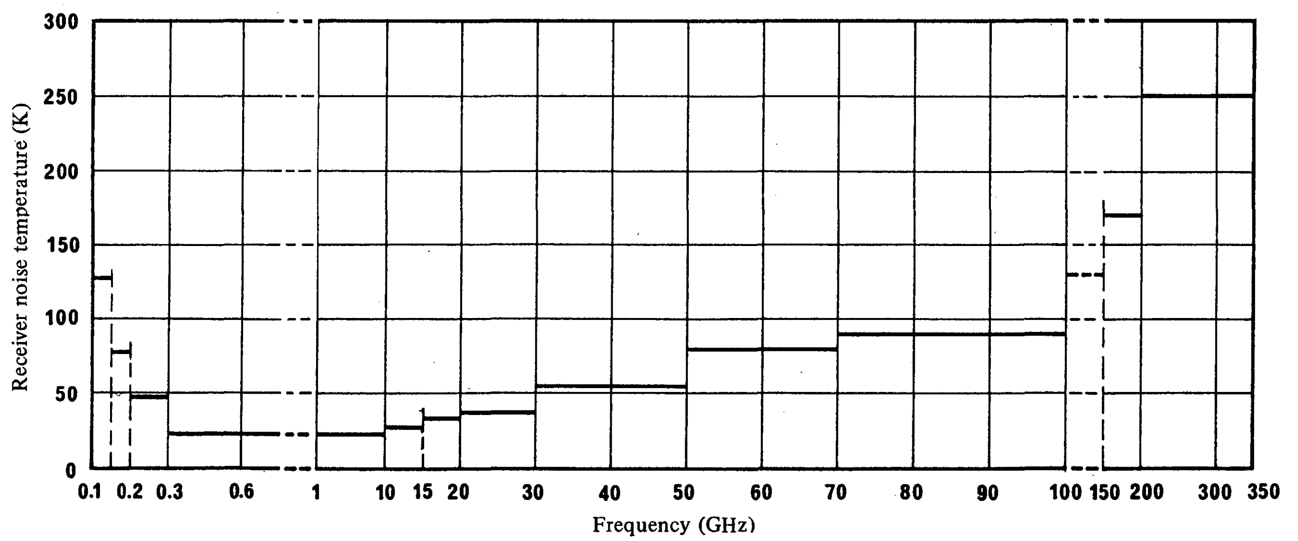


FIGURE 4 – *Assumed earth-station receiver noise temperature*

Note. – The values in Figs. 3 and 4 are derived from a number of technical references. They are typical of existing equipments in bands below about 20 GHz and represent anticipated developments in bands above 20 GHz.

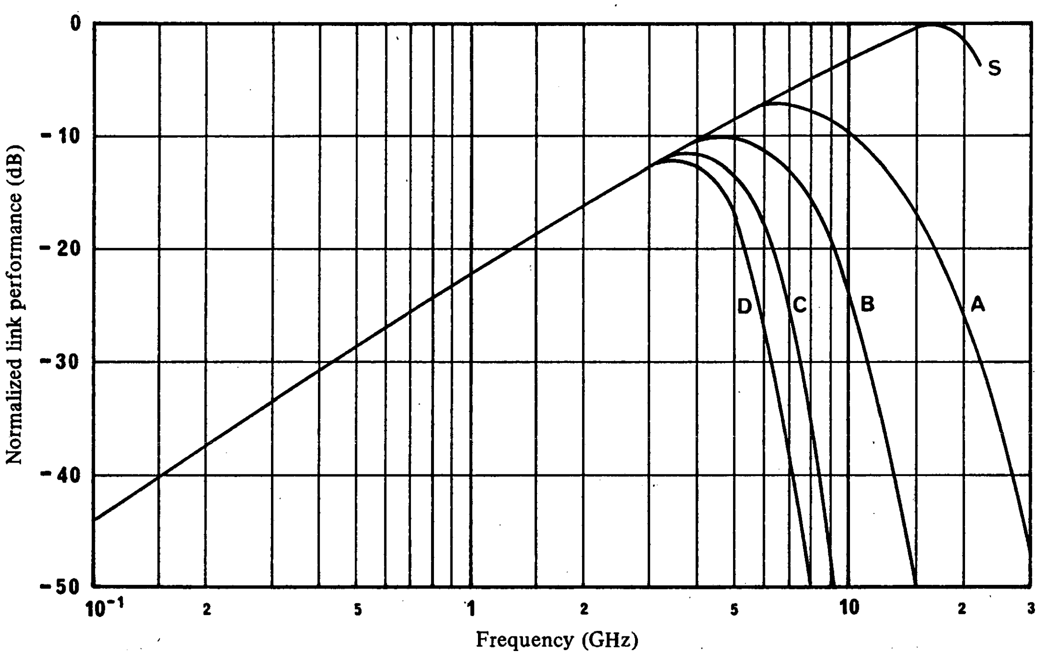


FIGURE 5 – *Normalized Earth-to-space link performance. Space station antenna diameter fixed*

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky

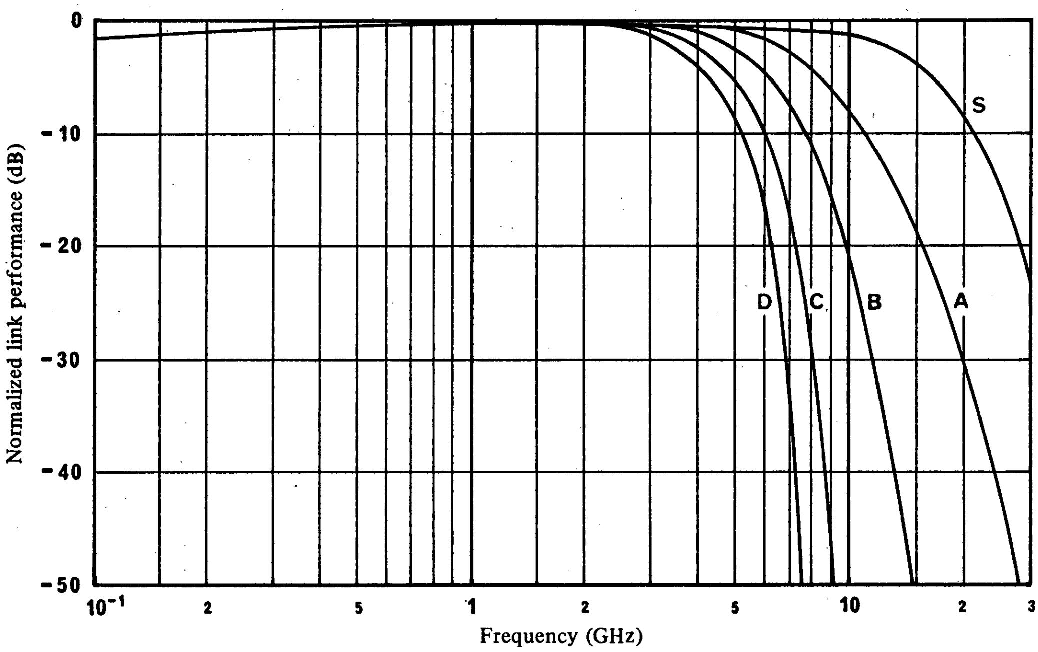


FIGURE 6 – *Normalized Earth-to-space link performance. Space station antenna beamwidth fixed*

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky

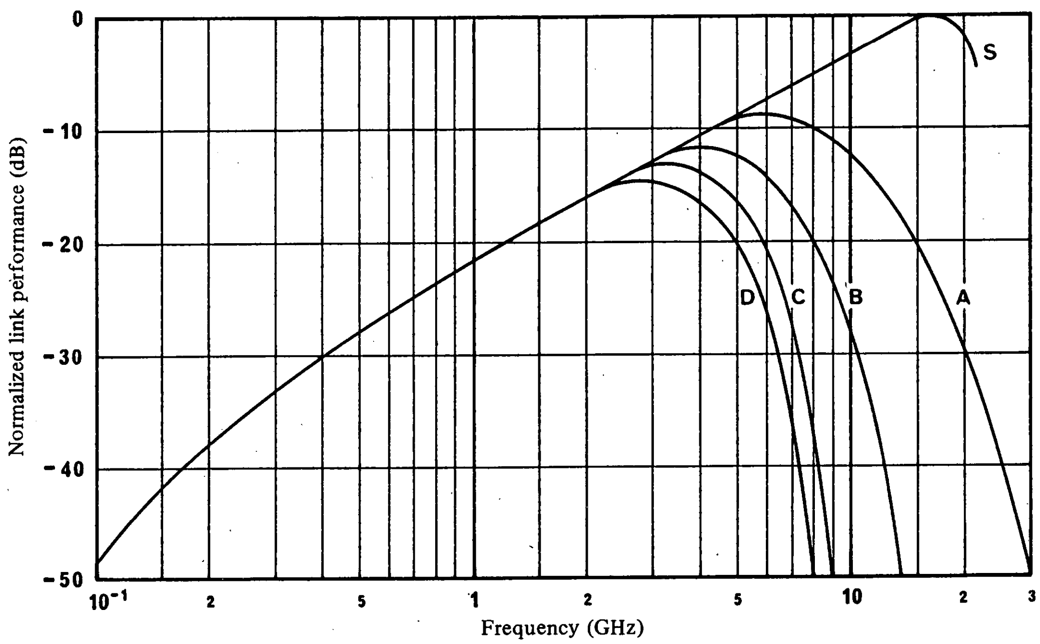


FIGURE 7 – *Normalized space-to-Earth link performance. Space station antenna diameter fixed*

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky

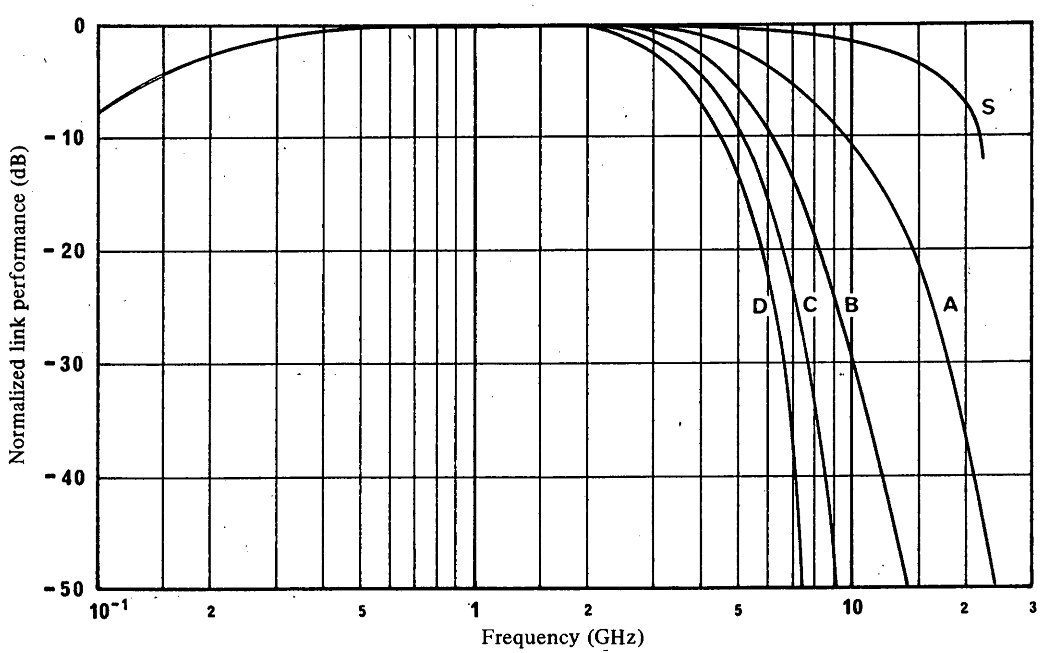


FIGURE 8 – *Normalized space-to-Earth link performance. Space station antenna beamwidth fixed*

Curves A: rain rate = 20 mm/h
B: rain rate = 50 mm/h
C: rain rate = 100 mm/h
D: rain rate = 140 mm/h
S: clear sky

5. Conclusions

In this Report, preferred frequencies for near-Earth space research have been presented based upon propagation (Table I) and technical considerations and the link performance analyses contained in Annex I.

TABLE I – *Frequency bands exhibiting maximum link performance*

Direction	Earth-station antenna	Space-station antenna	Frequency bands (GHz)				
			Clear sky	RR = 20 mm/h	RR = 50 mm/h	RR = 100 mm/h	RR = 140 mm/h
Earth-to-space (E-S)	Fixed diameter	Fixed diameter	14-20 28-37 85-104 127-138	5-10	3.5-6.5	3-4.5	3-4
	Fixed diameter	Fixed beamwidth	0.1-10 24-35 82-100	0.1-6	0.1-4.5	0.1-3	0.1-3
Space-to-Earth (S-E)	Fixed diameter	Fixed diameter	12-20 27-37 85-101 127-139	4.5-8	3-5	3-4.5	2.5-4
	Fixed diameter	Fixed beamwidth	0.3-10 24-32 82-100	0.3-4	0.3-3.5	0.3-3	0.3-2.5
Space-to-space (S-S)		Directive antennas on both relay and space stations	54-70 117-120 178-188 318-328				

RR: rain rate

Space-to-space links are best located in the frequency ranges of high atmospheric attenuation as this virtually eliminates any problem of interference to and from terrestrial sources. These ranges, located in the troughs between successive maxima shown in Figs. 9 to 12, correspond to the region around the oxygen and water vapour absorption peaks.

Above about 150 GHz, trans-atmospheric communications are subject to a high level of signal attenuation when the elevation angle is low. However, the range of frequencies above 150 GHz may be considered for links through the atmosphere, where the elevation angle of operation is not low.

The list of frequency bands given in Table II is intended to identify those frequency ranges which are preferred from a technical standpoint. The inclusion of a band in the table is not intended to indicate that there will be sufficient available link margin or bandwidth. Also, exclusion of other frequencies from the table does not necessarily preclude operations in these bands where frequency sharing considerations and state of the art equipment limitations dictate their use.

The list of typical individual link bandwidths given in Table III is intended to reflect link bandwidths which can be supported with current technology. The inclusion of a link bandwidth in the table is not intended to indicate the frequency band in which the individual link may be required to operate nor to limit the numbers of such links that may be required to support any particular spacecraft or mission systems.

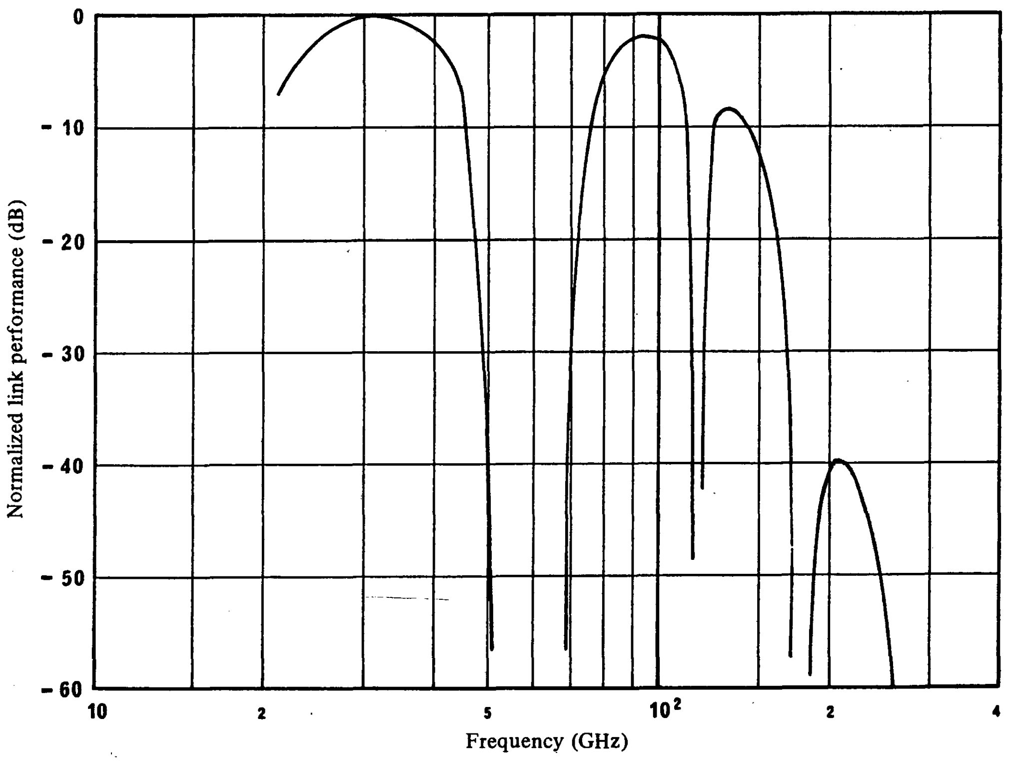


FIGURE 9 – *Normalized Earth-to-space link performance. Space station antenna diameter fixed*

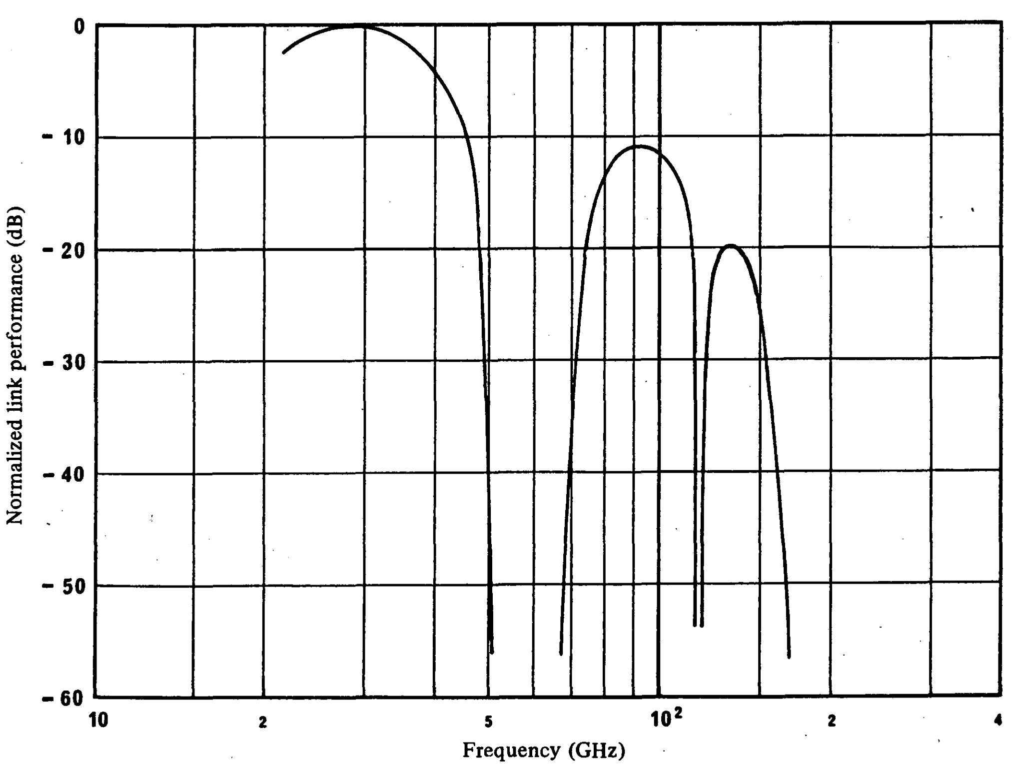


FIGURE 10 – *Normalized Earth-to-space link performance. Space station antenna beamwidth fixed*

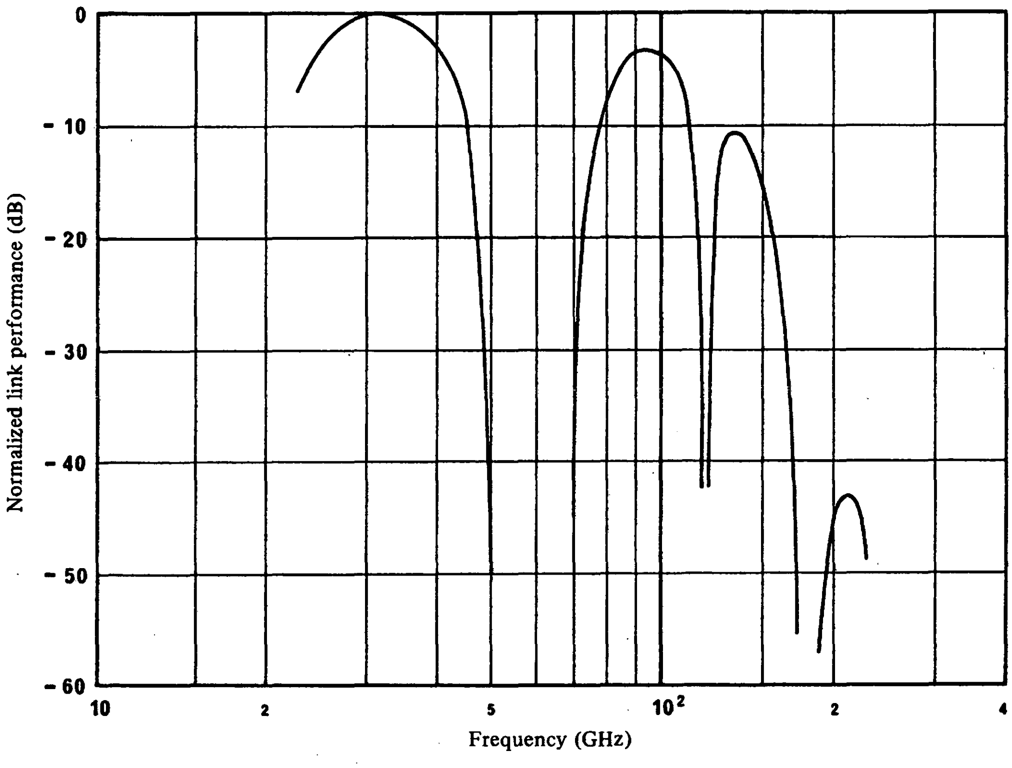


FIGURE 11 – *Normalized space-to-Earth link performance. Space station antenna diameter fixed*

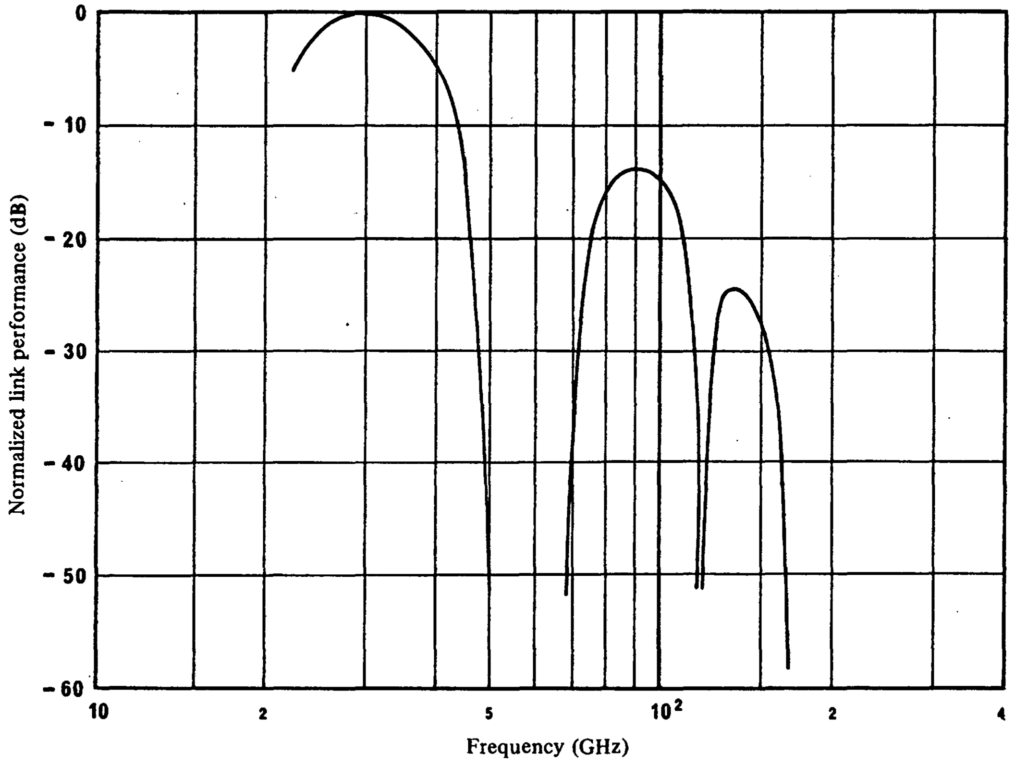


FIGURE 12 – *Normalized space-to-Earth link performance. Space station antenna beamwidth fixed*

TABLE II – *Preferred frequency bands and their uses*

Frequency (GHz)	Direction	Comments
0.3-2.5 0.1-3.0	S-E E-S	An all-weather link, optimum also when communications must be established regardless of spacecraft orientation
0.3-10 0.1-10	S-E E-S	A clear-weather link, optimum when a broad or fixed beamwidth antenna is required on the spacecraft
2-4 2-5	S-E E-S	An all-weather link for use with directive antennas
2-3 13.5-23	S-S S-S	Bands necessary to provide space-to-space communications with existing and proven space equipment and technology. Also necessary to provide continuity of service until other bands show practical and technical usability
12-20 14-20 28-35 27-32 85-100 127-137	S-E E-S E-S S-E E-S and S-E E-S and S-E	A clear-weather link, optimum for a high or medium gain antenna on the spacecraft
54-70 117-120 178-188 318-328	S-S S-S S-S S-S	Bands affording maximum clear-sky interference protection to space-to-space links from terrestrial applications, optimum for high to medium gain spacecraft antennas

TABLE III – *Typical individual link bandwidths and their uses*

Use	Direction	Typical bandwidth	Comments
Telecommand	E-S	10-500 kHz	
Maintenance telemetry	S-E	5-500 kHz	
Telemetry	S-E (direct)	100 kHz-100 MHz	Direct satellite to Earth
Telemetry	S-E (relay)	225-650 MHz	Relay satellite to earth station, data from one or more user satellites
Telemetry	S-S	5-225 MHz	User satellite to relay satellite
Telemetry	S-S	> 1 GHz	Relay satellite to relay satellite
Tracking	S-E	500 Hz-500 kHz	Interferometry
Tracking	E-S	1-3 MHz	Range and range rate systems
Tracking	E-S	1-10 MHz	Radar
Tracking	E-S	5-6 MHz	Bilateration ranging

ANNEX I

ANALYSIS OF FREQUENCY SELECTION FOR THE NEAR-EARTH SPACE RESEARCH SERVICE

1. Introduction

In this Annex, an analysis is provided that serves as the basis for the selection of radio frequencies for the near-Earth space research service.

By considering the frequency dependent elements of a basic link equation, the received signal power to noise density ratio (P_r/N_0) is established as an index of link performance and used in the determination of preferred frequencies.

2. Propagation considerations

2.1 *Ionospheric effects*

Ionospheric effects arise due to the interaction of the transmitted radio wave, the Earth's free electron density, which varies as a function of geomagnetic latitude, diurnal cycle, yearly and solar cycle, etc., and the Earth's magnetic field. Ionospheric effects above 10 GHz are generally small and not considered significant (see Report 263).

2.2 *Tropospheric effects*

In the absence of precipitation, tropospheric effects are unlikely to produce serious fading in space telecommunications systems at frequencies below about 10 GHz and at elevation angles above 10° (see Reports 718 and 881 (Geneva, 1982)). However, the magnitude of tropospheric amplitude scintillations can occasionally be serious at low elevation angles and at frequencies above about 10 GHz (see Report 564 (Geneva, 1982)). Signal attenuation due to absorption by molecular oxygen and water vapour and due to absorption and scattering by rain can severely affect link performance and therefore the selection of frequencies. Detailed discussion of these factors can be found in Reports 719 and 721 (Geneva, 1982) respectively.

3. Technical and operational considerations

Technical considerations may be divided into two categories, namely mission requirements and hardware or equipment factors.

3.1 *Mission frequency support requirements*

3.1.1 *Telecommand and maintenance telemetering*

The basic requirement of any mission is its safety and success. In order that this requirement be met, the telecommand and maintenance telemetry link must function with the spacecraft in any orientation. As this can only be achieved through the use of a broad-beam, omni-type antenna aboard the spacecraft, the use of such an antenna must be considered when selecting frequencies.

Telecommand bandwidths of 10-50 kHz are adequate for most missions, although more sophisticatd spacecraft may require link bandwidths of the order of 500 kHz or more. Maintenance telemetry link bandwidths range from several kilohertz to several hundred kilohertz.

3.1.2 *Mission telemetry*

For many missions, telemetry data are gathered and stored for play-back to Earth. For some of these missions, there may only be a single opportunity for the spacecraft to transmit the recorded data; these missions must therefore be capable of operating under all weather conditions. For missions which do not need to operate under such constraints, a frequency may be selected where data rate can be maximized for clear-sky conditions.

Link bandwidths depend on the complexity and sophistication of the spacecraft. For direct spacecraft-to-Earth station links, bandwidths of 100 kHz to 100 MHz can be expected. Bandwidths for relay satellite space-to-Earth links presently range from 225 to 650 MHz; however, this is expected to increase to above 1 GHz to meet future requirements.

Space-to-space link bandwidths presently range from about 5 to 225 MHz for direct user satellite to relay satellite communications. Inter-relay satellite bandwidths will be considerably wider, possibly greater than 1 GHz.

3.1.3 *Tracking*

Near-Earth space research involves various methods for determining spacecraft orbital information. For interferometer tracking, consideration of factors such as a good omnidirectional antenna on a spacecraft, transmitter efficiency, and earth-station antenna beamwidth, usually favours a frequency below 1 GHz. More elaborate moving antenna interferometers have been built for frequencies greater than 5 GHz, but atmospheric attenuation and noise usually limit their performance at frequencies greater than 6 GHz. Typical bandwidths range from several hundred hertz to several kilohertz.

Range and range-rate systems which must operate with the minimum of disturbances from ionospheric and trans-atmospheric effects are in the 1-8 GHz range for precision tracking systems. The main factor which dictates the maximum bandwidth needed per one-way channel is the range resolution required. Range resolutions of the order of metres can be obtaind by using appropriate modulation with bandwidths of about 1-3 MHz.

Radar tracking is also employed although atmospheric attenuation usually limits the use of frequencies above about 6 GHz for tracking by primary radar systems. For many of these systems, a bandwidth in the range of 1-10 MHz is usually sufficient.

Bilateration ranging is designed to supply precise information on the location of a relay satellite so that its movement can be taken into account when determining the orbital parameters of user spacecraft via the relay satellite. Typical links must be weather independent, and have bandwidths of about 5 to 6 MHz.

3.2 *Equipment factors*

Equipment factors which have an effect on link performance and whose characteristics depend on frequency to some extent are transmitter power, antenna gain (for a fixed-size antenna) and the receiver noise temperature. Of these three, the antenna gain is a function of the square of the frequency, whereas the transmit power and receiver noise are indirectly coupled to the frequency of operation. Their performance is therefore considered uniform over a wide frequency range.

The existence of proven space equipment and systems must also be considered in the selection of frequency bands to provide operational consistency.

Because of practical limits of diplexers, Earth-to-space and space-to-Earth pairs of frequencies should be separated by at least 7% to allow simultaneous transmit/receive operations using a single antenna.

4. **Link performance**

In this Report, the impact of propagation effects on the signal strength and system noise in a basic link equation has been considered, and an index of link performance, determined as the ratio of received signal power to noise spectral-density (P_r/N_0), has been established as the criterion for frequency selection.

The link analyses presented in § 4.1.1 are based upon a fixed diameter earth-station antenna, and cover both a fixed diameter and a fixed beamwidth space-station antenna. The fixed-diameter space station antenna is included to account for situations where a large antenna is employed on the spacecraft, and there are no pointing limitations. The fixed beamwidth case is included to account for situations where antenna pointing accuracy determines the minimum beamwidth, or where an antenna must provide wide coverage to permit communication without regard to spacecraft orientation as in the case of an emergency telemetry or command link.

In the analyses, the effects of precipitation are considered only for frequencies below about 22 GHz. The effects of precipitation above 22 GHz are not considered because even low rain rates can seriously degrade communications on trans-atmospheric links. Therefore only clear weather usage is assumed above 22 GHz.

Maximum data rate capability is obtained by using the frequency bands where P_r/N_0 is a maximum for the weather conditions and space-station antenna limitations considered. These bands are shown in Table I and are obtained from the normalized P_r/N_0 curves given in this Report. The general width of the bands was determined by noting the frequencies corresponding to the levels approximately 1 dB below the peaks of the curves. In order to provide a concise presentation of preferred frequency bands, the contents of Table I have been summarized and presented in Table II. A high rain rate was assumed when determining the width of all-weather frequency bands in Table II in order that the results be applicable world-wide. Bands outside this range may be suitable for areas of lower rain rates.

4.1 *Calculation of link performance as a function of frequency*

4.1.1 *Basic link performance equations*

The index of link performance, received power-to-noise spectral density ratio, is given by the basic link equation:

$$\frac{P_r}{N_0} = 10 \log \left(\frac{P_t \, G_t \, G_r}{L_s \, L_a \, L_r \, k \, T} \right) \quad \text{dB} \tag{1}$$

where:

P_r: received power (W),

N_0: noise spectral density (W/Hz),

P_t: transmitted power (W),

G_t: transmitting antenna gain,

L_s: free-space loss,

L_a: transmission loss due to attenuation in the clear atmosphere,

L_r: transmission loss due to rain attenuation,

G_r: receiving antenna gain (dBi),

k: Boltzmann's constant (J/K),

T: total system noise temperature (K).

Assuming no waveguide loss T is given by:

$$T = T_r + T_s + T_g$$

where:

T_r: receiver noise temperature (K),

T_s: sky contribution (due to atmospheric and precipitation effects) to antenna noise temperature (K),

T_g: ground contribution to antenna noise temperature (K).

By isolating the frequency-dependent terms in equation (1), the equation may, for a fixed distance between space and earth station, be written as follows:

Case 1: Earth and space-station antenna diameters are fixed:

$$\frac{P_r}{N_0} = C + 10 \log \left\{ \frac{1}{\lambda^2 \, L_a \, L_r \, T} \right\} \quad \text{dB} \tag{2}$$

Case 2: Earth-station antenna diameter is fixed, space-station antenna beamwidth is fixed:

$$\frac{P_r}{N_0} = C_1 + 10 \log \left\{ \frac{1}{L_a \, L_r \, T} \right\} \quad \text{dB} \tag{3}$$

where:

C and C_1 are constant in equations (2) and (3) respectively and expressed in dB and the terms in the brackets are the frequency-dependent terms. Any change in the value of the constant will merely raise or lower the P_r/N_0 curves, the overall shape of the curves will remain unchanged.

RECOMMENDATION 576

PREFERRED FREQUENCIES AND BANDWIDTHS FOR DEEP-SPACE RESEARCH

(Question 22/2, Study Programme 22A/2)

(1982)

The CCIR,

CONSIDERING

(a) that frequencies most suited for telecommunications between the Earth and spacecraft in deep space are determined partly by atmospheric and interplanetary propagation phenomena;

(b) that technology also influences the selection of preferred frequencies;

(c) that requirements for telecommunication reliability must be satisfied during periods of adverse atmospheric effects;

(d) that the same frequency may be used for spacecraft at different celestial coordinates, but that different spacecraft in the vicinity of the same coordinates and within the beamwidth of an earth station antenna will usually require different frequencies;

(e) that it is practical and desirable to effect telemetering and tracking functions on the same space-to-Earth link, and telecommand and tracking functions on the same Earth-to-space link;

(f) that to effect precision tracking, a pair of coherently-related Earth-to-space and space-to-Earth frequencies is desirable;

(g) that for more accurate calibration of the effects of charged particles on the velocity of propagation, simultaneous use of links with coherent frequencies in two or more widely separated bands is required;

(h) that voice and video links associated with manned spacecraft in deep-space could use frequency bands allocated for telemetering, telecommand and tracking functions;

(j) that Report 683 considers the selection of preferred frequencies for deep-space research in the 1 to 20 GHz range;

(k) that Report 849 considers the selection of preferred frequencies for deep-space research in the 20 to 120 GHz range,

UNANIMOUSLY RECOMMENDS

1. that frequency bands for deep-space research in the 1 to 20 GHz range be located, with due regard to the feasibility of sharing, in the preferred frequency ranges listed in Table III of Report 683;

2. that frequency bands for deep-space research in the 20 to 120 GHz range be located, where sharing is feasible, in the preferred frequency ranges listed in Table I of Report 849;

3. that widths of the allocated bands at preferred frequencies be in harmony with the bandwidth requirements discussed in Report 536 in order to provide for present and future deep-space telecommunications in a multi-spacecraft multi-mission environment.

REPORT 683-2*

FREQUENCY BANDS IN THE 1 TO 20 GHz RANGE THAT ARE PREFERRED FOR DEEP-SPACE RESEARCH

(Question 22/2, Study Programme 22A/2)

(1978-1982-1986)

1. Introduction

Mission requirements, equipment factors and link performance define the frequency bands preferred for deep-space research using manned and unmanned spacecraft. This Report presents the preferred bands and selection considerations. Report 536 contains a detailed discussion of the telecommunications requirements for deep-space research that were used in determining the preferred frequency bands. Examples are based on current systems used by the United States of America.

2. Mission requirements

2.1 *Telecommand and maintenance telemetering*

Mission safety and success require that telecommand and maintenance telemetering be accomplished regardless of weather conditions. These functions must be possible during planned and unplanned space station attitudes that preclude use of the space station high gain primary antenna. Where link performance permits, a low gain secondary antenna may be carried for use in such cases. This antenna is nearly isotropic and must be considered when selecting operating frequencies.

2.2 *Science telemetering*

Selection of the best frequency for mission science telemetering includes consideration of the risk of degraded link performance caused by weather conditions. For some missions, unique data must be sent at a particular time, and reliable telemetering during adverse weather conditions is a necessity. For missions where unique data can be stored for most effective playback to Earth, a frequency may be selected for maximum data rate during clear weather. The maximum data rate objective can also be satisfied for those missions where data timing is not important or when particular data may be repeatedly acquired, as in some planetary orbiter missions.

2.3 *Doppler and range tracking*

Doppler and range tracking must be accomplished with an exactitude that satisfies mission navigation and radio science requirements. These determine the needed ranging accuracy and the necessary precision in the measurement of the effects of charged particles.

Charged particle calibration can be done with paired Earth-to-space and space-to-Earth frequencies in a single band. Increasing tracking accuracy requirements will necessitate calibration using two or more frequency pairs in different bands.

2.4 *RF carrier tracking*

For missions when it is necessary to maintain communications as the ray path passes close to the Sun, frequency selection must consider the scintillation effects of transmission through the solar plasma. These cause modulation of the RF carrier and difficulty in maintaining coherence in a narrow band phase-locked loop. No telemetering, Doppler measurements, or ranging can be conducted unless the carrier can be phase-locked.

2.5 *Bandwidth*

Telemetering and telecommand data rates tend to rise as technology improves. Increased rates require wider bandwidths, particularly for coded transmission.

* This Report is brought to the attention of Study Groups 5 and 6 for their comment on how the analysis might be affected by recent changes in propagation data.

The need for increased ranging accuracy will require greater ranging bandwidths. In some cases, the ranging signal will determine the total bandwidth requirement, and frequency selection for this function may be constrained by the width of the allocated band.

Where simultaneous communication is conducted with several spacecraft within a single antenna beam, the total bandwidth is increased proportionally. A detailed discussion of bandwidth requirements will be found in Report 536.

3. Equipment factors

Earth stations include large steerable parabolic antennas, high power transmitters and sensitive receivers. All of these are very expensive and infrequently constructed. For this reason, analysis of link performance versus frequency assumes the earth station antennas to be of fixed diameter.

Earth station equipment has been built and is operating in the 2 and 8 GHz allocations. The selection of frequency bands must consider the realities of existing equipment. There is more freedom of choice in higher frequency bands, since operational capability has yet to be developed above 10 GHz.

The link analyses presented in Annex I are based upon a fixed diameter earth station antenna, and both fixed diameter and fixed beamwidth space station antennas. The fixed diameter space station case arises when the largest possible antenna may be used, free of pointing limitations. The fixed beamwidth case is in effect when antenna pointing accuracy determines the minimum beamwidth, or when the antenna must give wide coverage to permit communication without regard to space station attitude.

Because of practical limits of diplexers, Earth-to-space and space-to-Earth pairs of frequency bands must be separated by at least 7% to allow simultaneous transmit/receive operations with a single antenna.

Standard transponder designs currently used at 2 and 8 GHz employ specific receive/transmit frequency ratios which must be considered in determining preferred frequency bands.

4. Link performance

Maximum data rate capability is obtained by using bands appropriate for weather conditions and space station antenna limitations. Tables I and II show optimum link frequencies selected on the basis of the analysis in Annex I.

Optimum frequencies for clear weather will tend to increase as technology improves. For rain, the optimum space-to-Earth frequency will tend to decrease slightly because the sky noise caused by rain will dominate system performance.

TABLE I – *Optimum frequency bands for space-to-Earth links*

Space station antenna limitation	Weather condition	Best performance frequency band (GHz)
Fixed diameter	clear	10 to 14
Fixed diameter	rain	4 to 6
Fixed beamwidth	clear	1 to 2
Fixed beamwidth	rain	1 to 2

TABLE II – *Optimum frequency bands for Earth-to-space links*

Space station antenna limitation	Weather condition	Best performance frequency band (GHz)
Fixed diameter	clear	12 to 20
Fixed diameter	rain	7 to 9
Fixed beamwidth	clear	1 to 2
Fixed beamwidth	rain	1 to 2

5. Preferred frequencies

For each telecommunication function, i.e., maintenance and science telemetering, telecommand, tracking and radio science, there is a frequency band, or set of frequency bands which will provide best performance. Best performance refers to error ratio, measurement accuracy, data rate, link reliability or some combination of these parameters. The best performance that is obtainable at a particular time with a particular system depends upon propagation conditions. The objective of identifying preferred frequencies is to provide the basis for allocations from which the designer can select operating frequencies best suited to mission requirements.

Table III lists the preferred frequency bands and associated characteristics which would provide the needed range of choice for the conduct of deep-space research.

Table IV compares the preferred frequencies with current allocations for deep-space research. Existing earth and space stations use current allocations, even though these are not always optimum.

TABLE III – *Preferred frequencies and their uses*

Preferred frequency range	Use	Other requirements
1 to 2 GHz	All weather Earth-to-space and space-to-Earth links using either the spacecraft high-gain, or the widebeam low-gain antennas. Used for telemetering, telecommand, tracking, and as part of multifrequency charged-particle calibration.	Earth-to-space and space-to-Earth bands separated by at least 7%.
4 to 6 GHz	All weather space-to-Earth link using the spacecraft high-gain antenna. Used for telemetering, tracking, and as part of multifrequency charged-particle calibration.	Requires Earth-to-space band of equal width to support two way tracking. (See 7 to 9 GHz preferred frequency.)
7 to 9 GHz	All weather Earth-to-space link using the spacecraft high-gain antenna. Used for telecommand, tracking, and as part of multifrequency charged-particle calibration.	Requires space-to-Earth band of equal width to support two way tracking. (See 4 to 6 GHz preferred frequency.)
10 to 14 GHz	Clear weather space-to-Earth link using the spacecraft high-gain antenna. Used for telemetering, tracking, and as part of multifrequency charged-particle calibration.	Requires similar Earth-to-space band of equal width to support two-way tracking. (See 12 to 20 GHz preferred frequency.)
12 to 20 GHz	Clear weather Earth-to-space link using the spacecraft high-gain antenna. Used for telecommand, tracking, and as part of multifrequency charged-particle calibration.	Requires similar space-to-Earth band of equal width to support two-way tracking. (See 10 to 14 GHz preferred frequency.)

TABLE IV – *Preferred frequencies and current allocations*

Preferred frequency range (GHz)	Current allocations(1) (GHz)
1 to 2 Earth-to-space	2.110-2.120
1 to 2 space-to-Earth	2.290-2.300
7 to 9 Earth-to-space	7.145-7.190
4 to 6 space-to-Earth	8.400-8.450(2)
10 to 14 space-to-Earth	12.750-13.250
12 to 20 Earth-to-space	16.600-17.100

(1) Allocations listed are those parts of space research bands that are restricted to deep space only. See the Radio Regulations for more detailed information.

(2) This allocation is not in the preferred frequency range.

6. Conclusion

To meet the needs of the deep-space research service, at least three pairs of Earth-to-space and space-to-Earth bands are required. The preferred frequencies and allocated bands for these pairs are shown in Tables III and IV.

The 2110 to 2120 MHz and 2290 to 2300 MHz allocated bands meet the requirement for weather independent links using either high or low gain spacecraft antenna. The 10 MHz allocation width imposes a limit on telemetering data rate and ranging precision, especially when communicating with two or more spacecraft within the earth station antenna beam.

The 7145 to 7190 MHz and 8400 to 8450 MHz allocated bands provide increased link performance using the spacecraft high gain antenna. The 8 GHz allocation is not optimum, but provides acceptable performance. The 50 MHz allocation width allows telemetering and ranging that is adequate for current and near-future missions. These bands in combination with the 2 GHz allocations provide for multi-frequency charged particle calibration.

The 12.75 to 13.25 GHz and 16.6 to 17.1 GHz allocated bands provide the opportunity for high performance clear weather use by future missions. These bands are 500 MHz wide and permit advanced radio science experiments that require ranging to centimetre accuracy, very high telemetering rates, and simultaneous operation with several spacecraft. These bands will also provide reduced charged particle delays and scintillation and thus permit operations with ray paths passing close to the Sun. In combination with the 2, 7 and 8 GHz allocations, they will allow very accurate measurement of charged particle effects.

ANNEX I*

FREQUENCY SELECTION CONSIDERATIONS FOR DEEP-SPACE RESEARCH

1. Introduction

This Annex presents an analysis that provides the basis for the selection of frequencies for communication between deep-space research earth and space stations.

The Annex considers link performance as a function of frequency by establishing an index of performance, using propagation factors derived from Reports 564 and 263, and the principal elements of equipment technology which affect performance. Sets of curves are provided to illustrate the relative performance under various weather and antenna elevation angle conditions.

* Information in this Annex is based on several Reports in CCIR Volumes V and VI concerning propagation. The Reports referenced in the text are from the Geneva, 1982 Volumes. However, Figs. 1, 2 and 4 to 7 are based on Kyoto, 1978 Reports. Use of the more recent data would change some of the curves, but the conclusions drawn in this Report would not be affected.

2. Calculation of link performance as a function of frequency

Telecommunication link performance includes frequency dependent parameters related to propagation and equipment factors. One index of performance is the ratio of received power-to-noise spectral power density:

$$P_r - N_0 = P_t + G_t - L_p - L_a - L_{Ra} + G_r - 10 \log (kT_T) \qquad \text{(dB)} \qquad (1)$$

where,

P_r:	received power	(dBW)
N_0:	noise spectral density	(dB(W/Hz))
P_t:	transmitter power	(dBW)
G_t:	transmitting antenna gain	(dBi)
L_p:	free-space basic transmission loss	(dB)
L_a:	excess transmission loss through the atmosphere including water vapour	(dB)
L_{Ra}:	excess transmission loss through rain	(dB)
G_r:	receiving antenna gain	(dBi)
k:	1.38×10^{-23}	(Joule/K)
T_T:	total noise temperature	(K)

$$T_T = T_a + T_{Ra} + T_g + T_r \qquad \text{(K)} \qquad (2)$$

where,

T_a:	noise temperature related to L_a	(K)
T_{Ra}:	noise temperature related to L_{Ra}	(K)
T_g:	galactic background noise temperature, after transmission losses through the propagation media	(K)
T_r:	noise temperature of receiver	(K)

For an Earth-to-space link the noise power contribution of earth atmosphere and rain may be neglected and:

$$T_T = T_g + T_r \qquad (3)$$

The optimum frequency for a link with particular antenna and weather requirements may be determined by calculating the index of performance as a function of frequency.

3. Propagation considerations

Communication system performance depends on propagation characteristics, and these are frequency dependent.

3.1 *Absorption attenuation by atmospheric gases and precipitation*

Radio transmission through a clear atmosphere is subject to attenuation and re-radiation by molecular oxygen and water vapour. The attenuation is a function of radio frequency and the oxygen and water vapour content along the transmission path. This is discussed in detail in Reports 719 and 564.

Rain attenuation is a function of the radio frequency, rainfall rate, raindrop size, and drop distribution within the rain volume. This is discussed in detail in Report 721.

Figure 1 presents curves of attenuation between space and Earth as a function of frequency and elevation angle of the earth-station antenna. This figure is based on the type of data found in current Reports 563, 564, 719 and 721. The curves labelled "clear weather" were calculated for one-way attenuation through a moderately humid atmosphere (7.5 g/m^3 at the surface). The curves for rain are for a rate (32 mm/h) exceeded 0.01% of an average year in rain climate H (see Report 563), and include attenuation due to the gaseous constituents of the atmosphere.

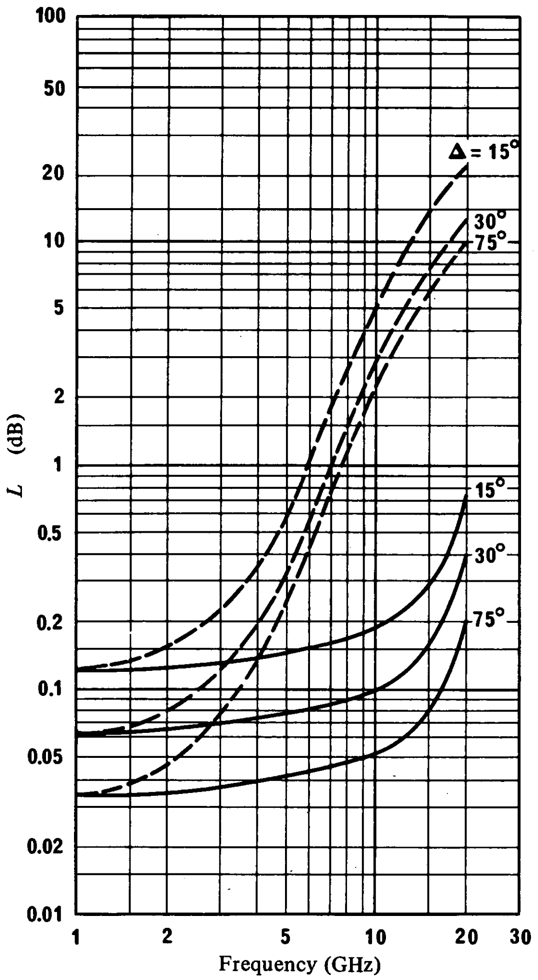


FIGURE 1 – *Attenuation L by atmosphere and rain*

———— clear weather, atmosphere only

– – – – – rain and atmosphere; 32 mm/h

Parameter Δ: elevation angle of earth station antenna

3.2 *Sky noise temperature*

The following factors contribute to sky noise: atmospheric gases (principally oxygen and water vapour), precipitation, and galactic noise and cosmic background. Sky noise temperature caused by atmospheric gases and precipitation is a function of temperature and the attenuation along the transmission path, and is thus related to frequency and antenna elevation angle as discussed in Report 720 which contains curves of galactic and cosmic background noise. The contribution of these sources to total sky noise is modified by the attenuation along the path.

Figure 2 presents curves of total sky-noise temperature for the weather conditions of Fig. 1, plus the contributions of galactic and cosmic background noise, calculated according to the preceding considerations.

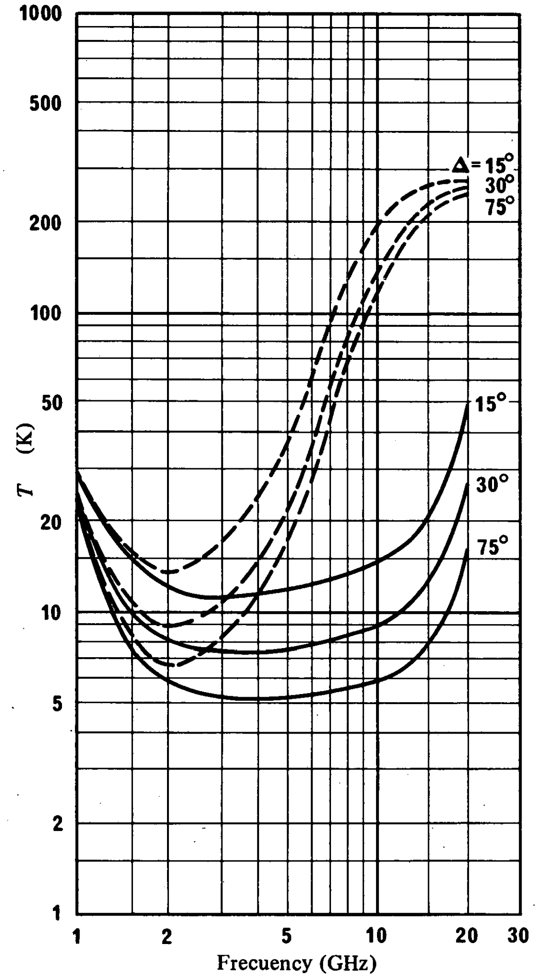


FIGURE 2 – *Sky-noise temperature, T*

——— clear weather, atmosphere only

– – – – rain and atmosphere; 32 mm/h

Parameter Δ: elevation angle of earth station antenna

3.3 *Tropospheric scintillation and refraction*

Reports 564, 718 and Report 881 (Geneva, 1982) indicate that the propagation effects caused by tropospheric scintillation and refraction may be negligible, if transmission frequencies are below 20 GHz and antenna elevation angles are greater than 3°. (See Report 564, Annex I, for practical data for the range 4 to 12 GHz at low elevation angles.) These effects have not been included in the analysis of preferred frequencies. Report 564, Annex I, also describes phase scintillation at 4 GHz at low elevation angles.

3.4 *Ionospheric scintillation*

Electron-density irregularities in the ionosphere create refractive inhomogeneities which result in signal amplitude and phase variations. Fading of 3 to 4 dB at frequencies in the 4 to 8 GHz range has been observed. Current information is insufficient for including this factor in frequency selection. Scintillation effects in the ionosphere are discussed in Report 263.

3.5 *Variations in propagation velocity caused by charged particles*

In passing through an ionized medium the phase velocity of a radio signal is increased and the group velocity is decreased. The effect is proportional to the integrated electron density along the ray path, and inversely proportional to the square of the frequency. The group delay due to free electrons has been shown to be the following (see Report 263 and [Trask and Efron, 1966; Flock, 1983]):

$$\Delta t = \frac{40.3}{cf^2} \int N \mathrm{d}s \qquad \text{seconds} \tag{4}$$

where,

Δt: group delay in seconds,

f: the frequency of signal transmission in Hz,

N: electron density in electrons/metre^3,

s: ray path length in metres,

c: speed of light in free space in metres/second.

The effect is not a constant. Velocity scintillation phenomena are also observed. These cause phase modulation and spectrum broadening of the signal traversing the ionized medium.

An estimate of the upper limit on the propagation group delay through the ionosphere ranges from 0.25 μs at 1 GHz to 0.62 ns at 20 GHz. Further discussion will be found in Report 263.

The solar plasma in interplanetary space modifies radio wave propagation velocity in the same way as the ionosphere. Deep space tracking measurements have yielded delay measurements from several locations in the solar system. The resulting electron density profile which those measurements provided is the basis for an approximate formula (see Report 887):

$$N(R) = \frac{2.21 \times 10^{14}}{R^6} + \frac{1.55 \times 10^{12}}{R^{2.3}} \tag{5}$$

where:

$N(R)$: electron density in electrons/m^3 at distance R from the Sun,

R: distance from the centre of the Sun in Sun radii (radius 6.96×10^8 m).

Propagation delay can result in range measurement error. Consider the case of a spacecraft at a distance of 1 AU (1.5×10^8 km). The difference between indicated and actual range depends upon charged particle density along the path from Earth to the spacecraft, and is shown in Fig. 3 for three different radio frequencies, as a function of the angle between the Earth-Sun (limb) line and Earth-spacecraft line. The figure was obtained by calculating propagation delay and then multiplying by the speed of light.

Spacecraft tracking depends on very accurate knowledge of propagation velocity to determine range for use in orbital calculations and charged particle effects are therefore important factors in frequency selection.

4. Equipment considerations

Equipment parameters considered in link performance analysis include transmitter power, antenna gain, and receiving system noise temperature. For additional discussion of these parameters see Report 536.

4.1 *Transmitter power*

Space station transmitter power is limited primarily by the available spacecraft primary power so that the obtainable RF output power is approximately independent of frequency in the 1 to 20 GHz range. Earth station transmitter power in the same frequency range is limited primarily by development cost.

For link performance analysis in this Annex, transmitter power is considered to be independent of frequency.

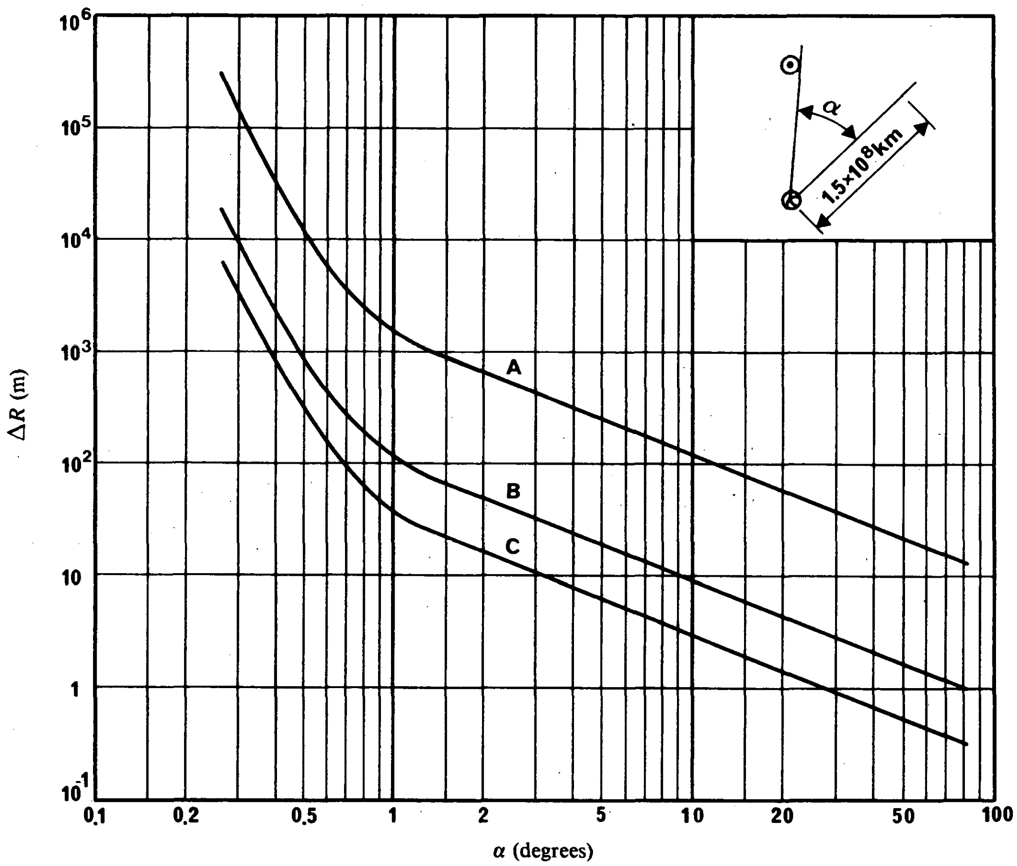


FIGURE 3 – *Approximate error ΔR, in indicated range caused by charged particles, as a function of angle from limb of Sun α*

(Curves based on Muhleman *et al.* [1977])

A: 2.295 GHz
B: 8.450 GHz
C: 15.0 GHz

⊙ Sun
⊕ Earth

4.2 *Antenna gain*

Antenna gain is limited by size, surface precision and structural deformation. For space stations, antenna size is limited by space available in the launch vehicle, by the state of development of unfurlable structures, and by the pointing capability of the space station.

Link analysis in this Annex assumes that the gain of a space station fixed diameter antenna increases directly as the frequency squared, since the effect of imperfections is negligible in the frequency range being considered. For the fixed beamwidth case the gain is assumed to be independent of frequency.

The earth station antenna gain is shown in Fig. 4 of Report 536.

4.3 *Receiving equipment noise temperature*

The space station receiving system noise temperature is dominated by the input preamplifier. Antenna feedline losses are relatively unimportant in their noise contribution.

At earth stations there is no important size, weight, or complexity limitation, and the most sensitive possible receiver is needed.

Link analysis in this Annex assumes that the noise temperatures are as shown in Fig. 1 of Report 536.

5. Link performance

The frequency dependence of link performance may be shown by the variation in the ratio (dB) of total received power to noise spectral density, $P_r - N_0$. Curves of $P_r - N_0$, shown in Figs. 4 to 7, were calculated by using data in Figs. 1 and 2, equipment characteristics described in Report 536, and the following assumptions:

Communication distance:	8×10^8 km
Diameter of earth station antenna:	64 m
Power of earth station transmitter:	100 kW
Diameter of space station antenna:	3.7 m
Power of space station transmitter:	25 W

The important features of the performance curves are the location of maxima and the effects of elevation angle and weather. The values of $P_r - N_0$ depend upon the assumed link parameters. Different assumptions about communication distance, antenna characteristics and transmitter power would not significantly change the shape of the curves.

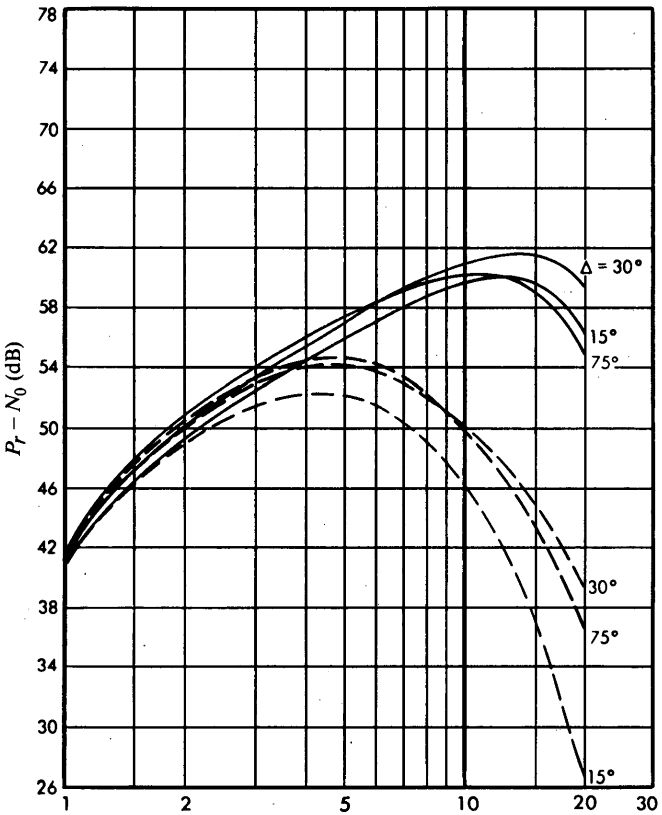
Figures 4 to 7 show curves for clear and rainy weather, and for earth station antenna elevation angles of 15° (near horizon), 30° and 75°. Figures 4a, 5a, 6a and 7a reflect the limitations typical of earth and deep space stations. Gravity induced structural distortions on large earth station antennas reduce gain to an extent dependent on elevation angle. This effect is included in the Figures, and is the cause of the crossing of several curves.

Figures 4b, 5b, 6b and 7b assume the use of perfect antennas and noiseless receivers. These curves illustrate ultimate performance as limited by natural phenomena, and demonstrate the effect of advancing technology.

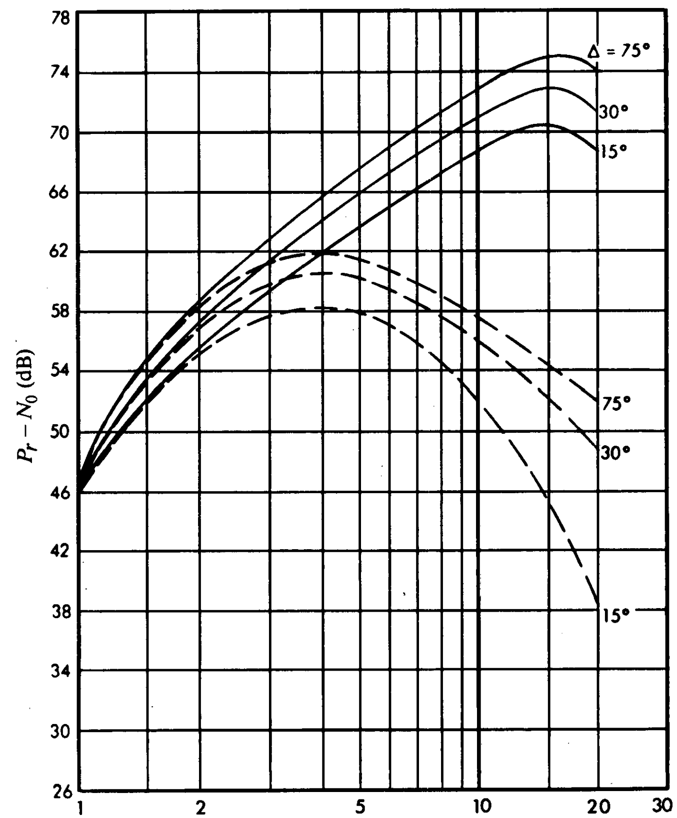
6. Discussion

The performance curves were developed for clear weather and for heavy rainfall conditions. The rainfall rate used in the analysis is 32 mm/h. This rate was chosen to allow frequency selection which will satisfy the requirement for reliable telecommunication under adverse conditions. In Annex II of Report 536, (Geneva, 1974) there are curves for the condition of clouds and 4 mm/h rain. Comparison of shape and maxima of the curves shows that selection of preferred frequencies is not significantly altered by consideration of more moderate weather.

The curves for the future performance as limited only by natural phenomena, i.e., weather and cosmic noise, show the link performance that may be approached as equipment and techniques become more fully developed.



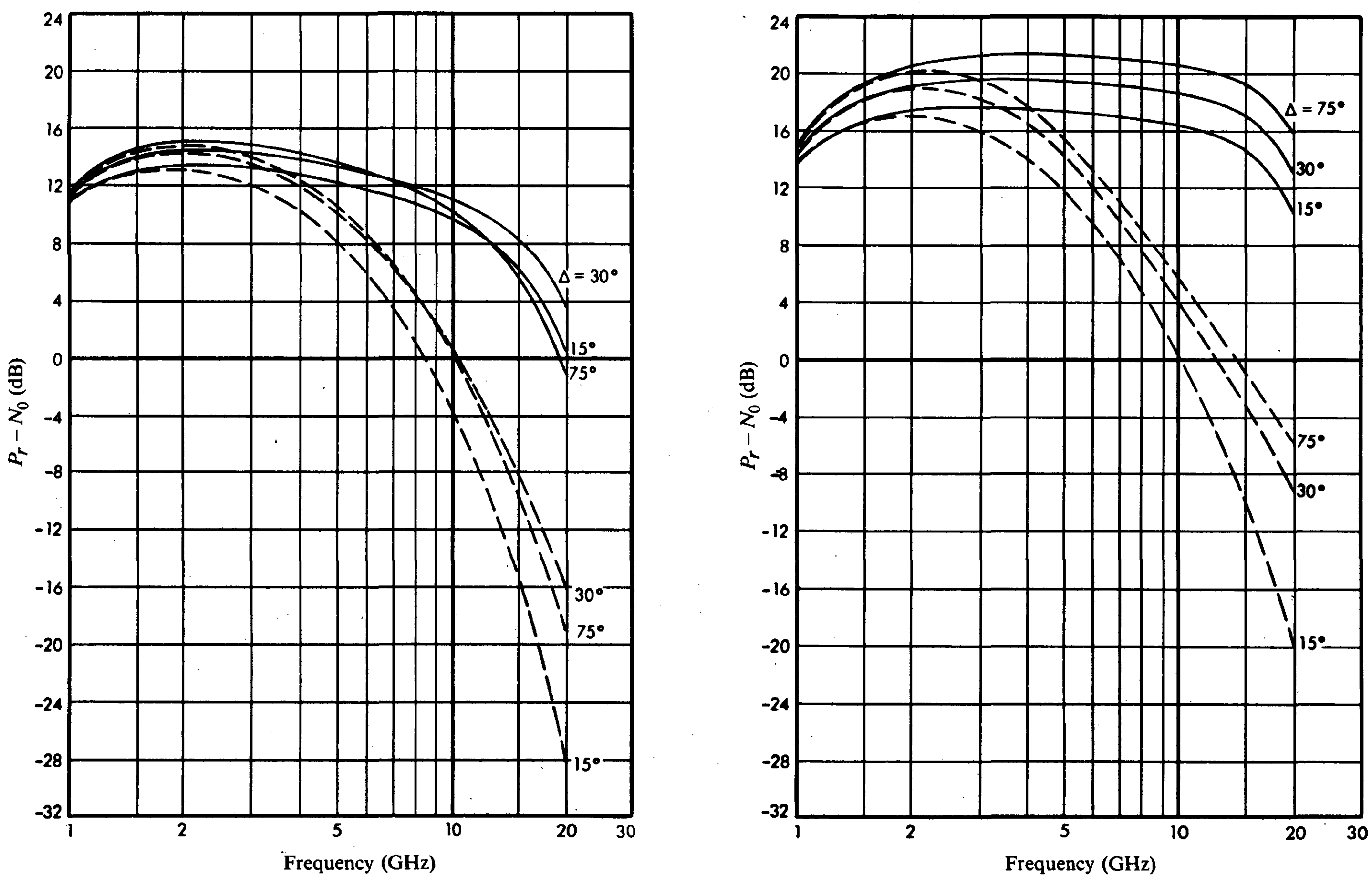
a) Performance as limited by equipment characteristics and natural phenomena



b) Performance as limited by natural phenomena only

FIGURE 4 – *Space-to-Earth link performance ($P_r - N_0$)*
Two fixed diameter antennas

———— clear weather, atmosphere only
– – – – – – rain and atmosphere
Parameter Δ: elevation angle of earth station antenna



a) Performance as limited by equipment characteristics and natural phenomena

b) Performance as limited by natural phenomena only

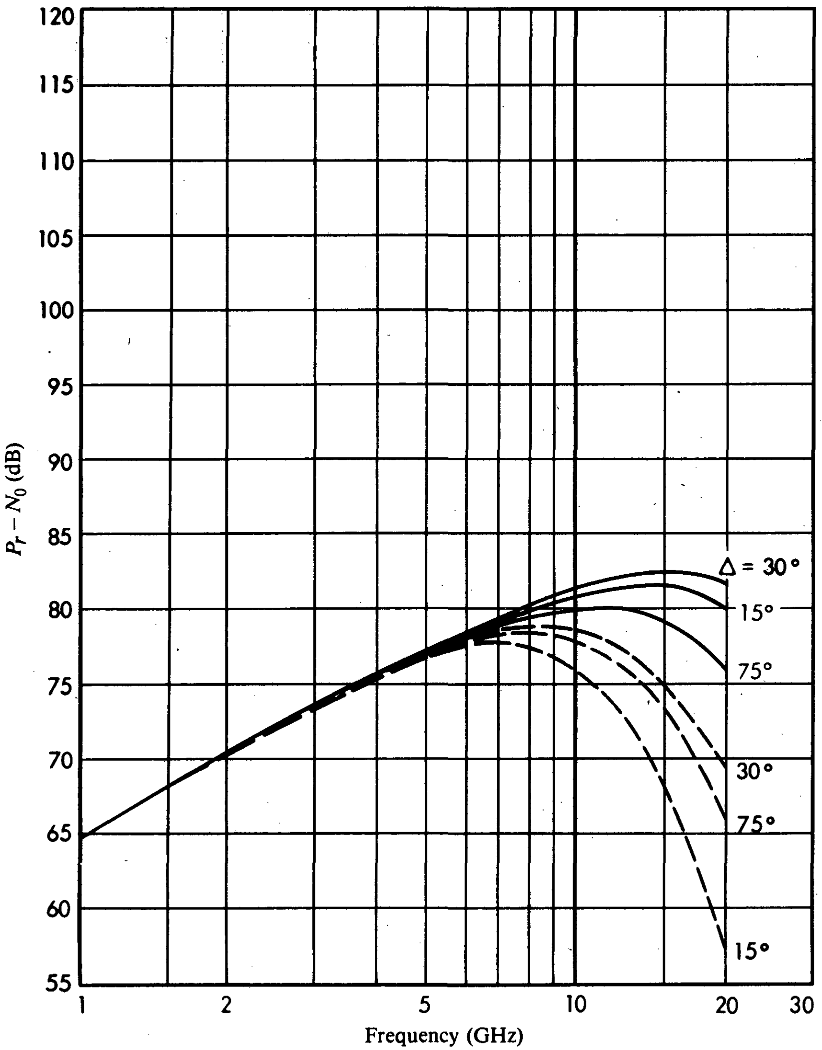
FIGURE 5 – *Space-to-Earth link performance ($P_r - N_0$)*

Fixed beamwidth station antenna, fixed diameter earth station antenna

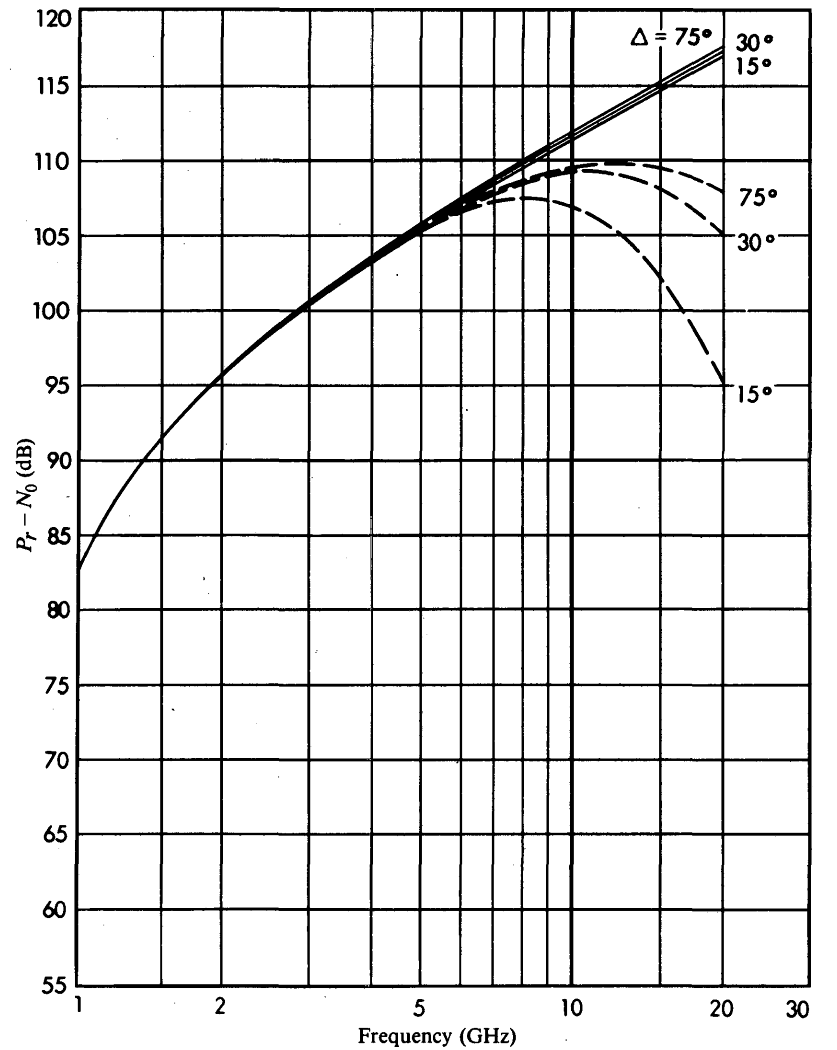
———— clear weather, atmosphere only

– – – – – – rain and atmosphere

Parameter Δ: elevation angle of earth station antenna



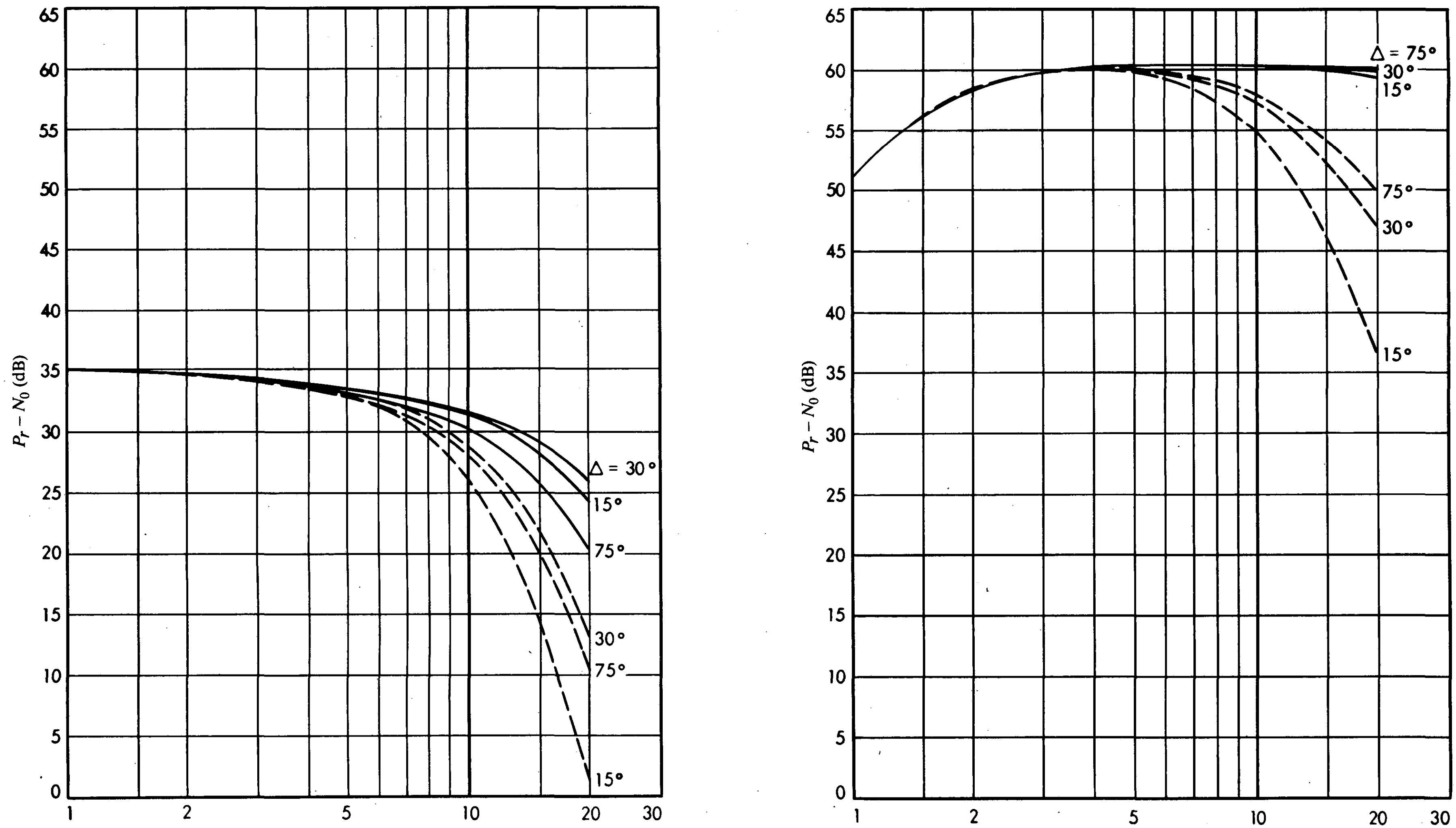
a) Performance as limited by equipment characteristics and natural phenomena



b) Performance as limited by natural phenomena only

FIGURE 6 – *Earth-to-space link performance* $(P_r - N_0)$
Two fixed diameter antennas

——————— clear weather, atmosphere only
– – – – – – rain and atmosphere
Parameter Δ: elevation angle of earth station antenna



a) Performance as limited by equipment characteristics and natural phenomena

b) Performance as limited by natural phenomena only

FIGURE 7 – *Earth-to-space link performance ($P_r - N_0$)*

Fixed diameter earth station antenna, fixed beamwidth space station antenna

———— clear weather, atmosphere only

– – – – – – rain and atmosphere

Parameter Δ: elevation angle of earth station antenna

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REPORT 849-1 *

FREQUENCY BANDS IN THE 20 TO 120 GHz RANGE THAT ARE PREFERRED FOR DEEP-SPACE RESEARCH **

(Question 22/2, Study Programme 22A/2)

(1982-1986)

1. Introduction

This Report pertains to the selection of preferred frequency bands for deep-space telecommunications in the 20-120 GHz range. The performance of links between earth stations and stations in deep space is affected by the atmosphere of the Earth. Attenuation and emission by the atmosphere generally limits deep-space telecommunications to frequencies below 20 GHz. There are, however, certain frequency bands in the 20-120 GHz range where atmospheric attenuation is low enough to permit links between earth stations and deep-space stations. Additionally, there are certain other bands in the 20-120 GHz range that would be particularly suitable for links between an earth-orbiting relay station and deep-space stations.

The selection of preferred frequency bands below 20 GHz is given in Report 683.

1.1 *Performance advantages of higher frequencies*

Radio frequencies above 20 GHz can provide advantages for deep-space telecommunications. The advantages are higher link performance, reduced errors in measurements that depend on the velocity of propagation, and the possibility of shielding from terrestrial interference.

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* This Report is brought to the attention of Study Groups 5 and 6 for their comment on how the analysis might be affected by recent changes in propagation data.

** This Report is based on the following Reports of Geneva, 1982 concerning propagation: Reports 263, 563, 564, 719, 720, 721 and 887. However, Figs. 1 to 7 are based on (Kyoto, 1978) Reports 205, 263, 563, 564 and 721. Use of the more recent data would change some curves, but the conclusions drawn in this Report would not be affected.

The net gain of a free-space link between perfect antennas with fixed apertures varies in direct proportion to the frequency squared. For certain frequencies where the attenuation of the atmosphere is low, links between Earth and space can benefit from the use of frequencies above 20 GHz.

The increased performance of higher frequency links may be utilized for command, telemetering and radiometric functions. Alternatively, the higher performance may be traded for smaller and lighter spacecraft antennas and transmitters.

Accurate navigation of deep-space probes depends upon determination of their position and velocity by means of phase and group delay measurements of received signals. These measurements are influenced by the velocity of propagation along the transmission path. The velocity of propagation is a function of the presence of charged particles along the path. The effect of these particles varies inversely with the square of the frequency and hence higher frequencies are preferable for purposes of navigation and certain other radio measurements.

1.2 *Shielding from terrestrial interference*

In the future it may be desirable to employ a geostationary relay station for signals to and from deep-space probes. The links between such a station and deep-space probes would be free of the perturbing effects of the atmosphere. These links could be protected from terrestrial interference by choosing frequencies where the atmosphere is relatively opaque to radio signals. There are such frequencies in the 20-120 GHz range.

1.3 *Basis for frequency selection*

Selection of preferred frequencies is based on link performance and by propagation and equipment characteristics. In the next three sections of the Report, the factors that influence frequency selection are examined. Some of these factors provide the information needed to calculate an index of link performance. This index is expressed as P_R/N_0, the ratio of total received power to noise spectral density for a particular set of propagation conditions and equipment parameters.

2. Frequency dependent characteristics of interplanetary propagation

Interplanetary propagation characteristics determine the performance of links between a deep-space probe and a relay satellite located outside the atmosphere of the Earth. These characteristics, discussed in Report 887, also affect the performance of links between earth stations and deep space.

2.1 *Sky noise temperature*

The sky noise temperature seen by a relay satellite will be determined by the cosmic background (3 K) and quantum noise as shown in curve A of Fig. 1, except when noise from the Earth, other planets or the Sun enters the antenna. This problem is also discussed in Report 720.

The sky noise temperature seen by a spacecraft will also be that shown in curve A of Fig. 1. Earth will generally be within the main lobe of a spacecraft antenna pointed at a relay satellite. The presence of Earth within the antenna beam will contribute to the noise temperature. For example, for a spacecraft at 4×10^7 km from the Earth (the minimum distance to Venus), the Earth subtends an angle of 1.8×10^{-2} degrees. If the spacecraft antenna is limited to a minimum bandwidth of 0.15° by pointing accuracy, then the Earth can fill less than 1/69 of the antenna main lobe. The effect of the black body temperature of the Earth is correspondingly reduced to a value that is small compared to the 600-1500 K noise temperature of a typical spacecraft receiving system. (In the frequency range 20-50 GHz, the black body temperature varies between 170 and 260 K, depending on frequency and sub-spacecraft longitude on the Earth.)

The increase in noise temperature when an antenna is pointed at the Sun is large. This can affect the timing and design of some deep-space missions and experiments.

For calculation of P_R/N_0 as a function of frequency, the sky noise temperature seen by a relay satellite or deep-space probe will be considered a negligible part of the system temperature.

2.2 *Attenuation*

A review of gaseous absorption and scattering by dust particles outside planetary atmospheres indicates that neither will attenuate the signal by as much as 0.1 dB in the 20-120 GHz range as long as the propagation path is restricted to our solar system. Attenuation by interplanetary space is considered as a negligibly small factor in the selection of preferred bands.

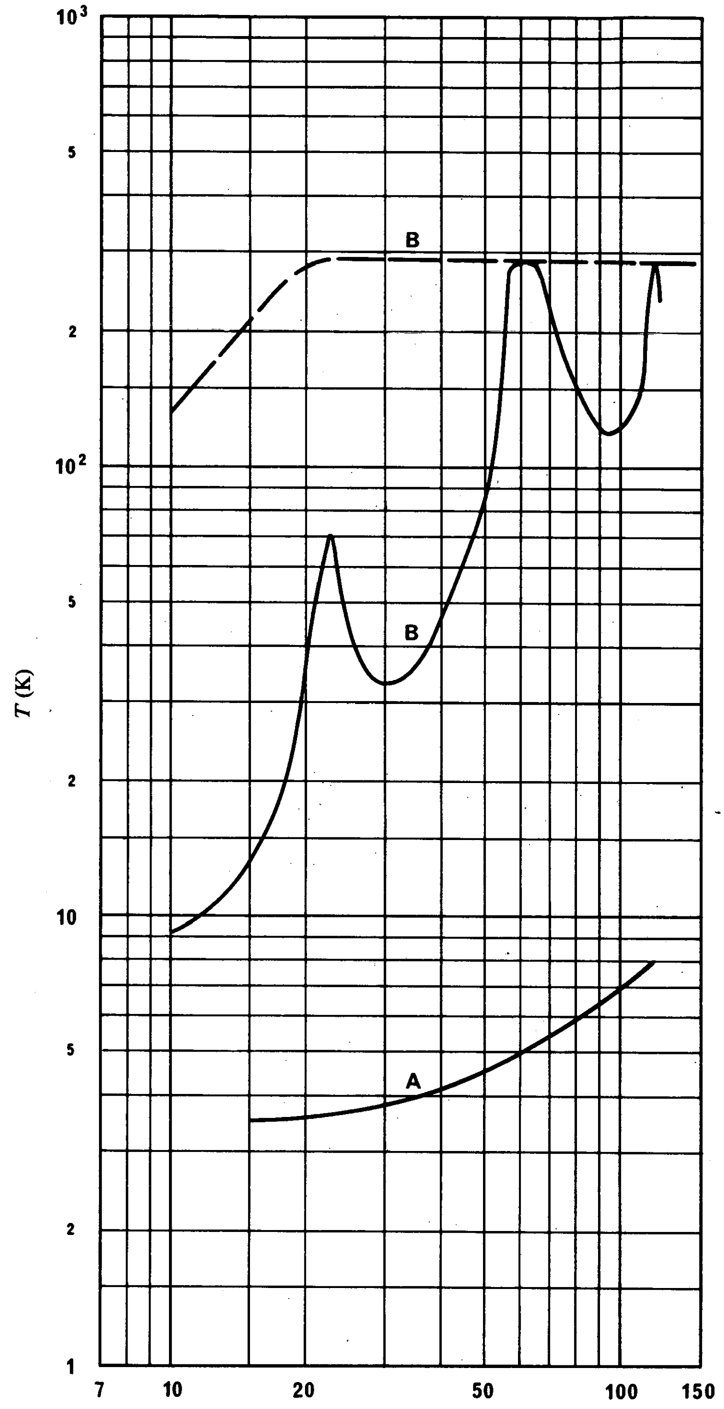

FIGURE 1 – *Sky noise temperature*

Curves A: as seen by deep-space station

B: as seen by earth station, antenna at 30° elevation angle

———— Gaseous atmosphere

– – – – – – Composite of gaseous atmosphere plus rain exceeded 0.001% of time (55 mm/h rain climate J)

Attenuation in dB due to charged particles varies as $1/f^2$ in the frequency range mentioned above and thus favours the highest frequency available.

2.3 *Velocity of propagation*

Charged particles along the communication path cause changes in the velocity of propagation. Figure 2 shows an example of the apparent range measurement error as a function of frequency and of the angle between the ray path and a line between the Sun and the earth station. This figure is based on the relationships described in Report 683. It is apparent from Fig. 2 that high frequencies are desirable for the most precise ranging.

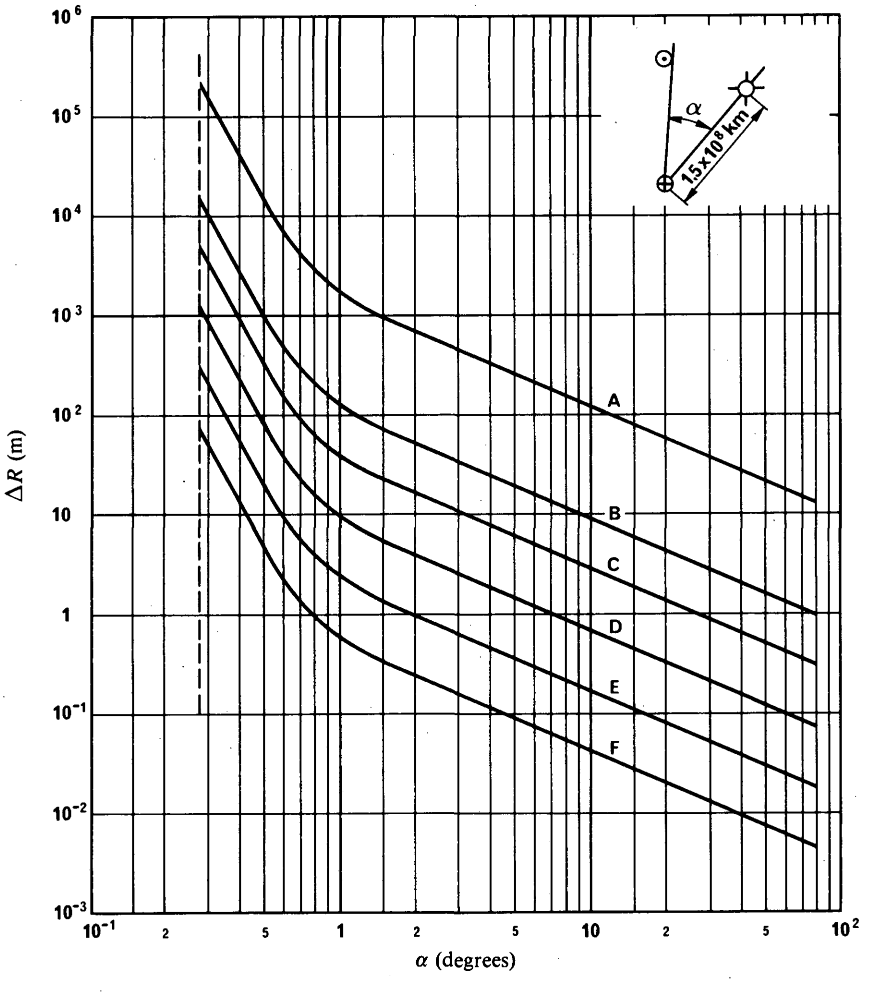

FIGURE 2 – *Approximate error (ΔR) in measured spacecraft range caused by charged particles along a 1.5 × 10^8 km path, as a function of angle α*

Curves A: 2.295 GHz	D: 30 GHz	⊙ : Sun
B: 8.450 GHz	E: 60 GHz	⊕ : Earth
C: 15.0 GHz	F: 120 GHz	-ф- : Spacecraft

2.4 *Scintillation*

Amplitude and phase scintillation from solar plasma is discussed in detail in Report 887 and will be a factor for ray paths close to the Sun. The magnitude of the scintillation decreases with increase in frequency.

3. Frequency dependent characteristics of propagation through an atmosphere

The foregoing interplanetary propagation factors affect links between deep space and a geostationary relay station. For links between deep space and Earth, the atmosphere plays a dominant role in the selection of preferred frequencies in the 20-120 GHz range.

Planetary atmospheres can affect paths that graze or penetrate them.

3.1 *Attenuation*

3.1.1 *Earth atmosphere*

Attenuation of signals passing through the ionosphere of the Earth is negligible at frequencies above 20 GHz, but the neutral atmosphere plays a major role at these frequencies. The attenuation for transmission through the atmosphere is shown in Fig. 3 (see also Report 719). Above 20 GHz, minimum attenuation on links between Earth and spacecraft would be obtained at frequencies near 30 GHz and 90 GHz.

The specific attenuation due to rain at rates greater than a few millimetres per hour is generally larger than that of the gaseous atmosphere and increases monotonically with frequency in the range of interest. The rain rate for 0.001% of the time in rain climate J is 55 mm/h (see Report 563). The attenuation in the 20-120 GHz region during rain at this rate is so high that propagation is not practicable and will not be considered further as a determinant of preferred frequencies.

For the satellite-to-spacecraft links, the line-of-sight propagation paths will be obscured at times by the interposition of the Earth or some portion of the Earth's atmosphere. From a geostationary satellite the solid Earth subtends an angle of 17.34°. If the atmosphere to 100 km altitude were opaque to radio waves the obscuration angle would increase by 0.27°, too small a difference to influence band selection.

The objective of protecting the paths between deep-space probes and an earth satellite from terrestrial interference may be satisfied by taking advantage of the high atmospheric attenuation in the 60 and 119 GHz regions (see Report 719). Molecular oxygen absorption lines at these frequencies are responsible for the high attenuation observed in Fig. 3.

A pair of links (probe to earth-satellite and vice versa) could be accommodated in the high attenuation region between 54 and 64 GHz. A frequency separation of approximately 7% is required (see Report 683). The absorption line at 119 GHz is much narrower and only one link of a pair could enjoy the maximum shielding. In this case shielding of the probe to earth-satellite link is most important.

3.1.2 *Planetary atmospheres*

From the standpoint of attenuation, the nature of planetary atmosphere does not influence the selection of communication frequencies in the 20-120 GHz range. This is not to say that the atmospheres of some planets do not contain spectral lines of scientific interest in the 20-120 GHz range, for example ammonia.

3.2 *Sky noise temperature*

Sky noise temperature as seen by an earth station is a function of frequency, elevation angle and atmospheric conditions (see Report 720). Noise temperature from absorption-related emission from the gaseous atmosphere of the Earth for the standard atmosphere and elevation angle of 30° is shown in Fig. 1. Attenuation caused by rain also influences sky noise temperature in a manner analogous to gaseous absorption. The 0.001% curve of Fig. 1 showing rain-related sky temperature has been computed from the attenuation experienced during 55 mm/h rainfall.

When the earth station antenna is pointed near the Sun, the noise temperature will increase.

3.3 *Scintillation*

Amplitude and phase scintillation from the neutral atmosphere is discussed in Report 881. The effects increase with frequency for a fixed antenna aperture and at 100 GHz may cause signal fluctuations between 0.4 and 3.8 dB for a 37 m parabolic dish antenna.

Scintillation due to the Earth's ionosphere will not be a selection factor for frequencies above 20 GHz (see Report 263), and the same conclusion can be drawn relative to planetary ionospheres. For some missions, scintillation caused by the solar corona could affect the choice of frequency.

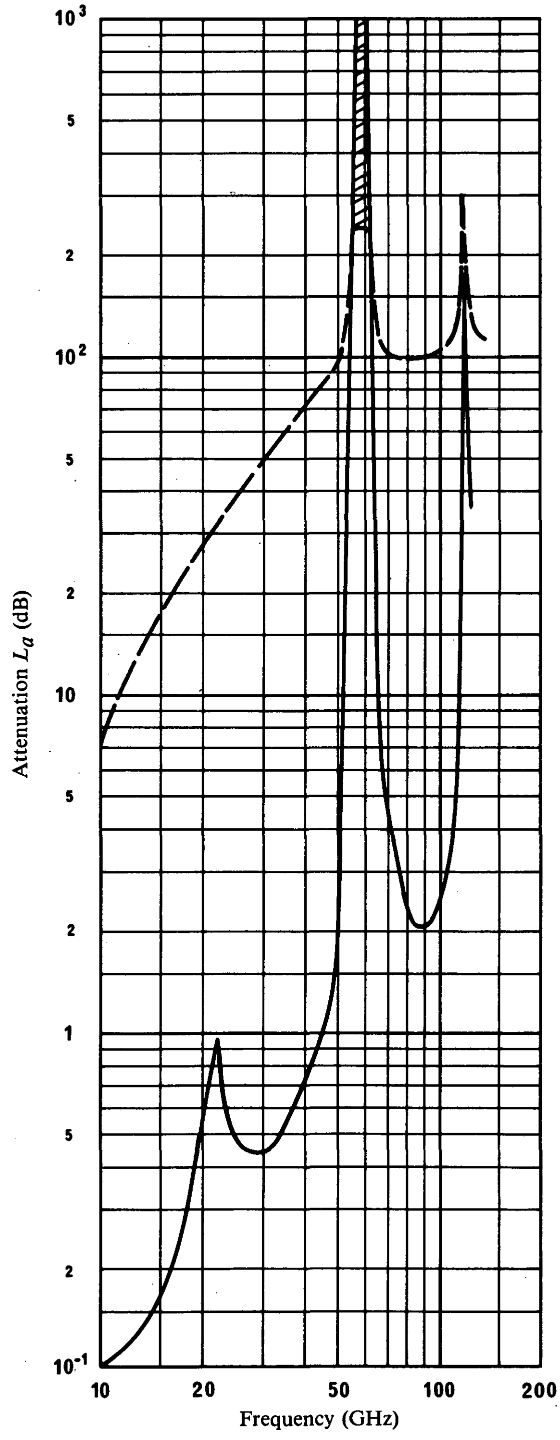

FIGURE 3 – *Attenuation due to the gaseous atmosphere and rain for an antenna elevation angle of 30° at an earth station*

——————— Gaseous atmosphere (7.5 g/m³ water vapour at surface)

– – – – – – Composite of gaseous atmosphere plus rain exceeded 0.001% of time (55 mm/h rain climate J)

4. Frequency dependent equipment factors

Equipment characteristics which determine link performance include transmitter power, antenna size, surface accuracy and pointing accuracy, and receiver noise temperature. These characteristics usually depend upon frequency to some degree. In the frequency range 20-120 GHz, propagation factors influence the link performance so strongly that the frequency dependent equipment factors have only a minor effect on the selection of preferred frequencies. For this reason, only the propagation factors are considered in the following link analyses; the arbitrarily selected equipment parameters are assumed to be independent of frequency.

5. Link performance

Figures 4-7 illustrate link performance as a function of frequency. Curves A are for a path in free space. Curves B include the effect of the atmosphere of the Earth. The index of performance P_R/N_0 (see § 1.3 above) was calculated on the basis of data in Figs. 1 and 3 and the following parameter values:

Communication distance	8×10^8 km
Earth station transmitter power	100 kW
Satellite transmitter power	100 W
Spacecraft transmitter power	25 W

Antenna parameters used in the calculation are shown in Figs. 4-7. The antennas are assumed to be ideal with gain that is proportional to frequency squared.

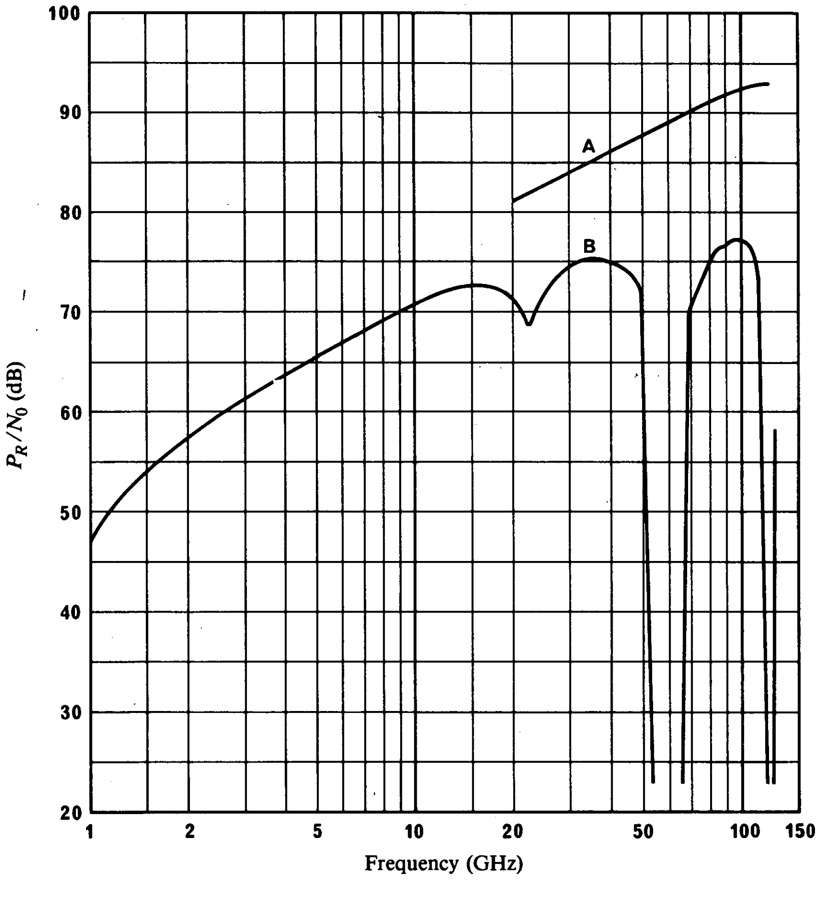

FIGURE 4 – *Link performance (P_R/N_0) limited by natural phenomena only; two fixed diameter antennas: 3.7 m on deep-space station, 64 m at receiving station*

Curves A: deep space to satellite

B: deep space to earth station

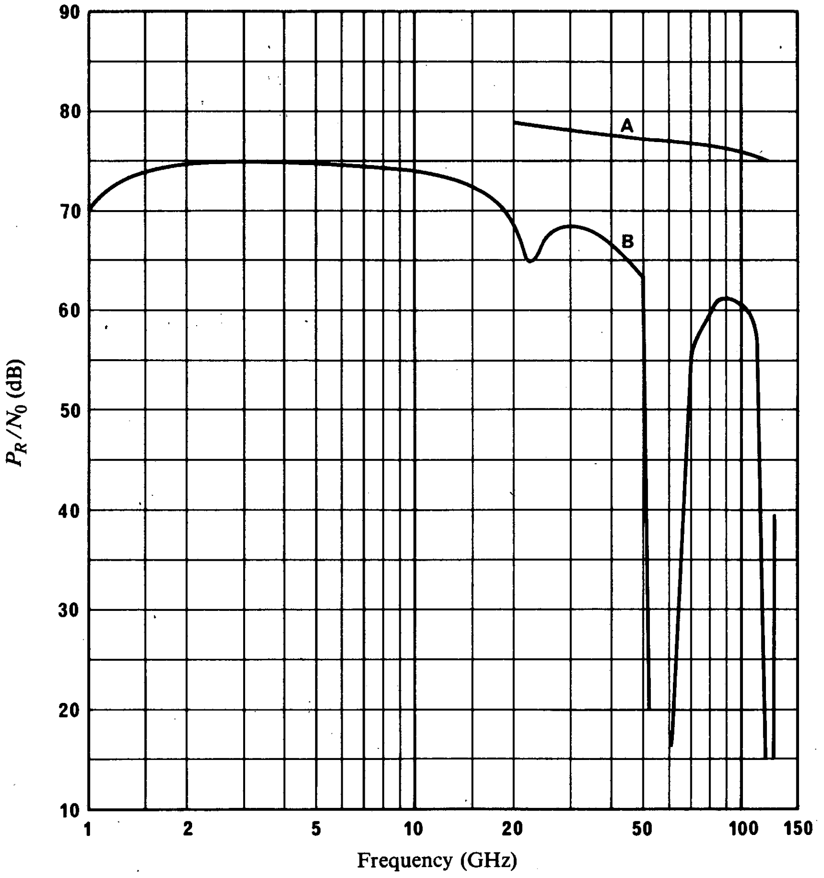

FIGURE 5 – *Link performance (P_R/N_0) limited by natural phenomena only; fixed beamwidth (55 dBi gain) antenna on deep-space station, fixed diameter (64 m) antenna at receiving station*

Curves A: deep space to satellite

B: deep space to earth station

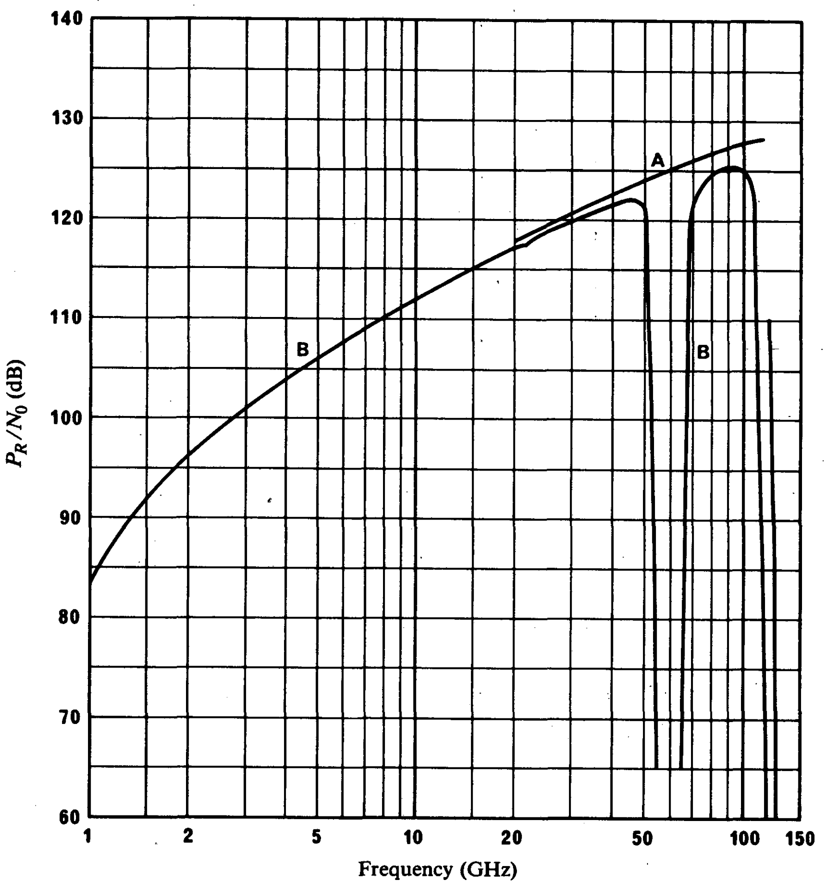

FIGURE 6 – *Link performance (P_R/N_0) limited by natural phenomena only; two fixed diameter antennas: 3.7 m on deep-space station, 64 m at transmitting station*

Curves A: satellite to deep space

B: earth station to deep space

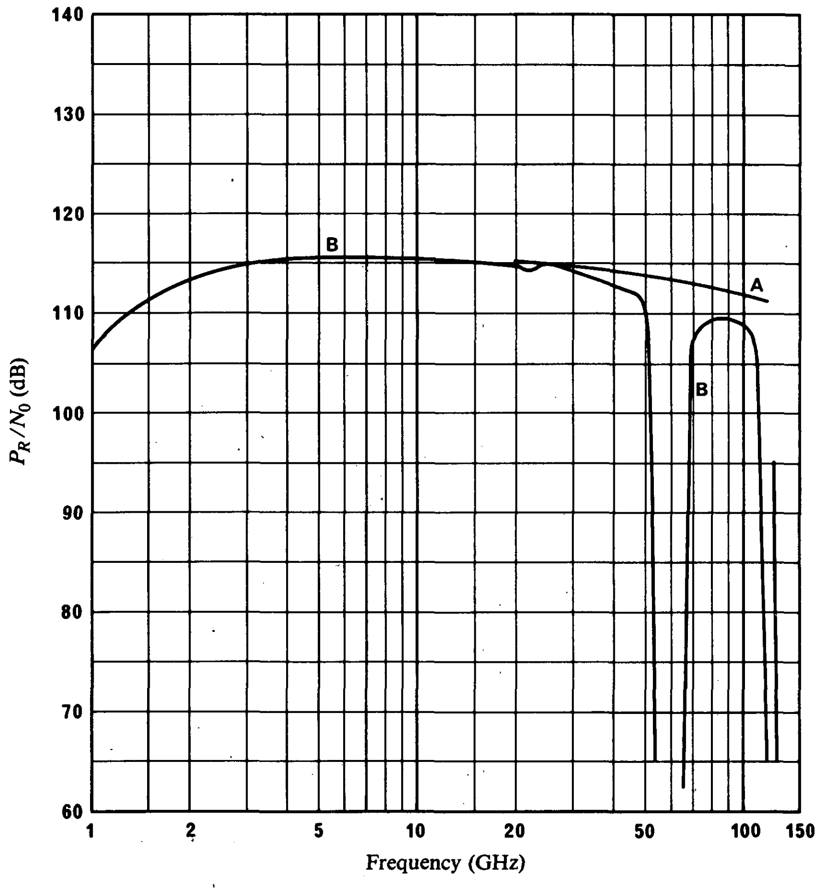

FIGURE 7 – *Link performance (P_R/N_0) limited by natural phenomena only; fixed beamwidth (55 dBi gain) antenna on deep-space station, fixed diameter (64 m) antenna at transmitting station*

Curves A: satellite to deep space
B: earth station to deep space

These values are illustrative only; other values could be used. Different numerical results would be obtained, but the shape of the performance curves and the corresponding frequency selection would not change.

Comparison of curves A and B shows the advantage in link performance that results from utilizing higher frequencies when the path is entirely in space. This is a principal reason for establishing a relay station in an earth satellite.

Curves B show that frequency bands within the 20-120 GHz range can provide for transmission through the atmosphere, and for shielding of paths between a relay satellite and deep-space probes from terrestrial signals.

6. Preferred frequency bands

The preferred frequency bands for deep-space research in the 20-120 GHz range are listed in Table I. The bands were selected on the basis of the index of performance curves and the requirement to provide links between a satellite and a station in deep space that are shielded from terrestrial signals, and links that permit communication between a deep-space station and either an earth satellite or an earth station. The feasibility of band sharing and the existing allocations in the Radio Regulations were not factors in the selection of bands. The frequency dependent characteristics of scintillation and velocity of propagation were not used as determinants of preferred frequency bands. These factors could influence the use of certain allocated bands for particular space research missions, but communication performance was considered the dominant factor in preferred band selection. Similarly, equipment characteristics that vary with frequency were not used to influence band selection. Bands that may be allocated will likely remain for many years, and equipment technology will develop to make best use of those frequencies, as limited by natural phenomena. The bandwidth and frequency separation requirements are discussed in Report 536.

TABLE I — *Preferred frequencies and their uses*

Range of preferred frequencies (GHz)	General applicability	Other requirements([1])
28.5-39	Deep space to Earth during clear weather, and deep space to satellite	500 MHz bandwidth
34-50	Earth to deep space during clear weather, and satellite to deep space	500 MHz bandwidth, spaced at approximately 7% from the space-to-Earth band in the 28.5-39 GHz range
56-64	Satellite to deep space and deep space to satellite shielded from terrestrial signals	A pair of 500 MHz wide bands spaced at approximately 7% within the 56-64 GHz range
117.7-119.8	Deep space to satellite shielded from terrestrial signals	500 MHz bandwidth
98-110	Satellite to deep space (up link for 119 GHz down link)	500 MHz bandwidth, spaced at approximately 7% from the space-to-satellite band in the 117.7-119.8 GHz range

([1]) The requirements shown are based on characteristics of telecommunication systems utilized or planned by several administrations.

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RECOMMENDATION 364-4*

PREFERRED FREQUENCIES AND BANDWIDTHS FOR MANNED AND UNMANNED NEAR-EARTH RESEARCH SATELLITES

(Question 22/2 and Study Programme 22B/2)

(1963-1966-1970-1978-1986)

The CCIR,

CONSIDERING

(a) that suitable operating frequencies and required radio-frequency bandwidths for near-Earth space research missions are determined by propagation factors and technical considerations given in Report 984;

(b) that two-way communication is required for many near-Earth missions, and is vital for manned missions;

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* This Recommendation should be brought to the attention of Study Groups 1, 4, 7, 8, 9, 10 and 11.

(c) that requirements for telecommunication reliability must be satisfied during periods of adverse atmospheric conditions;

(d) that it is practical and desirable to effect telecommunication functions on a single link;

(e) that to effect precision tracking, a pair of coherently related Earth-to-space and space-to-Earth frequencies is desirable;

(f) that for simultaneous transmit/receive operations involving a single antenna, the paired Earth-to-space and space-to-Earth frequencies should be separated by at least 7%;

(g) that space-to-space and Earth/space relay satellite telecommunications are necessary to accommodate the growth and development of near-Earth investigations in the space research service;

(h) that particular modulation and channel coding techniques may be required for some links in order to comply with power flux-density limits or to guard against multipath and/or interference effects,

UNANIMOUSLY RECOMMENDS

1. that frequency bands for near-Earth missions in the space research service be located, with due regard to the purpose of the link and to the feasibility of sharing, in the preferred frequency ranges listed in Table II of Report 984;

2. that the widths of the allocated bands at preferred frequencies satisfy the individual link bandwidth requirements listed in Table III of Report 984 in order to provide for present and future near-Earth telecommunications in multi-spacecraft, multi-mission systems, within the space research service.

RECOMMENDATION 609*

PROTECTION CRITERIA FOR TELECOMMUNICATION LINKS FOR MANNED AND UNMANNED NEAR-EARTH RESEARCH SATELLITES**

(Study Programme 1C/2)

(1986)

The CCIR,

CONSIDERING

(a) that limiting interference criteria for telecommunication links for near-Earth space research are determined by the technical considerations examined in Report 985;

(b) that, based on past experience, it is expected that up to 100 or more active near-Earth space research spacecraft may be in orbit simultaneously;

(c) that there is an increasing use of near-Earth space by both manned and unmanned space research missions;

(d) that two-way communication is required for many near-Earth missions, and is vital for manned missions;

(e) that typical operating noise temperatures of earth stations can be as low as 70 K (equivalent to −210 dB(W/Hz)) in the 1-10 GHz frequency range;

(f) that typical operating noise temperatures of space stations are near 600 K (equivalent to −171 dB(W/kHz)) in the frequency range below about 10 GHz;

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* This Recommendation should be brought to the attention of Study Groups 1, 4, 8, 9, 10 and 11.

** Protection criteria for space research (deep space) can be found in Recommendation 578.

(g) that link margins for typical space-to-Earth or space-to-space links are small, typically between 3 and 6 dB;

(h) that a 1 dB increase in overall system noise due to interference is considered harmful;

(j) that a noise to interference ratio of about 6 dB results in a 1 dB increase in overall system operating temperatures;

(k) that technical and/or regulatory limitations may restrict increases in spacecraft power as a means of minimizing interference;

(l) that difficulties can be expected when frequencies are shared between near-Earth spacecraft in the space research service and stations in other services,

UNANIMOUSLY RECOMMENDS

1. that protection criteria for earth stations in the space research service be established as follows:

1.1 −216 dB(W/Hz) at the input terminals of the receiver, for bands in the 1-20 GHz frequency range. For frequencies below 1 GHz, the protection criterion may be increased at the rate of 20 dB per decreasing frequency decade;

1.2 calculation of interference that may result from atmospheric and precipitation effects should be based on weather statistics for 0.001% of the time for manned missions and for 0.1% of the time for unmanned missions;

2. that protection criterion for space research space stations in low orbit be established as follows: −177 dB(W/kHz) at the input terminals of the receiver, for 0.1% of the time for both manned and unmanned spacecraft, for bands in the 100 MHz-30 GHz frequency range;

3. that frequency sharing be accomplished to the maximum extent feasible among near-Earth spacecraft in the space research service;

4. that note be taken of the difficulties to be expected in frequency sharing between near-Earth spacecraft in the space research service and stations in other services;

5. that note be taken of the difficulties to be expected in frequency sharing between near-Earth and deep-space stations in the space research service.

REPORT 985*

PROTECTION CRITERIA RELATING TO NEAR-EARTH SPACE RESEARCH SYSTEMS

(Question 1/2, Study Programmes 1C/2 and 1D/2)

(1986)

1. Introduction

Much of the spectrum suitable for space research is also allocated to one or more other services and consequently frequency sharing between the services is required. This Report discusses factors which affect the susceptibility of systems in the space research service to interference, and specifies appropriate protection criteria for the service in the frequency bands up to about 30 GHz. The protection criteria are for use in coordination and interference analyses when actual system data are unavailable.

* This Report should be brought to the attention of Study Groups 4 and 9.

2. General considerations

Space research communications are required for four types of functions: telecommand, maintenance telemetering, stored scientific data and real-time scientific data. Interference affects each of these somewhat differently (see Report 548).

For the telecommand function, it is a fundamental design principle of most research spacecraft that no false command should result in a completely aborted mission and that an unalterable state be reached as a result of any command. As there is usually an unavoidable severe dependence on the spacecraft telecommand system during critical mission phases such as during launch and injection sequences or during emergency situations, interference during these critical periods could severely compromise the mission.

Maintenance telemetering can be stored or sampled and transmitted in real time. Except during critical periods, such as launch and injection sequences, emergency situations, or during the transfer of bio-medical data of human occupants, a maintenance telemetry system is fairly tolerant of interruptions and interference. During critical periods, read-outs must of course be highly reliable. The diagnostic use of these data makes it clear that at critical times in a mission there may be long periods (several hours) in which the maintenance telemetry must be protected from harmful interference. For other periods of a mission, however, this class of function can accommodate limited interruption without serious effect.

Stored scientific data can usually be played back more than once for error detection. This is probably the class of data which is most tolerant of interference of limited duration.

Real-time non-stored data are the most susceptible to interference, in that the transmission occurs only once and is unrepeatable. Much of the value of an expensive spacecraft may be represented by such data, so it is imperative that this class be well protected against interruption or degradation. Usually, the time of reception of interesting non-stored data is known in advance to within several hours.

Many space research systems employ PCM-PSK-PM modulating techniques and phase-locked loop circuitry for the demodulation of system carriers and sub-carriers. High data rate transmissions are usually based upon 2-PSK or 4-PSK modulation. Phase-locked loop circuitry is also used during search, acquisition and tracking sequences, and is employed in both ground and spaceborne receivers. Discussion of an experimental investigation into the interference effects in phase-locked loops is presented in Report 544 (Geneva, 1982). In Report 545 (Geneva, 1982), the effects of interference on research spacecraft telemetering (especially binary bit detectors) are discussed.

3. Protection criteria

In a communication link, the permissible ratio of interference to system noise may be determined by the portion of design margin allocated to external interference. In space-to-space and space-to-Earth links, the incentive is to minimize link margins in order to save weight and power, to comply with emission limits, and in the interest of economy. Typical link design margins to allow for the effects of non-ideal conditions are generally in the range of 3 dB to 6 dB for spacecraft operating at frequencies below about 10 GHz. For spacecraft operating at frequencies above about 10 GHz, larger link margins are usually required to offset the effect of weather conditions.

Considering these low link margins, interference can be harmful to typical space research systems if the link threshold performance is decreased by more than 1 dB. This corresponds to a required ratio of system noise spectral density to interference spectral density (N/I) of about 6 dB.

Where it was initially anticipated that channel coding techniques would allow operation with N/I ratios of -10 dB, it has been found through experience that a value of $+6$ dB is required (see Report 687).

3.1 *Reference bandwidth*

The reference bandwidth in which a protection level must be specified depends upon the smallest bandwidth likely to be employed. For earth-station receivers, phase-locked loops may employ bandwidths of a few hertz. The detection bandwidth on the space station is usually greater (1 kHz or more) due to the need for rapid, automatic acquisition of signals from the Earth.

Thus, recommended values for the reference bandwidths for space research receivers are:

- earth-station receivers: 1 Hz
- space station receivers: 1 kHz.

3.2 *Reference percentage of time*

When considering interference to space research earth stations, it is necessary to note that sporadic interference from man-made sources can be expected due to trans-horizon propagation, fluctuating weather conditions, and the changing gain in the link between the interfering station and the receiving station due to the relative motions of the antennas, etc. Therefore, any criterion of interference which is established must be stringent enough to minimize the possibility of this type of interference.

Further, as propagation data are usually presented in the form of a percentage of time that certain conditions are exceeded, it is necessary to relate outage time with propagation data. For manned space missions, a loss of more than 5 min of communication during critical periods would seriously affect the mission. However, it is usual that propagation conditions are such that the lowest transmission loss between two stations will persist for much longer periods than 5 min. Therefore, to provide protection which will prevent interference for longer than 5 min per day, it is necessary not only to consider the worst hour in the year, but also the worst 5 min within that hour. This is approximately 0.001% of the time. For unmanned missions, where safety of life is not a factor, the reference percentage of time is 0.1%.

3.3 *Required protection levels*

3.3.1 *Earth-station receivers*

In the 1-20 GHz region, the total noise temperature of receiving earth stations is typically about 70 K or greater depending on the antenna contribution. This contribution is a function of frequency, antenna elevation angle, existing meteorological conditions and ground and thermal radiation into the antenna side and back lobes. Below about 1 GHz, cosmic noise increases the operating noise temperature of the system at a rate of about 20 dB per decade of decreasing frequency. Therefore, based on the required N/I ratio of 6 dB established in § 3, and a receive noise temperature of 70 K, the following criterion is the most directly appropriate for the protection of earth stations.

In the frequency range 1-20 GHz, harmful interference can occur if the total time during which the power density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands 1 Hz wide, is greater than -216 dB(W/Hz) at the input terminals of the receivers for a period exceeding 0.001% of the time for manned missions, and 0.1% of the time for all other near-Earth space research missions. For frequencies below about 1 GHz, permissible interference may be increased at the rate of 20 dB per decreasing frequency decade. This interference criteria applies to all three of the down-link communication functions discussed in § 2.

3.3.2 *Space-station receivers*

The total noise temperatures of a typical space-station receiver is generally 600 K or more. These levels are due, in part, to the requirement that the spacecraft antenna points at the Earth (290 K). Based on the required N/I of 6 dB, the following criterion is most directly appropriate for the protection of space stations.

In the frequency range 100 MHz-30 GHz, harmful interference can occur if the power density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands 1 kHz wide, is greater than -177 dB(W/kHz) at the input terminals of the receiver.

Due to the motion of low-orbit spacecraft, which can be susceptible to this level of interference, the amount of time of exposure to the interference is limited to 0.1% of the time for both manned and unmanned missions.

RECOMMENDATION 578*

PROTECTION CRITERIA AND SHARING CONSIDERATIONS RELATING TO DEEP-SPACE RESEARCH**

(Question 1/2)

(1982)

The CCIR,

CONSIDERING

(a) that manned deep-space research has unique requirements for extreme reliability of telecommunications so as to ensure safety of life;

(b) that both manned and unmanned deep-space research have unique requirements for extreme reliability of telecommunications so as to ensure successful reception of valuable scientific data collected at particular critical times, and that repeat transmission of these data is often not possible;

(c) that the extreme sensitivity of deep-space earth stations results in unusually low levels of permissible interference;

(d) that some terrestrial and earth stations in other services have sufficient e.i.r.p. to cause interference to stations in deep space;

(e) that sharing studies and protection criteria have been presented in Report 685 for deep-space research earth stations and for stations in deep space;

(f) that protection criteria for relay stations in earth orbit, used for deep-space research, have not yet been determined and are not considered in Report 685,

UNANIMOUSLY RECOMMENDS

1. that protection criteria for deep-space research earth stations be established as follows: −222 dB(W/Hz) in the bands near 2 GHz, −220 dB(W/Hz) in the bands near 8 GHz, −220 dB(W/Hz) in the bands near 13 GHz and −216 dB(W/Hz) in the bands near 32 GHz;

2. that protection criteria for stations in deep space be established as follows: −191 dB(W/20 Hz) in the bands near 2 GHz, −189 dB(W/20 Hz) in the bands near 7 GHz, −186 dB(W/20 Hz) in the bands near 17 GHz and −184 dB(W/20 Hz) in the bands near 34 GHz;

3. that calculation of interference that may result from atmospheric and precipitation effects be based on weather statistics for 0.001% of the time;

4. that with coordination, deep-space research can share Earth-to-space bands with stations in other services except:

- receiving aeronautical mobile stations, receiving satellite stations, and microwave sensor satellites, when any of these may come within line-of-sight;
- receiving mobile stations that come within the separation distance required for interference protection;
- transmitting terrestrial stations having an average e.i.r.p. exceeding 81 dBW in the bands near 2 GHz and 84 dBW in the bands near 7 GHz;

5. that with coordination, deep-space research can share space-to-Earth bands with stations in other services except:

- the radioastronomy service;
- transmitting aeronautical mobile stations, transmitting satellite stations, and active microwave sensor satellites, when any of these may come within line-of-sight;
- transmitting mobile stations that come within the separation distance required for interference protection.

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* This Recommendation is brought to the attention of Study Groups 4, 8, 9, 10 and 11.

** Protection criteria for near-Earth space research satellites can be found in Recommendation 609.

REPORT 684-1 *

PRELIMINARY ANALYSIS OF LOW-ORBIT SATELLITE VISIBILITY STATISTICS

(Question 1/2)

(1978-1986)

1. Introduction

1.1 *General*

This Report, based upon work carried out in the United States, deals with some of the statistical and geometric aspects of potential interference from space research spacecraft in low orbit to terrestrial services and to the terrestrial segments of space services.

1.2 *Background*

The present ITU power flux-density constraints (e.g. Article 28 of the Radio Regulations) were developed primarily on the basis of geostationary space stations interfering with ground communication systems, and as such were based upon a temporally static frequency sharing model (i.e. constant in direction and amplitude of interference). For the sake of generality the expressions "ground communication system", "ground antenna", "ground station" etc., refer to systems, antennas, and stations located on the surface of the Earth, regardless of whether they are functioning in a terrestrial or a space service. The increasing use of space stations in circular low orbit in the space research service (and other services) necessitates the development of a dynamic sharing model, in which the potential interference from the space station can be treated as a time varying function. Even for the simplest of dynamic sharing models, at least six specific system parameters must be evaluated to define precisely the primary time dependent statistics of a low-orbit space station as seen from a location on the Earth's surface.

The time dependent statistics are:

- the longest time of passage of a space station through the main beam of a ground antenna (discussed in § 3 of this Report);
- the long-term percentage of time that the space station spends in various areas of the orbit sphere as seen from the ground station.

The first statistic is important in that it defines the longest continuous duration of noise power into the ground receiving system from the space station. The second set of statistics, after convolution with transmit and receive antenna patterns, and range loss, can be used to develop interference-to-noise (I/N) relations as a function of time for the dynamic sharing model. In one sense then, I/N versus time relations can be treated in a method similar to the signal strength versus time relations derived from atmospheric propagation statistics. However, instead of a receiver experiencing change in the signal-to-noise ratio as a statistical function of time, it experiences a change in signal-to-noise-plus-interference ratio, as a statistical function of time, based upon the low-orbit space station model parameters.

The specific parameters which define the long-term visibility statistics of a space station in a low circular inclined orbit (see Note) as seen from a receiving system on the Earth's surface are:

- altitude of the space station H (km);
- inclination of the space station orbit i (degrees);
- latitude of the ground station La (degrees);
- pointing azimuth of the ground station antenna measured from North Az (degrees);
- pointing elevation of the ground station antenna measured from the local horizontal plane El (degrees);
- angular area of the region of interest δA.

Note. – This Report only deals with satellite orbits in which the orbital period is not an even multiple of the Earth's rotational period.

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* This Report should be brought to the attention of Study Groups 1, 8 and 9.

The last parameter may take on several different physical interpretations depending upon the purpose of the analysis. For instance, it may be the angular area of the main beam of the ground station antenna or it may be taken as an angular area expressed by an azimuth "width" of δAz degrees and an elevation "height" expressed as δEl degrees.

2. Bounding equation

The bounding equation (derived in Annex II of Report 684, Geneva, 1982) is given below and may be used to determine the percentage of time that a low-orbit spacecraft will reside in certain regions visible to a ground station over long periods of time.

$$T\,(\%) = \frac{\delta\lambda}{2\pi^2}\left\{\sin^{-1}\left[\frac{\sin\,(L + \Delta L)}{\sin\,i}\right] - \sin^{-1}\left[\frac{\sin L}{\sin\,i}\right]\right\} \times 100 \qquad (1)$$

where,

- $\delta\lambda$ is the longitudinal region on the orbital shell, between the latitude limits of L and $L + \Delta L$ (as seen in Fig. 1) and
- i is the inclination of the satellite orbit

(all angles in radians).

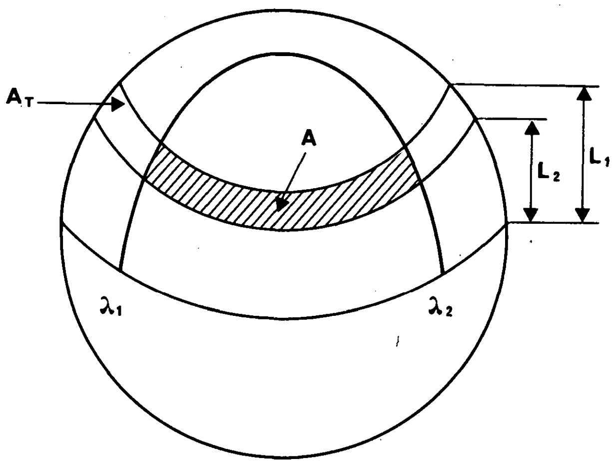

FIGURE 1

3. The maximum time a satellite spends in the beam of a ground station

This section provides worst case numerical data on one aspect of frequency sharing with low-orbit, inclined orbit satellites. Such sharing is influenced by the amount of time that an "unwanted" and potentially interfering satellite appears within the 3 dB beamwidth of a ground station. This parameter is evaluated for several orbit altitudes and for two "bounding" elevations of the receiving antenna. The numerical results developed in this paper represent an upper bound on the length of time a spacecraft at a given altitude will appear within the beam of a ground station.

The time a satellite spends in a ground station's beam is a function of the beam's width, the elevation of the beam and the altitude of the satellite. The worst case, i.e. when the satellite spends the maximum possible time in the beam, occurs when the ground station is located at the equator with a beam of elevation = 0° and the satellite is travelling east along an orbit with 0° inclination. The time the satellite spends in the beam depends upon the satellite's velocity relative to the velocity of the beam as it rotates with the Earth, and upon the length of the intersection of the orbit with the beam (see Annex III to Report 684, Geneva, 1982).

The maximum time that a spacecraft can spend in the main beam of an antenna is shown in Figs. 2 and 3 for antenna elevations of 0° and 90° respectively, and refers to a variety of orbital altitude and beamwidths.

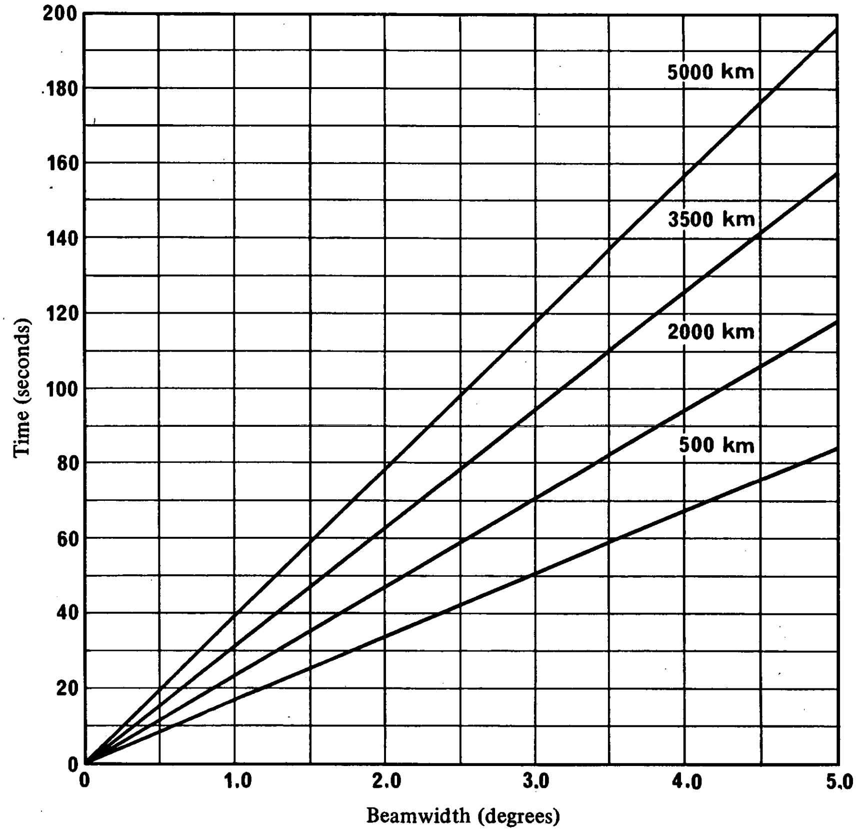

FIGURE 2 – *Maximum time in beam plotted against beamwidth at elevation of 0°*

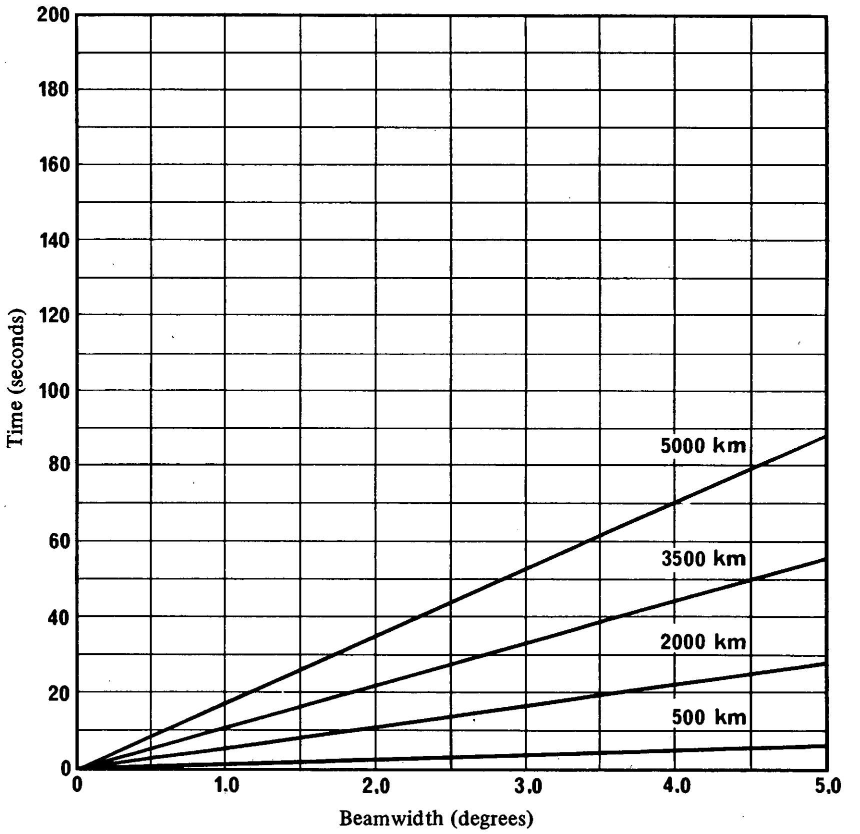

FIGURE 3 – *Maximum time in beam plotted against beamwidth at elevation of 90°*

4. Conclusions

This Report presents a simple method of calculating the percentage of time that a spacecraft in a circular inclined orbit will be visible within a selected region of the sky, as seen from a point on the Earth's surface. In addition, § 3 and Annex III of Report 684 (Geneva, 1982) presents information on the maximum time that a low-orbit spacecraft can spend in the main beam of a ground antenna.

The two factors mentioned above may be useful in developing sharing models between low-orbit, inclined spacecraft and ground receivers of several services.

REPORT 687-1 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH (NEAR-EARTH) AND FIXED AND MOBILE SERVICES IN THE 7 TO 8 GHz SPECTRAL REGION

(Question 1/2)

(1978–1986)

1. Introduction

The bands near 7 GHz (6425 to 7250 MHz) and near 8 GHz (7750 to 7900 MHz) are currently allocated to the world-wide fixed and mobile services. This Report analyzes the potential for frequency sharing in these bands between the fixed, mobile and space research services. Sharing with space research space-to-Earth transmission is covered in § 2, sharing with Earth-to-space transmissions is covered in § 3 below.

2. Space-to-Earth transmissions in the space research service

2.1 *Interference to fixed and mobile line-of-sight receivers from space research satellite transmitters*

The power flux-density (pfd) limits used in this analysis are:

-152 dB(W/m^2) in 4 kHz	for $0° \leqslant \delta \leqslant 5°$
$-152 + (\delta - 5)/2$ dB(W/m^2) in 4 kHz	for $5° < \delta \leqslant 25°$
-142 dB(W/m^2) in 4 kHz	for $25° < \delta < 90°$

where

δ : angle (in degrees) of incoming radiation relative to the horizontal.

These pfd limits are identical to those given in Recommendation 358, which were developed for sharing between the fixed-satellite service and the fixed service in this portion of the frequency spectrum.

For the purpose of evaluating the technical feasibility of frequency sharing, the technical characteristics and calculation of pfd of a typical space research satellite emission are given in Table I.

This level of spectral pfd is 2 dB below the limit of -152 dB(W/(m$^2 \cdot$ 4 kHz)) for low angles of arrival.

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* This Report should be brought to the attention of Study Groups 5, 8 and 9.

TABLE I – *Technical characteristics of space-to-Earth transmissions*

Transmitter power in 100 MHz bandwidth (dBW)	+ 16
Maximum antenna gain (1) (dBi)	+ 6
Allowance for spreading loss (2) to satellite horizon (1000 km orbit) (dB)	– 142
Factor for conversion to 4 kHz bandwidth (dB)	– 44
Spectral distribution factor (3) (dB)	+ 10
Maximum pfd in a 4 kHz band (dB(W/m^2·4 kHz))	– 154

(1) Pattern shaped to provide constant pfd across the satellite field of view.

(2) Defined as the ratio of e.i.r.p. in the direction considered to the power passing in that direction through unit area (1 m^2) at the specified distance (3.7 × 10^6 m in this example).

(3) Defined as the ratio of the maximum power in a 4 kHz band to the mean of the powers in all such bands. The value of 10 dB is assumed to be the worst case for causing interference.

2.2 *Interference to space research earth station receivers from fixed and mobile transmitters*

Table II presents representative technical characteristics of earth stations in the space research service.

TABLE II – *Reception by a space research earth station*

Typical power flux-density from satellite in a 100 MHz band (1) (dB(W/m^2))	– 120.0
Allowance for effective area of receiving antenna (2) (dB)	+ 14.4
Allowance for miscellaneous losses (dB)	– 2.0
Received power, P_r (dBW)	– 107.6
Receiver noise power, $kT_\delta B$ (dBW) (T_δ = 150 K, B = 100 MHz)	– 126.8
Carrier-to-noise ratio, C/N (dB)	– 19.2

(1) For an e.i.r.p. of +22 dBW at a range of 3700 km.

(2) For a parabolic reflector having a diameter of 8 m and an efficiency of 55%.

With this value of C/N, the maximum tolerable value of interference P_i, at the earth station receiver is assumed to be 6 dB below $kT_\delta B$, or – 132.8 dBW.

The sharing criterion for this interference path is based upon the application of coordination distance procedures to ensure sufficient separation between the two systems. The minimum permissible basic transmission loss to protect the earth station receiver is given by:

$$L(1\%)^* = P_t + G_t - (P_i - G_r) \qquad \text{dB} \qquad (1)$$

where

P_t : terrestrial transmitter power (dBW)

G_t : terrestrial antenna gain in direction of earth station (dBi)

* $L(1\%)$: the value of minimum acceptable basic transmission loss to be exceeded for all but 1% of the time along the interference path between the terrestrial transmitter and the earth station receiver. The value of 1% is derived from the service probability requirement of the system; and from the statistical variability of G_r in the case of an earth station tracking a low-altitude, inclined-orbit satellite, and the fact that the earth station would not be continuously active. Coordination distance data is not yet available for $L(1\%)$.

G_r : gain of earth station antenna in direction of terrestrial station (dBi)

P_i : maximum permissible interference level at earth station receiver input (dBW)

or

$$L(1\%) = P_t + G_t + G_r + 132.8 \qquad \text{dB}$$

As the earth station antenna in the space research service is continually tracking a low orbit spacecraft, the value of G_r is a function of time. If the minimum working elevation angle is assumed to be 5°, the maximum gain in the direction of any terrestrial station would be approximately 32 – 25 log (5°) or 14.5 dB. Appendix 28 to the Radio Regulations and Report 382 show a value of G_r of 10 dB below the level of maximum gain towards the horizon, or 4.5 dB.

G_t, the gain of the terrestrial station antenna in the direction of the earth station is taken to be 47 dBi. Therefore:

$$L(1\%) = 8 + 47 + 4.5 + 132.8 \qquad \text{dB}$$

or

$$L(1\%) = 192.3 \qquad \text{dB}$$

3. Earth-to-space transmissions in the space research service

3.1 *Interference to space research satellites from fixed and mobile emissions*

Table III lists technical characteristics of space research earth stations and satellites and derives a carrier-to-noise ratio of 14 dB at the satellite receiver. Considering this C/N ratio, it is assumed that interference should not be greater than 6 dB below the receiver noise power, or –121.5 dBW in the full 100 MHz band.

The satellite antenna (6 dB gain, 70° beamwidth) would sweep a 1200 km swath on the surface of the Earth from a 1000 km orbital altitude. The level of interference experienced by a single receiver based on assumed +55 dBW e.i.r.p. of fixed and mobile systems is calculated below. This calculation for worst case analysis assumes that the satellite is in the main beam of the fixed station transmitting antenna.

This received interference power is 5 dB below the calculated receiver noise power. It should be noted that a satellite in a 1000 km near-polar orbit would receive main beam illumination from a single fixed service transmitter for less than 0.008% of the time.

TABLE IIIa – *Technical characteristics of the Earth-to-space link in the space research service*

Typical earth-station transmitter power (dBW)	8
Earth-station antenna gain (dBi)	55
Allowance for spreading loss (dB)	–131
Satellite antenna gain (dBi)	6
Allowance for satellite antenna (10 log (antenna area in m^2)) (dB)	– 39.5
Received carrier power (dBW)	–101.5
Receiver noise power (dBW) (noise temperature 2000 K, bandwidth 100 MHz)	–115.5
Carrier-to-noise ratio, C/N at the satellite (dB)	14.0

TABLE IIIb – *Technical characteristics of the terrestrial station to satellite interference path*

Terrestrial station transmitter power (dBW)	8
Terrestrial station antenna gain (dBi)	47
Allowance for spreading loss (dB)	–142
Satellite antenna gain (dBi)	6
Allowance for satellite antenna (10 log (antenna area in m^2)) (dB)	– 39.5
Received interference power (dBW)	–120.5

3.2 *Interference to fixed and mobile receivers from space research earth station emissions*

The sharing criterion for this interference path is the application of coordination distance procedures to ensure sufficient separation between the space research earth station and the fixed or mobile stations. The minimum permissible basic transmission loss to protect the fixed and mobile systems can be calculated by:

$$L(0.01\%) = P_t + G_t - (P_i - G_r) + (B_T/B_E) \qquad \text{dB} \qquad (2)$$

where:

P_t : earth station transmitter power (dBW)

G_t : earth station antenna gain in direction of terrestrial station (dBi)

G_r : gain of terrestrial station in direction of earth station (dBi)

B_T : receiver bandwidth of terrestrial system (MHz)

B_E : emission bandwidth of earth station (MHz)

P_i : maximum permissible interference level at terrestrial receiver input (dBW)

Typical terrestrial systems in this band have the characteristics listed in Table IV.

TABLE IV – *Technical characteristics of fixed systems*

Transmitter power (dBW)	8
Antenna gain (dBi)	47
Bandwidth (MHz)	20
Receiver noise temperature (K)	750
Receiver noise power (dBW)	–126.8

The assumed maximum interference level at the terrestrial station in this case is 10 dB below the noise power of the receiver, or –136.8 dBW. Therefore:

$$L(0.01\%) = 8 + 4.5 + 47 + 136.8 - 7 \qquad \text{dB}$$

or

$$L(0.01\%) = +189.3 \qquad \text{dB}$$

and the required coordination distance is determined to be 290 km for a 5° earth station elevation angle, assuming no site shielding and Zone A propagation conditions (great circle mode propagation over land). The value of 290 km has been determined using Appendix 28 to the Radio Regulations.

4. Conclusions

Although coordination distance contours for $L(1\%)$ have yet to be developed, it appears that the space research service (near Earth) and (space-to-Earth) can share frequencies in the 6 to 8 GHz spectral region with the fixed and mobile services. This is provided that the pfd limits given in § 2.1 are imposed on the space research satellite and that care is taken in the siting of the space research earth station. This matter is brought to the attention of Study Group 5, with a view to extending the coverage of Report 724.

Regarding Earth-to-space transmission in this spectral region, sharing is possible with fixed and mobile systems provided care is taken in the siting of the earth station and that the space research satellite can accept the possibility of interference from a single fixed or mobile station for up to 0.008% of the time.

REPORT 685-2*

PROTECTION CRITERIA AND SHARING CONSIDERATIONS RELATING TO DEEP-SPACE RESEARCH

(Question 1/2, Study Programmes 1C/2 and 1E/2)

(1978–1982–1986)

1. Introduction

This Report discusses the sharing of frequency bands between deep-space research stations and stations of other services. Allowable maximum levels of interference are specified for the deep-space research stations. These protection criteria may be used in calculations of coordination distance or for other analysis. The protection criteria are also relevant to studies of sharing within the space research service. Potential interference with other services is considered, and conclusions are drawn about the feasibility of sharing. Future relay satellites for use with deep-space missions are not considered in this Report.

The Report is based on the requirements and characteristics discussed in Report 536, and on the interference susceptibility of receivers typically used for deep-space research, as described in Annex I.

1.1 *Interference effects and consequences*

The consequence of interference that impairs the proper functioning of an earth-station or space-station receiver can be a reduction or interruption in the ability to navigate and control a spacecraft, and in the ability to receive scientific and engineering data sent by a spacecraft.

The receiver contains several synchronization loops, each of which looks to, and tracks, a particular signal component. With sufficiently strong interference, one or more of the several loops will lose lock on the desired signal. Momentary interference can also cause this unlocking and it may take several minutes in the case of the weakest signals to retain locking. During the critical periods that occur during most deep-space missions, it is essential to transmit and receive scientific data without error or interruption. Loss of lock during these periods results in irretrievable data loss. It is this characteristic that leads to such severe requirements for protection from interference. In contrast, the data communicated by some other radio services are often available for retransmission.

1.2 *Loop bandwidth considerations*

For some modes of operation, the loop bandwidths are unusually narrow. A particular example is the carrier tracking loop in the earth-station receiver. This loop may be as narrow as 1 Hz. It might be concluded that it would be unlikely that an interfering signal would lie exactly within that bandwidth, but it must be remembered that the frequency of the desired signal is Doppler shifted as a result of Earth rotation. For example, an 8.4 GHz signal will be shifted ± 11 kHz when received during a 24 h period by an earth station located at a latitude of

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* This Report should be brought to the attention of Study Groups 4, 8, 9, 10 and 11.

35°. An interfering signal with a fixed frequency that is anywhere within the Doppler-shifted range of the deep-space signal will appear to sweep through the carrier tacking loop bandwidth, and unlocking can result. In addition, interference does not have to be exactly within the loop bandwidth in order to affect the loop. As long as the interference is near the loop bandwidth and has sufficient power, severe degradation is possible. Interference that is remote from the loop bandwidth can also cause degradation through other mechanisms, such as maser saturation.

1.3 *Development and application of protection criteria*

In the following sections of this Report, protection criteria are developed. These are based on the receiver function that is most sensitive to interference. Since the receivers are tunable throughout the bands allocated for deep-space research, the protection criteria are considered to apply anywhere in those bands. If this is not recognized, the freedom to choose frequencies for new missions is compromised.

In the concluding sections of the Report, the protection criteria are used to analyze the possibilities of band sharing.

2. Deep-space earth station factors pertinent to sharing

2.1 *Intersections of satellite orbits and antenna beams from deep-space earth stations*

The probability that a satellite will be in the main beam of the antenna of a deep-space earth station strongly affects the possibility of band sharing between the concerned links.

Statistics on antenna pointing at the three deep-space earth stations of the United States network (see Report 536) have been analyzed for a comprehensive set of accomplished and potential deep-space missions. It was found that the earth-station antenna gain in the direction of the geostationary-satellite orbit will be 10 dBi or more for 20% of the time.

Satellites that are not geostationary can pass through one or more deep-space tracking beams each day. Details of visibility statistics and in-beam duration times for satellites in low orbits are contained in Report 684.

2.2 *Susceptibility of deep-space earth station receivers to interference*

The interference susceptibility of earth-station receivers is discussed in Annex I. There are four receiver sub-systems that are sensitive to interference: maser pre-amplifier, carrier tracking loop, telemetering sub-system, and ranging sub-system. Annex I discusses the effects of CW interference and of noise-like interference on each of the four sub-systems.

2.3 *Protection criteria and degradation of performance*

To ensure proper operation of the entire receiving system, each of the four sub-systems must be protected against interference. A protection criterion specifies the amount of interference power that will result in a maximum acceptable degradation of performance. The maximum acceptable degradation for each sub-system is given in Table I.

TABLE I – *Maximum acceptable degradation of receiving sub-systems*

Receiving sub-system	Maximum acceptable degradation
Maser pre-amplifier	1.0 dB gain compression
Carrier tracking	10° of loop-static phase error or peak-phase jitter
Telemetry	1.0 dB equivalent reduction in symbol energy-to-noise spectral density ratio (E/N_0 = 1.0 dB)
Ranging	1.0 dB equivalent reduction in ranging signal-to-noise ratio (E/N_0 = 1.0 dB)

The gain of a maser amplifier is reduced as a function of the input power of very strong signals or interference. This gain compression results in non-linear operation. Strong interference can thus produce non-linear effects on the desired signal, including generation of spurious signals. The maximum acceptable gain compression is considered to be 1 dB. The use of gain compression as a measure of non-linear effects is in agreement with common practice.

The response of the carrier tracking loop to interference is an increase in phase error and jitter. (Very strong interference can cause loss of lock.) The maximum acceptable degradation is considered to be a 10° increase in static phase error or a 10° increase in peak phase jitter.

The degradation of telemetry bit error performance and ranging accuracy as a result of interference can be expressed in terms of a corresponding reduction in signal-to-noise ratio. The maximum acceptable degradation for the telemetry sub-system corresponds to a 1 dB reduction in the symbol energy-to-noise spectral density ratio. This reduction applies to both coded and uncoded telemetry. For the ranging sub-system, the acceptable degradation corresponds to a reduction in ranging signal-to-noise ratio of 1 dB.

The maximum allowable interference for each receiver sub-system is derived from the corresponding maximum acceptable degradation. The protection criterion for the entire receiver is the maximum allowable interference for the most sensitive sub-system.

2.4 *Determination of allowable interference*

Annex I presents data that describe the susceptibility of the four receiver sub-systems to CW and noise-like interference. Using the criteria listed in Table I, the corresponding maximum interference may be determined.

2.4.1 *Maser pre-amplifier*

Table II shows the interference power that causes a 1 dB gain compression in the maser pre-amplifier.

TABLE II – *Maximum allowable interference power for 1 dB gain compression in maser pre-amplifier*

Interference type	Data source	Maximum interference
CW	Fig. 6	–114 dBW
Noise (40 MHz bandwidth)	Fig. 6	–190 dB(W/Hz)

2.4.2 *Carrier tracking, telemetry, and ranging sub-systems*

2.4.2.1 *Interference ratios for carrier tracking, telemetry, and ranging*

Table III shows the interference-to-carrier ratio (I/C), interference-to-signal ratio (I/S), or interference-to-noise ratio (I/N) that corresponds to the allowable degradation of the carrier tracking, telemetry, and ranging sub-systems. The ratios are found as follows:

For CW interference, the allowable interference ratio for each sub-system may be found directly from curves given in Annex I.

For noise-like interference to the carrier tracking loop, Fig. 12 shows that a reduction in signal-to-noise ratio from 10 dB (the typical minimum operating point) to 5.7 dB results in an additional 10° of phase jitter. The corresponding I/N ratio is given by:

$$I/N = 10 \log \left(\frac{10^{(CM_0/10)}}{10^{(CM_I/10)}} - 1 \right) \quad \text{dB} \tag{1}$$

where:

I/N: interference-to-noise ratio,

CM_0: carrier margin (dB) without interference,

CM_I: carrier margin (dB) with interference.

For noise-like interference to the telemetry and ranging sub-systems, the allowable interference-to-noise ratio is given by:

$$I/N = 10 \log \left(10^{(E/N_0)/10} - 1\right) \quad \text{dB} \tag{2}$$

where:

I/N: ratio of interference noise spectral density to receiver noise spectral density,

E/N_0: criterion given in Table I and the reduction in equivalent symbol energy-to-noise spectral density ratio or signal-to-noise ratio.

TABLE III – *Maximum allowable I/C, I/S or I/N for CW and noise-like interference*

Sub-system (criterion)	Interference type	Data source	Maximum interference ratio
Carrier tracking (10° added peak phase jitter)	CW Noise-like	Fig. 7 Fig. 12 and calculation	$I/C = -15$ dB $I/N = +2.3$ dB
Telemetry (1 dB E/N_0 from interference in carrier tracking loop)	CW	Fig. 9	$I/C = -1.5$ dB
Telemetry (1 dB E/N_0 from interference in telemetry detection bandwidth)	CW Noise-like	Fig. 8 Calculated	$I/S = -11$ dB $I/N = -5.9$ dB
Ranging (1 dB E/N_0 from interference in carrier tracking loop)	CW	Fig. 10	$I/C = -5$ dB
Ranging (1 dB E/N_0 from interference in range estimator bandwidth)	CW Noise-like	Fig. 11 Calculated	$I/S = -7.1$ dB $I/N = -5.9$ dB

2.4.2.2 *Maximum allowable interference for carrier tracking, telemetry, and ranging*

For CW interference, the maximum allowable interference depends upon the I/C (I/S) and the minimum carrier (signal) level determined by the receiver design point. If it is assumed that the carrier, telemetry, and ranging signal powers are equal, Table III shows that the maximum allowable CW interference is dictated by the carrier tracking loop because it requires the smallest I/C.

For carrier tracking, the minimum carrier-to-noise ratio is 10 dB. The corresponding allowable interference power for noise-like interference is:

$$P_I = N_0 + 10 \log B + 10 + I/C \tag{3}$$

where:

P_I: maximum allowable interference power for carrier tracking (dBW),

N_0: receiver noise spectral density, given in Table IV (dB(W/Hz)),

B: carrier tracking loop bandwidth, taken as 1 Hz (Hz),

I/C: interference-to-carrier ratio as given in Table III (dB).

The resulting P_I is −220.9 dBW for the 8.4 GHz band, as shown in Table IV. Values are also shown for the other bands allocated to deep-space research.

TABLE IV – *Maximum allowable interference power to earth-station receivers*

Band (GHz)	Receiver noise spectral density (dB(W/Hz))	Maximum CW interference power (dBW)	Maximum noise-like interference power spectral density (dB(W/Hz))
2.3	−216.6	−221.6	−222.5
8.4	−215.0	−220.0	−220.9
13.0	−214.6	−219.6	−220.5
32.0	−211.4	−216.4	−217.3

Table III shows that the maximum allowable noise-like interference is dictated by the telemetry and ranging sub-systems because they require the smallest I/N. Table IV shows the corresponding maximum allowable power spectral density for this type of interference.

2.5 *Protection criteria for deep-space earth station receivers*

Table V gives the maximum interference that will not exceed the allowable degradation of earth-station receiver performance. These values are the protection criteria for deep-space earth station receivers. Also shown is the corresponding spectral power flux-density at the aperture of a 64 m antenna.

TABLE V – *Interference protection for earth-station receivers*

Band (GHz)	Maximum allowable interference spectral power density (dB(W/Hz))	Maximum allowable interference spectral power flux-density (1) (dB(W/m²·Hz))
2.3	−222.5	−255.5
8.4	−220.9	−253.2
13.0	−220.5	−251.7
32.0	−217.3	−239.1

(1) For a 64 m antenna.

To protect earth-station receivers, the spectral power density of noise-like interference, or the total power of CW interference, should not be greater than the amount shown in Table V for an aggregate of 5 min in any one day (5 min per day is generally taken as 0.001% of the time).

3. Deep-space station parameters and protection pertinent to sharing

Space station and earth station receivers for deep-space research function in a similar manner, except that the space station does not include a maser. Space stations are susceptible to interference in ways similar to those described earlier for earth stations.

The criterion for protection of deep-space station receivers is that interference power must be no stronger than receiver noise power. Compared to deep-space earth station criteria, this is less severe and is a consequence of generally larger performance margins on the earth-to-space link. For protection of deep-space stations, the power spectral density of wideband interference, or total power of CW interference, in any 20 Hz band should be no larger than the amount shown in Table VI, for an aggregate of 5 minutes per day. The 20 Hz bandwidth specification is the carrier tracking loop bandwidth of the spacecraft transponder operated with threshold signal strength. The values of noise temperature shown in Table VI are estimates of currently practical systems that could be used in deep space.

Considerations regarding space station transmitter power are given in a later section.

TABLE VI – *Interference protection for receivers in deep space*

Frequency (GHz)	Noise temperature (K)	Maximum interference power spectral density (dB(W/20 Hz))
2.1	300	–190.8
7.2	500	–188.6
17.0	900	–186.1
34.5	1500	–183.8

4. Sharing considerations: Earth-to-space bands

Table VII and the following paragraphs consider the possibility of interference in the deep-space research Earth-to-space bands.

TABLE VII – *Potential interference in Earth-to-space bands*

Source	Receiver
Deep-space earth station	Terrestrial or earth station
Deep-space earth station	Near-Earth satellite
Terrestrial or earth station	Deep-space station
Near-Earth satellite	Deep-space station

4.1 *Potential interference to terrestrial or earth station receivers from deep-space earth station transmitters*

The normal maximum total power for current US deep-space earth stations is 50 dBW. For a typical minimum elevation angle of 10°, the e.i.r.p. directed towards the horizon does not exceed 57 dB(W/4 kHz), assuming the reference earth station antenna radiation pattern of Recommendation 509. For spacecraft emergencies, the maximum total power may be increased to 56 dBW, giving not more than 63 dB(W/4 kHz) at the horizon. These values of e.i.r.p. meet the requirements of No. 2540 of the Radio Regulations.

Aircraft stations within line-of-sight of a deep-space earth station may encounter total power flux-densities as shown in Fig. 1. For an aircraft altitude of 12 km, the maximum line-of-sight distance to an earth station is 391 km and the total power flux-density at the aircraft can never be lower than -83 dB(W/m^2), again assuming the antenna pattern of Recommendation 509. Depending on distance and earth station antenna direction, the aircraft station may experience much higher flux-densities and interference levels. Coordination with airborne stations is generally not practicable.

Tropospheric phenomena and rain scatter may couple deep-space earth station transmitting signals into transhorizon, space system and other surface stations. When practicable, coordination should provide sufficient protection for terrestrial receivers and earth station receivers. See § 6 for coordination considerations.

4.2 *Potential interference to satellite receivers from deep-space earth station transmitters*

Satellites that come within the deep-space earth station beam will encounter power flux-densities as shown in Fig. 1. When the earth station is tracking a spacecraft so that the antenna beam passes through the geostationary satellite orbit, the power flux-density at a point on that orbit will vary with time as shown in Fig. 2. For example, the total power flux-density will be -95 dB(W/m^2) or more, for 32 minutes. The figure assumes a transmitter power of 50 dBW, a 64 m antenna, and the reference earth station pattern of Recommendation 509. An important observation is that the minimum power flux-density at the geostationary satellite orbit within line of sight of a deep-space earth station is -122 dB(W/m^2), regardless of the antenna pointing direction.

The duration and magnitude of signals from deep-space earth station transmitters which may interfere with satellites in non-geostationary orbits depends upon those orbits and the particular deep-space tracking at that time.

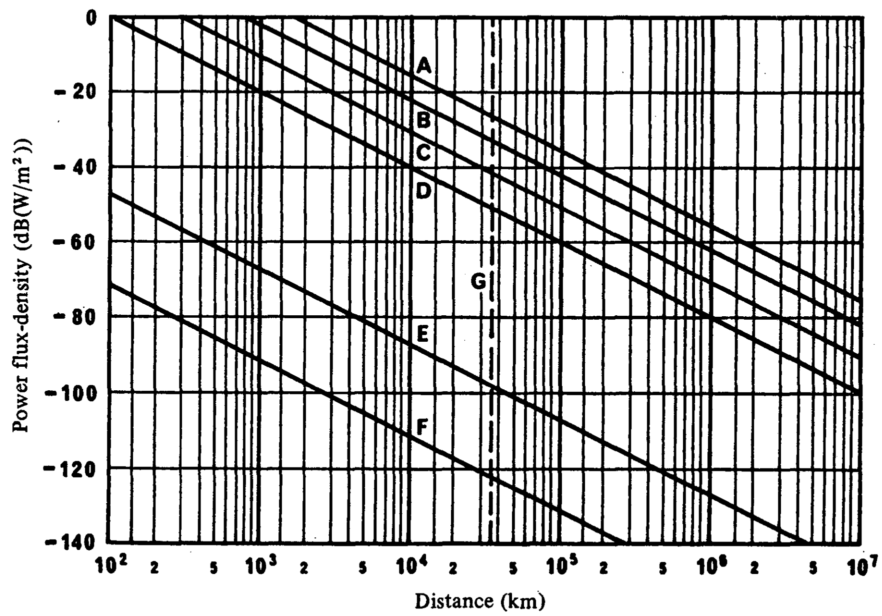

FIGURE 1 – *Power flux-density from earth-station transmitter 100 kW, 64 m antenna*

A: main beam, 34 GHz
B: main beam, 17 GHz
C: main beam, 7200 MHz
D: main beam, 2110 MHz
E: 5° off-axis (14.5 dBi gain, Recommendation 509)
F: ⩾48° off-axis (−10 dBi gain, Recommendation 509)
G: altitude of geostationary-satellite orbit: 35 600 km

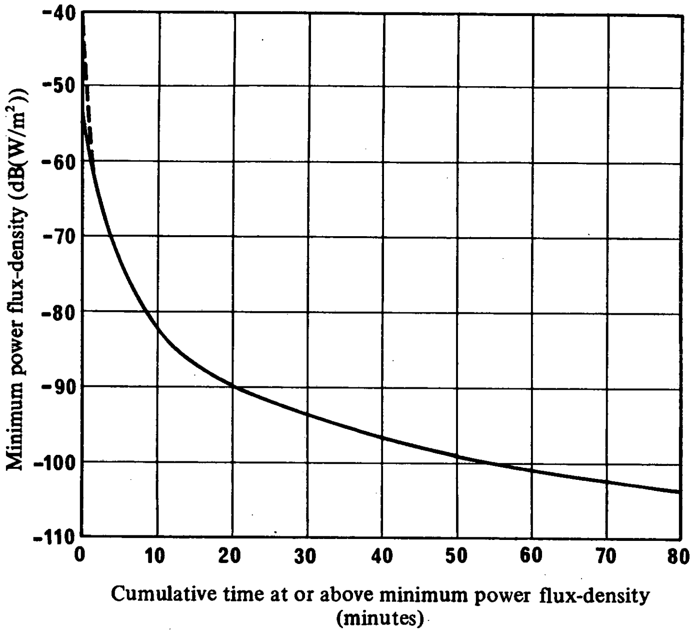

FIGURE 2 – *Duration of potential interference to geostationary satellite intersecting beam axis from earth station with 100 kW transmitter and 64 m antenna*

———— : 2.1 GHz

– – – – : 17 GHz

4.3 *Potential interference to deep-space station receivers from terrestrial or earth station transmitters*

Terrestrial or earth station transmitters within sight of a deep-space station are potential sources of interference. Figure 3 shows the space station distance at which interference power density from such a transmitter equals the receiver noise power density. For example, a transhorizon station with 93 dB(W/10 kHz) e.i.r.p. in the 2.1 GHz band could interfere with a space station receiver at ranges up to 4.1×10^9 km (600 K noise temperature, 3.7 m spacecraft antenna). The possibility of interference at such a great distance poses a threat to space missions to planets as far away as Uranus. Stations with lower e.i.r.p., or with antennas pointing away from the ecliptic plane, have less potential for interference.

4.4 *Potential interference to deep-space station receivers from near-Earth satellite transmitters*

Near-Earth satellites typically have antennas directed to the Earth or to other satellites. Interference with deep-space station receivers may occur for those brief periods when the satellite antenna is directed so as to permit main beam coupling. As received at deep-space stations, signals from satellites will usually be relatively weaker than those from earth stations.

5. Sharing considerations: space-to-Earth bands*

Table VIII and the following paragraphs consider the possibility of interference in the deep-space research space-to-Earth bands.

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* Report 688 (Geneva, 1982) discusses the feasibility of sharing between space research satellites in eccentric orbits and deep-space research earth stations. The band 2290-2300 MHz was used for the analysis presented in that Report. The Report was originally adopted in 1978. In 1979, the band 2290-2300 MHz was restricted to deep-space research. Report 688 is therefore no longer directly applicable to sharing in that band, but the analysis itself may be of interest.

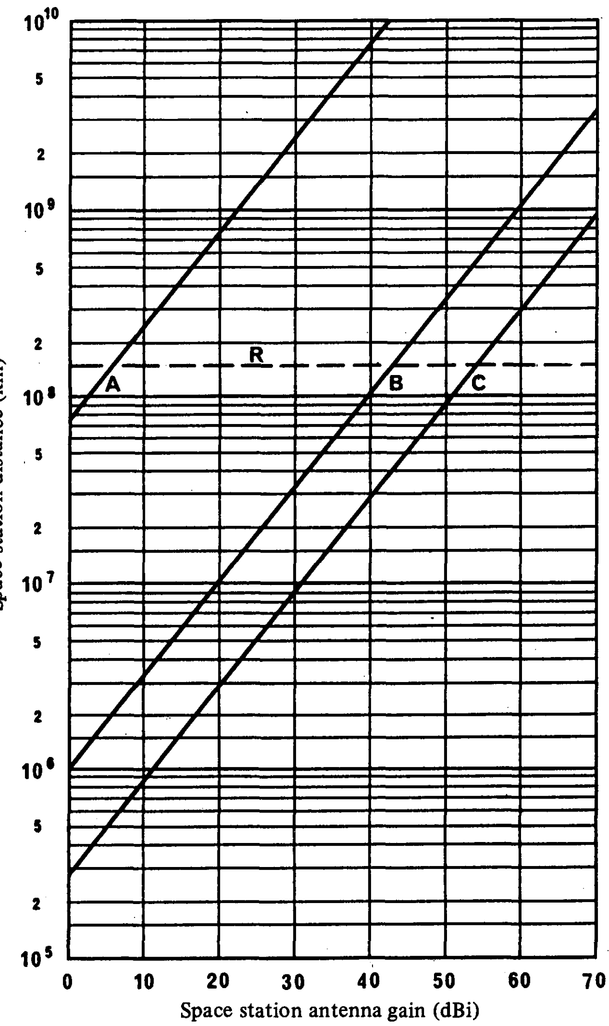

FIGURE 3 – *Space station distance from terrestrial transmitter for interference power equal to receiver noise power*

A: 2.1 GHz trans-horizon transmitter, 93 dB(W/10 kHz); –191 dB(W/20 Hz) receiver noise power
B: 2.1 GHz relay transmitter, 55 dB(W/10 kHz); –191 dB(W/20 Hz) receiver noise power
C: 7.2 GHz relay transmitter, 55 dB(W/10 kHz); –189 dB(W/20 Hz) receiver noise power
R: Space station range of 1 astronomical unit: 1.5×10^8 km

TABLE VIII – *Potential interference in space-to-Earth bands*

Source	Receiver
Deep-space station	Terrestrial or earth station
Deep-space station	Near-Earth satellite
Terrestrial or earth station	Deep-space earth station
Near-Earth satellite	Deep-space earth station

5.1 *Potential interference to terrestrial or earth station receivers from deep-space station transmitters*

Figure 4 shows the power flux-density at the surface of the Earth caused by deep-space stations with characteristics as shown in Report 536. These stations typically use low gain, wide beam antennas while near Earth. After a time not exceeding six hours from launching, they are usually at a sufficient distance for the power flux-density at the surface of the Earth to be less than the maximum permitted by the Radio Regulations for protection of line-of-sight radio-relay systems. For example, the Voyager Jupiter/Saturn spacecraft used the low gain antenna until 4.2×10^7 km from Earth, at which time the power flux-density would be -198 dB(W/m^2) in 4 kHz after switching to the high gain antenna.

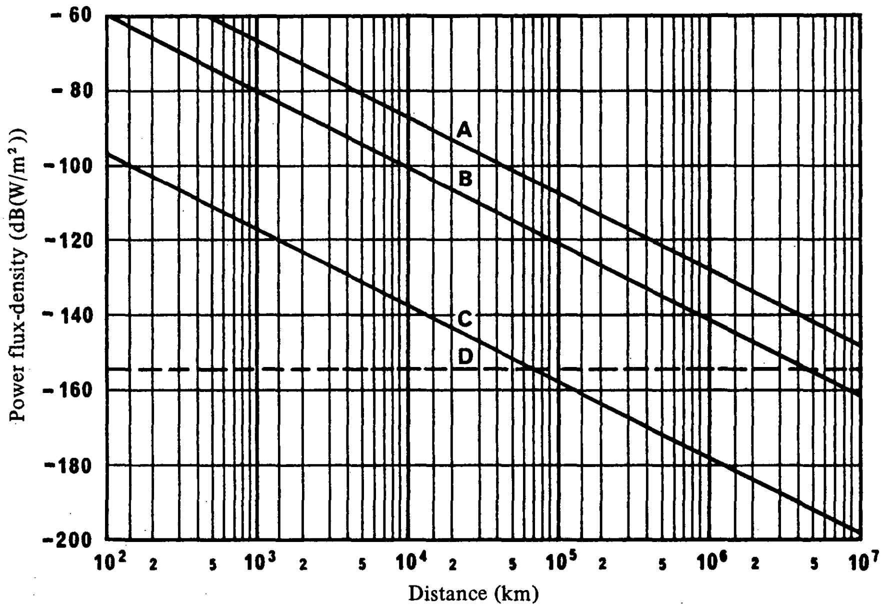

FIGURE 4 – *Power flux-density at the surface of the Earth from space station transmitter*

A: 13 dBW transmitter, 50 dBi antenna (3.7 m antenna, 8425 MHz)
B: 13 dBW transmitter, 37 dBi antenna (3.7 m antenna, 2295 MHz)
C: 13 dBW transmitter, 0 dBi antenna
D: -154 dB(W/m^2) PFD (No. 2557 of the Radio Regulations)

When the transmitting space station is using a higher gain directional antenna, there is the potential for interference with sensitive terrestrial receivers if their antennas are directed so as to permit main beam coupling. A space station operating at 2.3 GHz with an e.i.r.p. of 51 dBW at a distance of 5×10^8 km could create an input of -168 dBW to a trans-horizon receiver (27 m antenna, main beam). The duration of such interference would be of the order of a few minutes, once a day, because of the rotation of the Earth.

5.2 *Potential interference to near-Earth satellite receivers from deep-space station transmitters*

Considerations of this interference are similar to those for the space station to terrestrial receiver case, § 5.1, with the exception of the path geometry. Depending on the changing conditions of that geometry, occasional brief interference is possible.

5.3 *Potential interference to deep-space earth station receivers from terrestrial or earth station transmitters*

Interference to deep-space earth station receivers may come from terrestrial or earth stations over line-of-sight paths, by tropospheric phenomena, or by rain scatter. For coordination considerations see § 6.

In particular, services utilizing high power transmitters and high gain antennas are potential interference sources. Earth station transmitters are less likely sources of interference, depending on e.i.r.p. in the direction of the deep-space earth station. Coordination should enable adequate protection from radio-relay stations to be provided.

Aircraft transmitters within sight of a deep-space earth station may cause serious interference. At maximum line-of-sight distance in any direction (391 km for an aircraft at 12 km altitude), an e.i.r.p. of −26 dB(W/Hz) (for example, 10 dB(W/4 kHz) and 0 dBi antenna) will exceed the earth station interference limit by at least the amount shown in Table IX, assuming the reference earth station antenna pattern.

Coordination with airborne stations is generally not practicable.

TABLE IX – *Interference from assumed aircraft transmitter*

Frequency (GHz)	Deep-space earth station interference limit (dB(W/Hz))	Harmful interference from aircraft (1) (dB)
2.3	−222.5	35.7
8.4	−220.9	22.1
15.0	−219.3	15.5

(1) Aircraft signal less deep-space earth station interference limit

5.4 *Potential interference to deep-space earth station receivers from near-Earth satellite transmitters*

An analysis of the case for satellites in highly eccentric orbits may be found in Report 688 (Geneva, 1982). It is concluded that sharing is not feasible. This conclusion is also valid for satellites in circular and moderately eccentric orbits.

6. Discussion

The very high e.i.r.p. and extreme sensitivity of deep-space earth stations usually result in exceptionally large coordination areas.

Sharing with stations that are within line-of-sight (LOS) of deep-space earth stations is not feasible. Stations within LOS will create excessive interference to receivers of deep-space earth stations, or will be exposed to excessive interference from transmitters of these stations. Aeronautical mobile stations and near-Earth satellites frequently come within LOS of deep-space earth stations.

Sharing of deep-space Earth-to-space bands with stations utilizing high average e.i.r.p. is not feasible because of potential interference to stations in deep-space. It is currently considered that stations with an e.i.r.p. that is more than 30 dB below the implemented or planned e.i.r.p. for space research earth stations do not pose a significant problem. From the data in Report 536, this means an average e.i.r.p. no greater than 81 dBW at 2 GHz, and 84 dBW at 7 GHz. The deep-space earth station e.i.r.p. for other frequencies is not now known.

7. Conclusion

Criteria and considerations presented in this Report lead to the following conclusions.

7.1 *Sharing of Earth-to-space bands*

With coordination, deep-space research can share Earth-to-space bands with stations in other services except:

- receiving aeronautical mobile stations, receiving satellite stations, and microwave sensor satellites, when any of these may come within line-of-sight, and
- receiving mobile stations that may come within the separation distance required for interference protection, and
- transmitting terrestrial stations having an average e.i.r.p. exceeding 81 dBW in the 2 GHz region and 84 dBW in the 7 GHz region.

7.2 *Sharing of space-to-Earth bands*

With coordination, deep-space research can share space-to-Earth bands with stations in other services except:

- the radioastronomy service;
- transmitting aeronautical mobile stations, transmitting satellite stations and active microwave sensor satellites, when any of these may come within line-of-sight;
- transmitting mobile stations that may come within the separation distance required for the interference protection.

ANNEX I

INTERFERENCE SUSCEPTIBILITY OF RECEIVING SYSTEMS FOR DEEP-SPACE RESEARCH

1. Introduction

This Annex presents information on the interference susceptibility of receiving systems used for telecommunications associated with deep-space research. Two classes of interference are considered: CW and noise-like interference. The particular receiving systems that have been analyzed are those of the deep-space network (DSN) operated by the United States of America [Yuen, 1983].

The effects of interference on particular parts of a receiver have been examined in Reports 544 and 545 (Geneva, 1982). Report 544 discusses the effect of CW interference on a phase-locked loop. The analysis does not include a bandpass limiter ahead of the loop. Report 545 examines the effect of CW and noise-like interference on the error ratio of a maximum likelihood detector. It does not consider the effect of the interference on the preceding sub-carrier or carrier tracking loops, both of which influence the error ratio of the entire receiver. Although the two Reports provide some understanding of interference effects, they do not accurately characterize the susceptibility of a receiver typically used for deep-space telecommunications.

2. The receiving system

The receiving system includes four major elements, each of which must be protected from interference: the maser pre-amplifier, the carrier tracking loop, the telemetry sub-system, and the ranging sub-system. The interference susceptibility of each of these will be discussed in § 4 below. A simplified block diagram of the receiving system is shown in Fig. 5.

3. Results of interference

Interference can result in performance degradation, non-linear operation or loss of data. The effect of the interference depends on its strength and separation in frequency from the wanted signal.

At weak-to-moderate power levels, co-channel interference can increase the static phase error and phase jitter of the carrier tracking loop, increase the telemetry bit error ratio, or reduce the accuracy of the range estimate. This performance degradation can generally be expressed as an equivalent reduction in signal-to-noise ratio and can, in theory, be compensated by increasing the power level of the wanted signal. In practice, the power of the wanted signal is usually not adjustable.

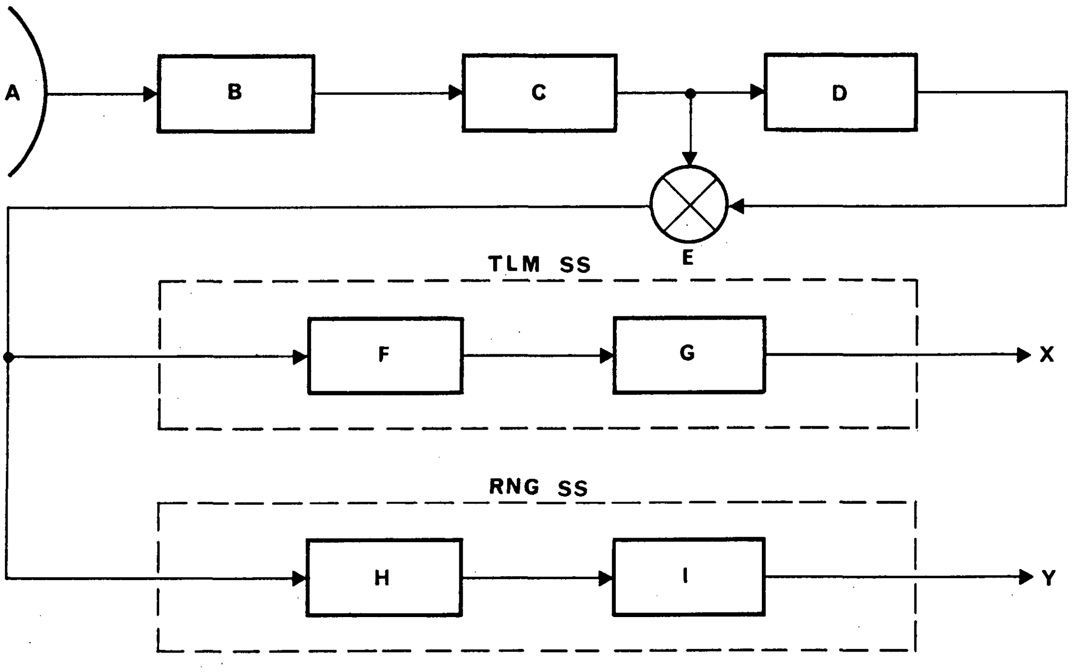

FIGURE 5 – *Simplified functional block diagram for a typical deep space network receiving system*

TLM SS: telemetry sub-system
RNG SS: ranging sub-system
A: antenna
B: maser
C: pre-selector
D: carrier tracking loop
E: carrier demodulation
F: telemetry sub-carrier tracking loop
G: symbol synchronization and data detection
H: dual channel range code correlator
I: range computer
X: telemetry data stream
Y: range delay estimates

Strong interference having a large frequency separation from the wanted signal can result in a performance degradation and simultaneously drive one or more of the receiver components into a non-linear region, resulting in gain compression and the generation of harmonics, spurious signals, and intermodulation products. These non-linear effects are collectively referred to as saturation effects. Unlike performance degradation, saturation effects generally cannot be compensated even if the power level of the wanted signal is increased.

Strong interference having a small frequency separation from the wanted signal can cause the receiving system to lose lock or synchronization, resulting in a total loss of data.

4. Effects of CW interference

The specific interference effects are to be discussed in the following sub-sections for each of the four receiving sub-systems. Although the receiving system is most sensitive to co-channel interference, adjacent-channel interference and even out-of-band interference can sometimes cause detrimental effects. A co-channel interference is one whose frequency is in the passband of the sub-system. The frequency of the interference is assumed to be fixed unless specified otherwise.

4.1 *RFI susceptibility of the maser pre-amplifier*

The principal interference susceptibility of a maser is saturation (gain compression) by strong signals. The maser is most sensitive to interference that has a frequency in or near the maser passband, or the maser idler frequencies. Interference power that causes 1 dB maser gain compression is shown in Fig. 6 for a typical maser operating at the 8.4 GHz band. This curve is based on [Bautista and Petty, 1981; Hersey and Sue, 1980; Clauss, 1977].

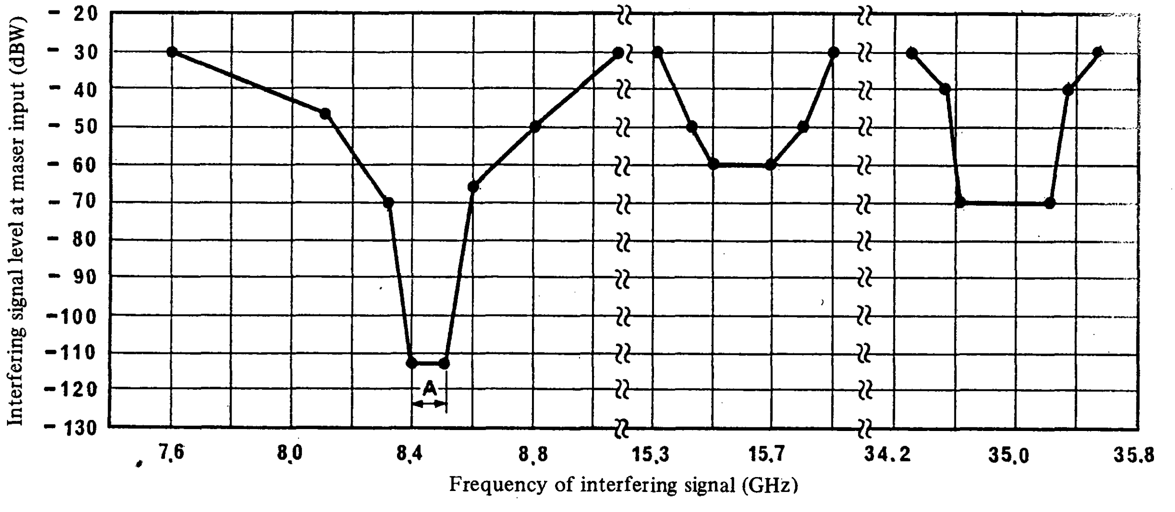

FIGURE 6 – *Signal level required to reduce the gain of a 8.45 GHz maser by 1 dB, versus frequency*

RFI type: CW
A: maser signal bandpass

4.2 *CW RFI susceptibility of the carrier tracking loop*

The carrier tracking loop is a double heterodyne tracking loop which incorporates a synchronous-detector AGC (automatic gain control) loop and second-order phase-locked loop preceded by a bandpass limiter.

Strong interference can cause the loop to lose lock to the wanted signal, and the loop may lock to the interference [Kliger and Olenberger, 1976]. Both fixed frequency and sweeping (changing frequency) CW interference can result in this effect. If the interference is changing in frequency, the loop may first lose lock to the wanted signal and then lock to the interference as it moves close to the frequency of the wanted signal. As the interference moves through and away from that frequency, the loop then loses lock to the interference and may later re-lock to the wanted signal. The time it takes for the loop to re-lock to the wanted signal depends on the signal strength, the interference strength, and the sweep rate. It may vary from seconds to minutes. If the interference is fixed in frequency, re-locking to the wanted signal may never occur.

As a weaker level, interference can increase the static phase error and the phase jitter in the loop [Bruno, 1973; Blanchard, 1974; Levitt, 1979]. This is true for both fixed and sweeping interference.

Figure 7 shows peak jitter as a function of CW interference-to-carrier ratio.

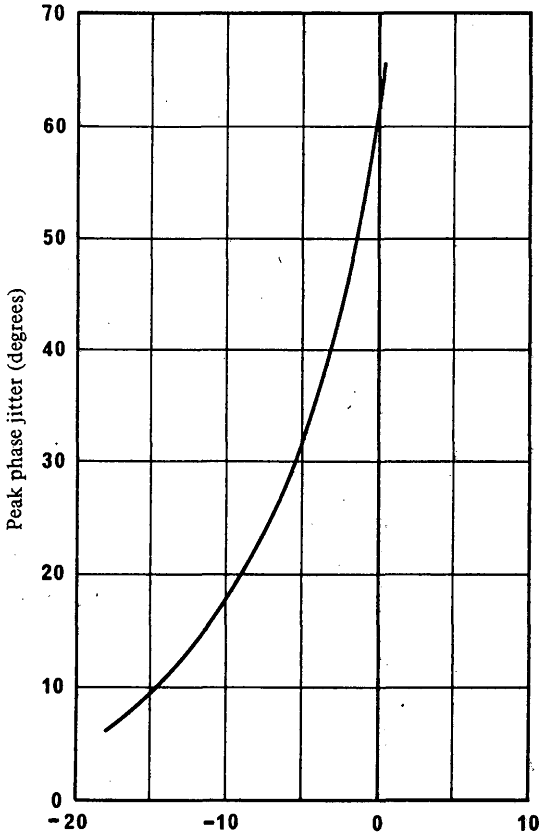

FIGURE 7 – *Peak phase jitter versus interference-to-carrier ratio*

RFI type: CW

4.3 *CW RFI susceptibility of the telemetry receiving sub-system*

Telemetry degradation can be expressed as an equivalent reduction in symbol energy-to-noise spectral density ratio (E/N_0) which is defined as the amount by which the symbol energy-to-noise spectral density ratio would have to be reduced in the case of no interference in order to obtain a symbol error ratio equal to that in the presence of interference.

The E/N_0 ratio resulting from CW interference that is within the telemetry detection bandwidth is given in Fig. 8.

Telemetry performance can also be degraded by CW interference that falls within the carrier loop bandwidth. Figure 9 shows E/N_0 ratio as a result of carrier loop phase jitter versus interference-to-carrier ratio, for a 10 Hz frequency offset and for a typical receiving mode operating at the 8.4 GHz band.

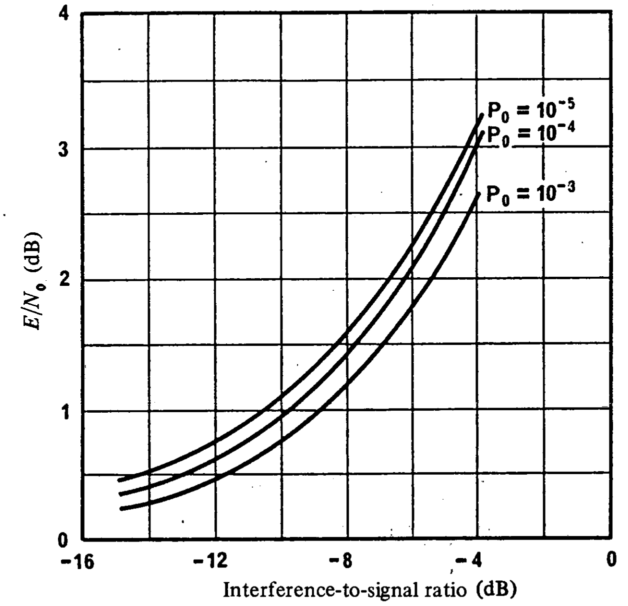

FIGURE 8 – *Equivalent reduction in telemetering signal-to-noise ratio (E/N_0) as a result of interference in the telemetering channel, versus interference-to-signal ratio, for selected values of probability of symbol error*

RFI type: CW

P_0 : probability of symbol error

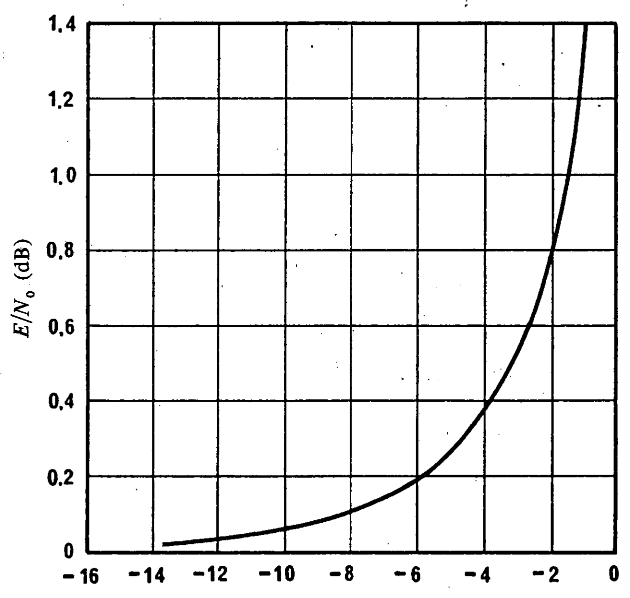

FIGURE 9 – *Equivalent reduction in telemetering signal-to-noise ratio (E/N_0) as a result of carrier loop phase error and jitter, versus interference-to-carrier ratio*

RFI type: CW

Band: 8.45 GHz

Frequency offset: 10 Hz

4.4 *CW RFI susceptibility of the ranging sub-system*

Interference can degrade the performance of the ranging sub-system by increasing the variance of the range delay estimates. The degradation can be expressed in terms of an equivalent reduction in the effective ranging signal-to-noise ratio.

CW interference in the carrier tracking loop bandwidth affects the ranging system performance, as shown in Fig. 10. The effect of CW interference in the ranging signal bandwidth is shown in Fig. 11. The I/S ratio refers to the ratio of the interference power to the ranging-signal power.

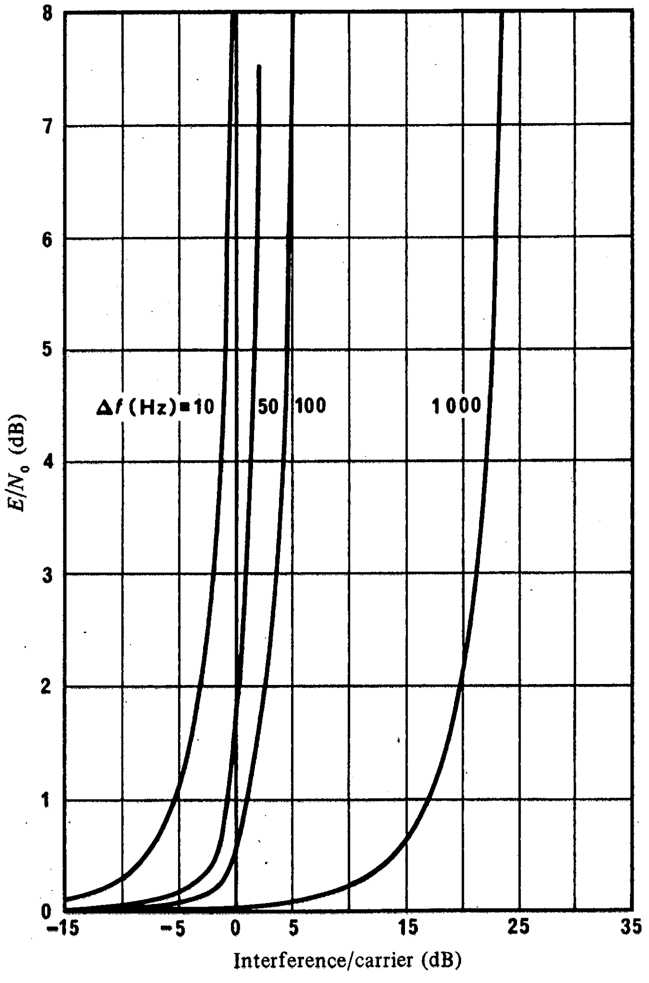

FIGURE 10 – *Equivalent reduction in ranging signal-to-noise ratio (E/N_0) as a result of carrier loop phase error and jitter versus interference-to-carrier ratio, for selected values of frequency offset*

RFI type: CW

Band: 8.45 GHz

Δf: frequency offset

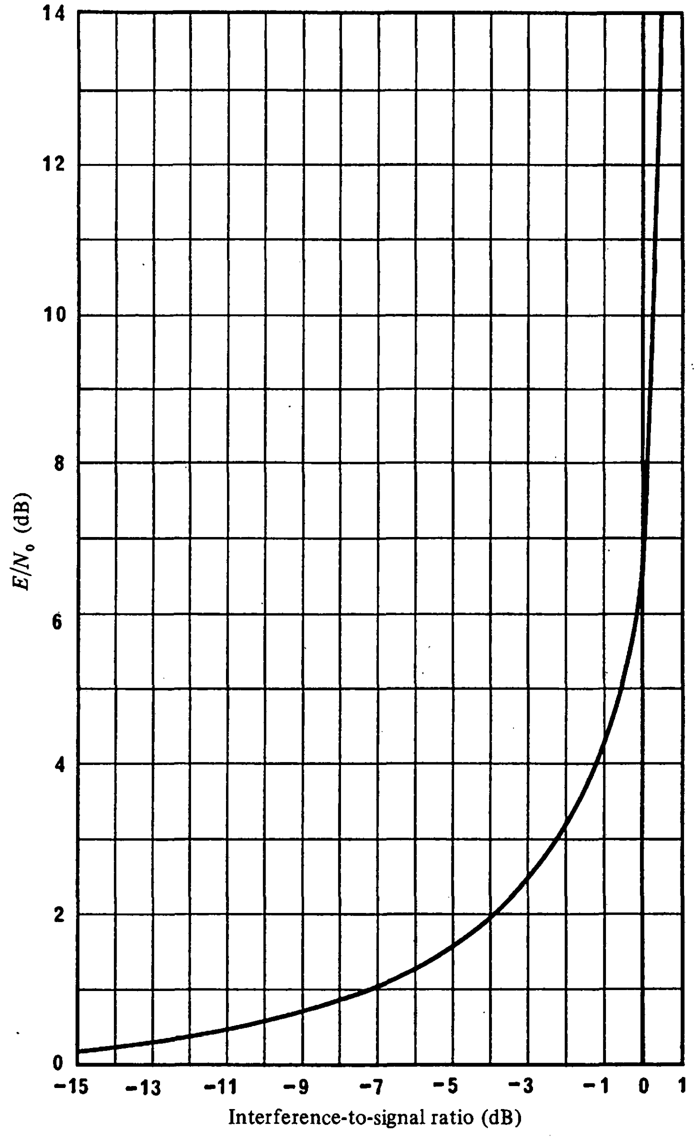

FIGURE 11 – *Equivalent reduction in ranging signal-to-noise ratio as a result of interference in ranging channel, versus interference-to-signal ratio*

RFI type: CW

5. Effects of noise-like interference

Noise-like interference can saturate the maser pre-amplifier and can degrade the performance of the carrier tracking loop, the telemetry sub-system, and the ranging sub-system. To cause a maser gain compression of 1 dB, the spectral density of the noise-like interference, I_0, would have to be -190 dB(W/Hz), assuming a maser bandwidth of 40 MHz.

For the carrier tracking loop, the peak phase jitter depends on the carrier margin (Fig. 12). Noise-like interference reduces the carrier margin and hence increases the phase jitter. The carrier margin is related to I_0/N_0 by the expression:

$$CM_{RFI} = CM + 10 \log \left(\frac{1}{1 + \frac{I_0}{N_0}} \right) \tag{4}$$

where:

CM_{RFI} : carrier margin in the presence of interference;

CM : margin without interference; and

I_0/N_0: interference-to-noise spectral density ratio.

Given a particular carrier margin without interference, and the acceptable increase in phase jitter, Fig. 12 and the foregoing expression allow the I_0/N_0 to be calculated. For example, at a typical margin of 10 dB, an increase of 10° in peak-phase jitter will be caused by interference that reduces the margin to 5.5 dB. The I_0/N_0 for this circumstance is 2.3 dB.

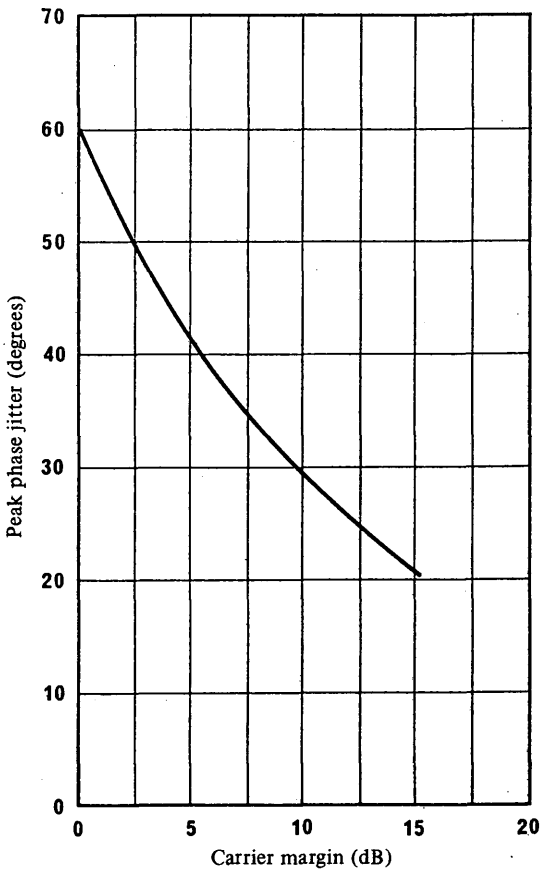

FIGURE 12 – *Peak phase jitter versus carrier margin*

The effect of a noise-like interference on the telemetry and ranging sub-systems is to reduce the effective symbol energy-to-noise spectral density ratio and thereby increase the telemetry error ratio and the range delay estimate variance.

The reduction in equivalent symbol energy-to-noise spectral density ratio, E/N_0, can be expressed as:

$$E/N_0 = 10 \log (1 + I_0/N_0) \tag{5}$$

where I_0/N_0 is the interference spectral density-to-noise spectral density ratio. Knowing the acceptable E/N_0 ratio, the corresponding I_0/N_0 may be calculated.

6. Conclusion

The susceptibility of a receiving system for deep-space telecommunications has been presented for two kinds of interference, CW and noise-like. Although interference with other spectral characteristics may be encountered, experience has shown that the effects of these two kinds of interference may be used in the determination of criteria needed to ensure protection from harmful interference.

Information in this Annex I is primarily concerned with earth-station receivers. Similar interference effects can be expected for the carrier tracking, command, and ranging functions of a corresponding space station receiver. Numerical values and curves will differ because of differing system noise temperature, the absence of a maser, and different bandwidths.

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RECOMMENDATION 513-1

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(Question 10/2)

(1978-1986)

The CCIR,

CONSIDERING

(a) that a continuing need is envisaged for space experiments for research of the neutral and ionized atmosphere;

(b) that the conclusions drawn in Report 456 indicate the necessity for certain frequencies in order to contribute to these studies and measurements;

(c) that to measure differential Doppler effect, use should be made of two harmonically related frequencies;

(d) that simple techniques to measure Faraday rotation effects need two VHF frequencies differing by 1 to 3%;

(e) that based on frequency dependence of the atmospheric attenuation, frequencies near 15, 20, 30, 90 and 150 GHz are technically suitable for measurement of the neutral atmosphere;

(f) that sharing of beacon frequencies in the space research service with other services has introduced serious difficulties through interference,

UNANIMOUSLY RECOMMENDS

1. that in addition to frequencies presently allocated, a frequency harmonically related to 20 MHz and located in the range 80 to 200 MHz is technically suitable and desirable for differential Doppler observations;

2. that consideration be given to improved protection of the 40.98 to 41.015 MHz band allocated for Faraday rotation measurements;

3. that frequencies near 15, 20, 30, 90 and 150 GHz are desirable for measurements of the neutral atmosphere.

REPORT 456-3 *

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(Question 10/2)

(1970-1974-1978-1986)

1. Introduction

Beacon transmitters on satellites are used for scientifc experiments and also for several applications in which space techniques are used. The present Report is concerned with beacons used for studies of the atmosphere. Other applications of beacons to geodesy and geodynamics are described in Report 988.

The frequency bands at present allocated to the Space Research Service have been used mainly to satisfy the necessity for receiving telemetered scientific and technological data from spacecraft, and for controlling their movements and condition. Radio transmissions between satellites and the Earth are also used for research into the

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* This Report should be brought to the attention of Study Groups 5 and 6.

behaviour of the radio waves themselves rather than the information which they carry as communication links. Some of these activities are described below under four headings. The first three are closely linked in that they depend upon the influence of the ionized and non-ionized regions of the atmosphere on the radio waves. It is convenient to consider them separately because the objectives and frequency requirements are somewhat different.

The first type of study is referred to as radio propagation, its objectives being to determine how waves travel between two points, one of which is on a spacecraft. The second is ionospheric research, with the main objective of determining the characteristics of the ionosphere as a physical medium. The third is research on propagation through the atmosphere, with the objective of determining the propagation characteristics of the atmosphere (atmospheric research, *per se*, is performed within the Meteorological Service). It will be apparent that radio propagation studies will often yield information on the atmosphere, and conversely, atmospheric research will help in the understanding of propagation mechanisms. However, the research discussed here is based on special techniques which have rather specific frequency requirements.

The fourth category of research, the study of orbits, is based on techniques related to those of the other categories; but the atmosphere is a disturbing influence, and frequencies need to be chosen to minimize its effects.

2. Radio propagation

At frequencies mainly in the decametric range, long range propagation between ground stations and satellites of low altitude has been observed up to antipodal distances. It is generally assumed that ducting inside the ionosphere is the important mechanism [Chvojková, 1965]. However, detailed information is lacking and important features such as the exit paths from the duct, leakage, and attenuation need further study. A study of the ducting mechanism is of interest not only for communication with satellites, but also for efficient long distance communication on the Earth by mechanisms without repeated ionospheric and ground reflections. It is therefore, important that suitable experiments be made over a sufficiently long time scale and over a large geographical area. Transmission from a satellite on a suitable selection of frequencies is the best way to allow a great number of earth stations to participate.

As the phenomenon depends in a critical way on ionospheric refraction, a series of frequencies must be used, which extend over a large part of the high-frequency range, say 2 to 20 MHz, taking into account the variations of iononospheric electron density with hour, solar cycle, season and geographical position. The range from about 2 to 5 MHz is suitable for rather low satellite altitudes and for high geomagnetic latitudes, while the higher frequencies are preferable for low latitudes and for the study of very long range propagation.

The requirements have been partially met by secondary allocations to space research at 15.76 and 18.03 MHz and in the standard frequency bands at 2.5, 5, 10, 15, 20 and 25 MHz. It should be noted that the practice of radiating standard-frequency signals at frequencies which are staggered within the allocated bands, may lead to increased interference to space research. It is expected that the propagation problems described above, and similar problems, will be a subject of interest to scientists for many years.

As it becomes increasingly necessary to utilize frequencies above 10 GHz, transmission characteristics in the lower atmosphere become an additional important mechanism needing further study. Propagation effects at millimetre wavelengths can be more severe than at longer wavelengths. These are particularly due to precipitation and to oxygen and water vapour absorption. Several experiments and many theoretical analyses have been conducted on the effects of the atmosphere on radio waves, with varying objectives. Such work can be conveniently considered as beacon-related, and accordingly, is discussed as part of this Report.

3. Ionospheric research

Ionospheric beacon satellites transmitting at harmonically related frequencies have proved to be powerful tools for the investigaton of ionospheric electron content; in particular, that of the outer ionosphere. As they can be used by many earth stations simultaneously, the information obtained by the relevant techniques provides complementary data to that obtained with top-side sounders. Two techniques have given most useful results.

Observation of the *differential Doppler-effect* at two harmonically related frequencies allows separate identification of the modification of waves due to the refractive effect of the ionospheric plasma. Moreover, with a simple electronic device the rather small plasma effect can be directly recorded to a high accuracy [Rawer, 1964; Rawer and Suchy, 1967].

A second technique is the observation of the Faraday rotation of waves transmitted through the ionosphere. The Faraday rotation of the plane of polarization is caused by double refraction in the ionospheric plasma situated in a magnetic field. It is possible to apply this technique in the frequency range of 100 to about 1000 MHz, by for example, observing the beacon signals with elaborate equipment which measures the polarization angles to a high degree of accuracy. However, most observations have been made by simpler techniques at lower frequencies, and there will be a continuing need for this type of measurement at many stations all over the world. It should also be mentioned that these observations give, as a side-product, much valuable information concerning the ionospheric propagation phenomenon of scintillation [Aarons *et al*, 1961; Rawer, 1962]. For evaluation of the electron content these techniques are based on a count of the number of rotations of the plane of polarization. If this number is large, as is the case with frequencies below 100 MHz, changes of the ionospheric electron content can be determined accurately with simple recording of the output of a receiver. However, with only one transmitted frequency in this lower range, the total number of rotations, and hence the total electron content of the ionosphere, cannot be determined absolutely. The addition of a second frequency, differing from the first by only a small per cent, permits the observation of the *differential Faraday effect.* The total number of rotations is then determined by comparing two time-series of nulls and their relative phases. The fractional frequency difference determines the scale-factor relating the total number of rotations to the number of nulls [Rawer, 1964; Rawer and Suchy, 1967]. In typical ionospheric observations a scale-factor of the order of 30 to 100 is convenient; two frequencies differing by 1 to 3% are therefore technically suitable.

Frequencies usable for both techniques should be high enough to penetrate the ionosphere, but low enough to give appreciable ionospheric refraction effects. In view of the large variations of ionospheric electron density, a satisfactory set of frequencies could be in the range of 15 to 60 MHz. One higher frequency is desirable to provide a phase reference with small refraction effects. Thus a technically suitable series of frequencies for measurements at HF and VHF is:

- three harmonically related frequencies for differential Doppler observations, the two lower ones between 15 and 60 MHz, and one other between 80 and 200 MHz,
- one additional frequency, differing by a few per cent from that of the second of the above frequencies, for differential Faraday observations.

The allocations at 20 and 40 MHz partially meet these requirements. It would be feasible for the highest frequency of the series to be in the space research band just above 400 MHz, but a lower frequency would be preferable. A frequency of 41 MHz has been used with 40 MHz on a non-interference basis for the Faraday rotation work, but there has been no protection at this frequency for these measurements.

Similar techniques are also used in some experiments using rockets. Frequencies of the order of 1 MHz, for example, are suitable for the study of the lower regions of the ionosphere using Faraday rotation. The D region can be explored by measuring the fields in the ionosphere from a low-frequency transmitter on the ground.

4. Research on the non-ionized atmosphere

Some experimental data have been obtained, and extensive theoretical modelling has been done on the efficiency of the atmosphere as a transmission medium for radio waves at frequencies above 10 GHz. The experimental efforts to date, have been at frequencies below 40 GHz. Results have indicated that precipitation in the atmosphere severely degrades transmission, but that by careful selection of earth station sites and orbits, and use of such techniques as site diversity, reliable communication systems may be feasible.

Above 40 GHz, theoretical models have indicated that oxygen absorption becomes the controlling factor in atmospheric transmission, and that attenuation characteristics rapidly increase with frequency. However, the characteristic curves indicate that in certain frequency bands, for example, around 90 GHz and 150 GHz, attenuation may be lower than at neighbouring frequencies.

Accordingly, a technically suitable set of frequencies for conducting atmospheric research is as follows (see Report 205):

- 15 to 20 GHz range
- 30 GHz
- 90 GHz
- 150 GHz.

5. The feasibility of frequency sharing

As far as protection of the frequencies used for space research is concerned, it is shown in the Annex that in many cases, particularly over great distances, the possibility of carrying out measurements is already severely limited by the natural noise level. An increase of the effective noise level by other transmissions would, therefore, lead to intolerable interference. Experiments made at several frequencies indicate that the sharing of these frequencies reduces the measuring possibilities of beacon transmissions to a minimum. Therefore, it must be stated that:

- sharing of beacon frequencies by other services has introduced serious difficulties to the space research service;
- the protection ratios should correspond to those already specified for the reception of telemetering transmissions in space research (Recommendation 364).

6. Conclusion

A continuing need, for many years, is envisaged for space research experiments involving Doppler and Faraday rotation techniques, for measurement of atmospheric transmission characteristics above 10 GHz. Existing allocations in the standard frequency bands from 2.5 to 25 MHz will fulfil some of the need if they prove to be usable without harmful interference. Frequencies below 2 MHz are suitable for some types of experiments but no common requirement on a continuing basis is apparent.

For Doppler measurements an additional frequency is required which is harmonically related to 20 MHz, preferably by a simple multiple, and in the range of 80 to 200 MHz. Faraday measurements can be made with elaborate equipment at frequencies greater than 100 MHz, for example those radiated for tracking purposes, but some of the simpler and more widely used techniques require two VHF transmissions differing by 1 to 3%. In many cases, some frequencies can be common to both Doppler and Faraday measurements.

For atmospheric measurements below 40 GHz, there is a continuing need for frequencies near 15, 20 and 30 GHz. Above 40 GHz it appears frequencies will be needed near 90 and 150 GHz.

The transmissions used in Doppler and Faraday rotation experiments can be accommodated in bandwidths of the order of 0.02% of the frequency.

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ANNEX I

SIGNAL STRENGTH AND NOISE CONSIDERATIONS IN BEACON SATELLITE EXPERIMENTS

1. Field strength and Faraday rotation measurements

Field strength observations, mainly as regards the Faraday effect, are made for a relatively large receiving bandwidth of about 3 kHz, on frequencies of about 40 and 41 MHz, which are normally used by most observing stations to obtain reliable amplitude values in spite of the Doppler effect. Although automatic tuning would permit the bandwidth to be reduced considerably, it would require extensive technical expense if locking were to be maintained continuously, even during the deep fading minima.

The different types of application call for varying degrees of protection (signal-to-noise ratio) which depend on the particular measuring parameter to be determined. Experience gained from a long series of measurements indicates that the following values are desirable for the signal-to-noise ratio (relative to the median value of the wanted signal field strength):

- observations of the Faraday effect for determining the electron content: 10 dB;
- observations of ionospheric scintillations: 20 dB;
- observations of the differential absorption from the ratio of the maximum to the minimum value of the Faraday effect: 30 dB.

The use of directional antennas is not feasible for the majority of scientific observation stations, so that, for these stations, a value of 0 dB must be assumed for the gain of the receiving antenna.

As the number of observation stations is large it would not be possible to use directional antennas except on board geostationary satellites. However, even in the case of these satellites, the technical expense of installing directional antennas is prohibitive because of the relatively low frequencies involved. Given the foregoing, and given also the fact that the satellite transmitter power lies between 10 and 50 mW, the range of field strengths shown in the following table can be expected on the ground:

Ground field strengths (dB(μV/m))

Distance from satellite (km)	Transmitter power (mW)	
	50	10
1 000	2	−5
10 000	−18	−25
40 000	−30	−37

Taking into account the unavoidable cosmic noise, which is, for example, −18 dB(μV/m), in a bandwidth of 3 kHz at 40 MHz, these field strength values will frequently not allow the required signal-to-noise ratios to be achieved.

For the small number of better-equipped observation stations, a considerable reduction in noise level can be achieved with the aid of phase-locked frequency tracking (with a separate field-strength recording channel), but the bandwidth must not be less than 30 Hz if rapid variations of field strength are to be reproduced correctly. Compared with a 3 kHz bandwidth, this means an improvement of 20 dB. However, the observation of differential absorption, requiring a protection ratio of 30 dB is of particular interest for these stations, and, for this application, the limits of reception capabilities are reached with respect to cosmic noise, even when using the phase-lock technique, although at greater distances.

Within a few years, new types of application will emerge for beacon techniques at very large planetary distances (greater than 1 astronomical unit). Distances twice as great as that between the Earth and the Sun will be covered by space probes. The same situation will, therefore, still prevail even if much more elaborate systems are in use.

2. Phase measurements

Phase observations, especially by means of the differential Doppler effect, are made both during rocket flight and in satellite operation. While observations of the first type can usually be arranged on a non-interference basis, the observation of satellites requires that many terrestrial receiving stations have the relevant frequencies free of interference.

In the case of the differential Doppler technique, the same receiving antenna is preferably used for both frequencies to minimize direction-dependent phase errors. In any case, non-directional antennas are needed; that is, the gain of the receiving antenna must be assumed to be zero.

The differential Doppler system in itself has a very small bandwidth. This bandwidth should, however, not be too small if rapid changes due to ionospheric irregularities are still to be detectable.

Here, too, such applications are envisaged in planetary missions of space probes (see above).

3. Conclusions

It is pointed out that, even with the present application of beacon satellites, natural noise occasionally limits measuring possibilities. Such limitations will occur even more frequently in envisaged future applications over very large (planetary) distances.

REPORT 986

CLASSIFICATION OF DEEP SPACE FOR PURPOSES OF SPACECRAFT UTILIZATION

(Question 14/2)

(1986)

1. Introduction

Some of the bands that are allocated to the space research service are restricted to deep-space telecommunications. The band in which a research spacecraft may operate is thus dependent upon the orbital path of the spacecraft and upon the definition of deep space. To ensure the most effective use of all space research bands, it is important that the definition of deep space results in frequency assignments that minimize potential interference between space research missions. Orbit and interference considerations affect the selection of a useful definition of deep space. This Report discusses these considerations and proposes a new definition of deep space.

Deep space has been defined in Report 204 (Geneva, 1982), Recommendation 573 and in No. 169 of the Radio Regulations as:

"Space at distances from the Earth approximately equal to, or greater than, the distance between the Earth and the Moon."

Near-Earth has been defined in Report 548 as:

"Space at altitudes above the major portion of the atmosphere of the Earth, but significantly less than the distance of the Moon."

2. Orbit considerations

For the purpose of spacecraft utilization, space-research missions have hitherto been adequately classified by the existing definitions of near-Earth and deep space. There are, however, two new types of mission that are not as successfully classified. One type has a highly elliptic orbit around the Earth; the other new type of mission has an orbit around either of two unique points beyond lunar distance.

An example of the highly elliptic orbit is a mission to explore the geomagnetic tail. As described in Annex I, the minimum perigee at 1.3×10^4 km would be near Earth, below the altitude of the geostationary-satellite orbit. The maximum apogee would be at 1.6×10^6 km, well beyond the lunar distance which is currently defined as the boundary of deep space.

An example of the second new type of mission is a spacecraft in a halo orbit around the Sun-Earth L_1 Lagrangian point, as also described in Annex I. L_1 is located 1.5×10^6 km from Earth, and has the characteristic of being a point about which a spacecraft orbit can be maintained. A spacecraft orbiting L_1 could be used to study the flow of plasmas from the Sun to the Earth.

Spacecraft in the highly elliptic orbits would repeatedly enter and leave deep space, as currently defined. Using the same definition, the L_1 halo orbit mission would have to be classified as a deep-space mission.

3. Interference considerations

The possibility of band sharing between systems is affected by the degree to which they are homogeneous. The probability of interference is increased if, at a particular earth station, the strength of a wanted signal is much less than the strength of other signals in the band. The two new classes of missions described above, combined with the defined boundary of deep space at lunar distance, can result in band sharing difficulty. Table I illustrates the problem. The strength of a down-link signal from the Geomagnetic Tail Laboratory (GTL) in a highly elliptic orbit would be 55 to 31 dB stronger than a signal from a Voyager-class spacecraft at Saturn. The signal from the Interplanetary Physics Laboratory (IPL) in halo orbit around the L_1 Sun-Earth Lagrangian point would be 31 dB stronger. This large difference in signal strength suggests that deep-space missions should not have assigned frequencies in the same band as missions like GTL and IPL. The definition of deep space should be changed in order to allow missions with characteristics similar to IPL and GTL to have frequency assignments in bands that are not restricted to deep space.

The analysis presented in Table I supports and extends the conclusion of Report 685 that band sharing between deep-space down links and those of other research spacecraft is not practicable. Similarly, the very high e.i.r.p. used for up links to deep space makes band sharing with up links to other research spacecraft not practicable.

TABLE I – *Comparison of signal strength received from research spacecraft in deep space, in L_1 halo orbit, and in highly elliptic earth orbit missions (f = 2.3 GHz)*

Parameter	Spacecraft				
	Voyager at Saturn distance (1.2×10^9 km)	IPL (1) L_1 halo orbit distance (1.5×10^6 km)	GTL (2) perigee distance (9.6×10^4 km)	GTL (2) lunar distance (3.8×10^5 km)	GTL (2) apogee distance (1.5×10^6 km)
Transmitter power (dBW)	+13	+13	+13	+13	+13
Spacecraft antenna gain (dBi)	+33	+6	+6	+6	+6
Basic transmission loss (dB)	−281	−223	−199	−211	−223
Earth-station antenna gain (dBi)	+56	+56	+56	+56	+56
Received signal strength (dBW)	−179	−148	−124	−136	−148

(1) Proposed "Interplanetary Physics Laboratory".

(2) Proposed "Geomagnetic Tail Laboratory".

4. Discussion

The objective of restricting some space research allocations to deep-space telecommunications is to avoid the interference problems that are associated with inhomogeneous systems. The selection of lunar distance as the beginning of deep space no longer satisfies this objective: a greater distance seems appropriate. A natural, easily specified and understood distance would be useful.

A distance that meets these requirements is one that includes all orbits that are closely related to the Earth. Because of gravitational and dynamic relationships between the Earth, Moon and Sun, spacecraft orbits around the Earth cannot extend beyond 2×10^6 km. Figure 1 of Annex I shows the relationship between the current boundary of deep space, a 2×10^6 km boundary, and the halo and elliptic orbits discussed in Annex I.

If a distance of 2×10^6 km was adopted as the beginning of deep space for the purposes of frequency allocation and assignment, the new types of mission that are described above would be excluded from bands intended for deep-space telecommunication links. Rather, they would utilize frequencies in the space research bands that are not restricted to deep space, and this is considered appropriate from the standpoint of mutual interference protection.

5. Conclusion

Considerations of interference potential and the orbit characteristics of space research missions lead to the conclusion that the definition of deep space should be changed to:

"Space at distances from the Earth equal to or greater than 2×10^6 km."

The proposed change in the definition of deep space will lead to the need for band sharing between satellites in low earth orbits and satellites operating beyond the Moon but at less than 2×10^6 km from the Earth. The resulting potential for interference may be avoided by careful frequency selection and coordination.

ANNEX I

SPACECRAFT AND ORBITS FOR THE EXPLORATION OF GEOSPACE

1. Introduction

Satellites engaged in space research have been placed in a variety of orbits. Some have travelled in circular orbits at various altitudes above the Earth. Others have been in earth orbits that have modest ellipticity and apogees of much less than lunar distance. This Annex presents information about research satellites in highly elliptic orbits around the Earth, or in halo orbits about unique points in space. These orbits are particularly useful for certain kinds of scientific mission.

2. Scientific objectives

The Earth travels through space which is filled with a hot, tenuous plasma flowing away from the Sun. This flowing plasma behaves as if it were an electrified wind. When the solar wind strikes the magnetic field of the Earth, a shock wave forms. The shape of the magnetic field is compressed on the day (Sun) side of the Earth, and is blown into a long teardrop shape on the night side. The space that includes this activity and interaction has come to be called geospace.

Measurements made by earlier spacecraft led to the discovery of the solar wind and the Van Allen radiation belts of high-speed electrons that are trapped in the magnetic field of the Earth. These spacecraft passed through small parts of geospace.

To make further measurements, it would be useful to utilize spacecraft in special orbits that allow exploration of the long and narrow shape of geospace.

3. Highly elliptic orbits around the Earth

Figures 1 and 2 show orbits that might be used to explore various parts of geospace. An example of a mission to use these orbits is the proposed Geomagnetic Tail Laboratory (GTL). To accomplish the survey of the geomagnetic tail and its boundaries, the orbit perigee would be varied from 2 to 15 Earth radii (1.3×10^4 to 9.6×10^4 km) and the apogee would be varied between 60 and 250 Earth radii (3.8×10^5 to 1.6×10^6 km).

Because of their shape, these orbits are often referred to as highly elliptic orbits. The maximum apogee of an orbit around the Earth is limited to a distance less than 2×10^6 km.

GTL will use occasional gravitational pull from the Moon to keep most of its orbit in the long comet-like magnetospheric tail. By properly controlling the timing and distance of lunar passages, it will be possible to vary the GTL distance down the tail, from near the orbital path of the Moon to points as far as 1.6×10^6 km downstream.

Some characteristics of the proposed GTL are given in Table I.

4. Halo orbits

Most satellite orbits in the solar system are around a body, e.g. the Earth or another planet, a moon, or the Sun itself. It is also possible to establish an orbit around certain special points in interplanetary space. Figure 3 shows five special points that are associated with the Sun, Earth and Moon system. The points are called Lagrangian, after the French astronomer and mathematician, and orbits around these points are often called halo orbits. (There are Lagrangian points associated with the Earth and Moon. These points are not more than 500×10^3 km from the Earth, and do not affect the proposed definition of deep space.)

In connection with the study of geospace, it is proposed to place an Interplanetary Physics Laboratory (IPL) in orbit around the L_1 Lagrangian point. The orbit would be in a plane perpendicular to the ecliptic plane and have a diameter of approximately 1.8×10^5 km. Viewed from Earth at the equator, the halo orbit would describe a circle around the Sun. The spacecraft would be in a position to measure the solar wind as it approached the Earth.

Some characteristics of the proposed IPL are given in Table I.

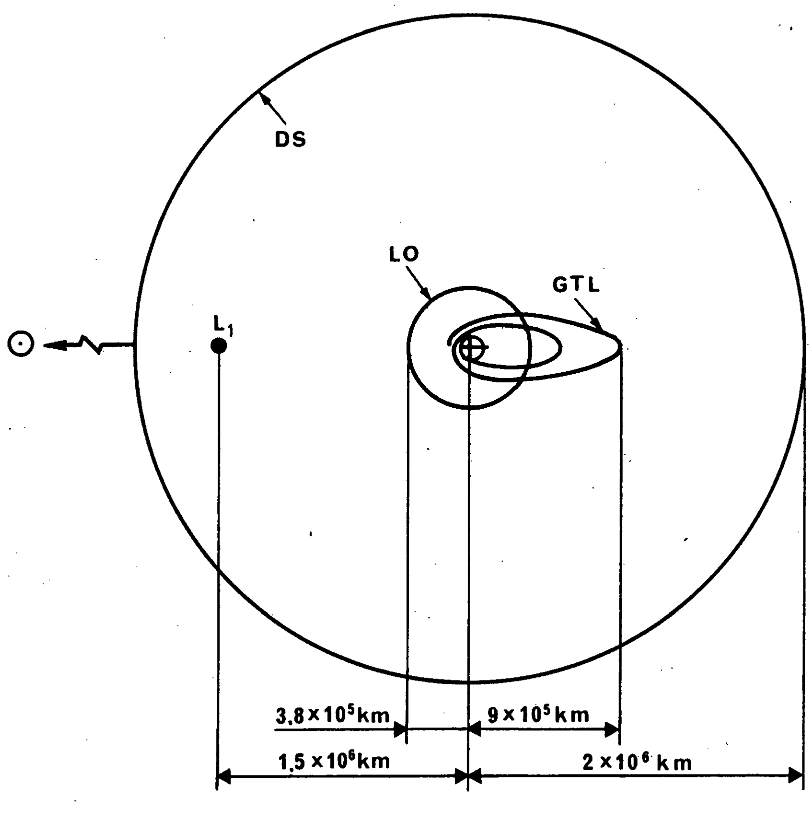

FIGURE 1 – *The relationship between the L_1 Lagrangian point, a highly elliptic orbit around the Earth, and the defined boundary of deep space*

LO: existing defined boundary of deep space (lunar-orbit)
DS: proposed boundary of deep space
⊙: Sun
⊕: Earth (shown larger than scale)
L_1 : L_1 Sun-Earth Lagrangian point
GTL: highly elliptic orbit of proposed Geomagnetic Tail Laboratory

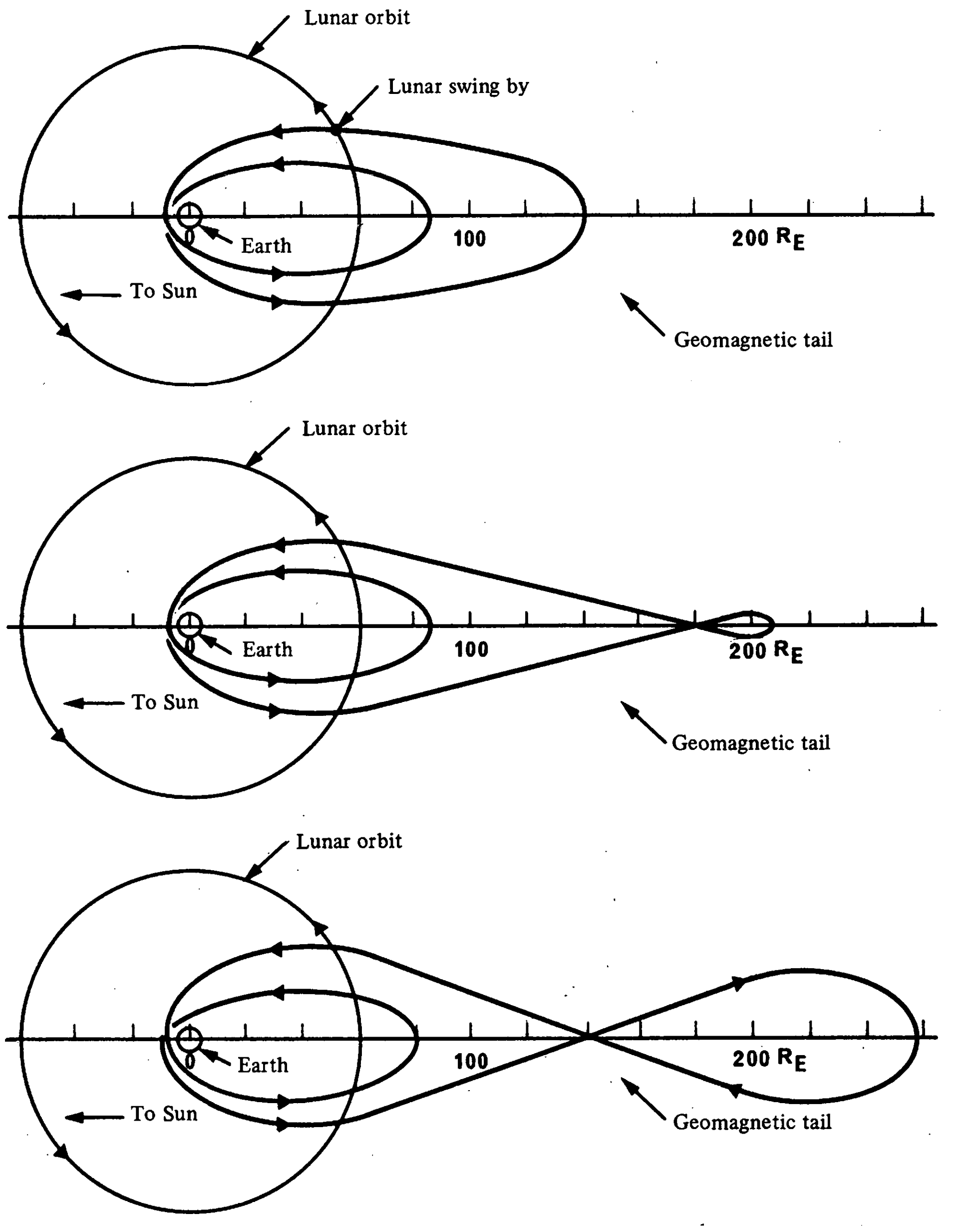

FIGURE 2 – *Examples of orbits for exploration of the geomagnetic tail*

R_E: Earth radius

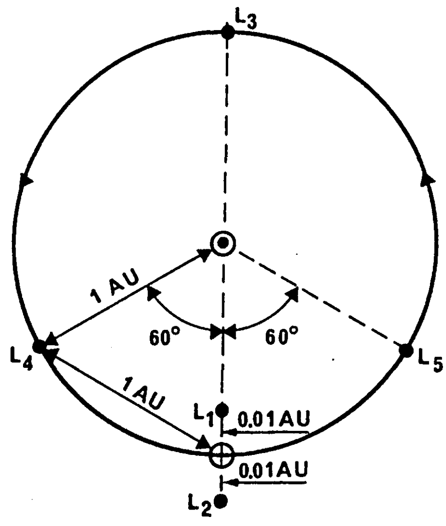

FIGURE 3 – *Sun-Earth Lagrangian points*

⊙ :	Sun
⊕ :	Earth
1 AU:	1 astronomical unit = 1.5×10^8 km
L_1 -L_5:	Sun-Earth Lagrangian points

RECOMMENDATION 610*

CLASSIFICATION OF SPACE DISTANCES FOR SPACECRAFT UTILIZATION

(Question 14/2)

(1986)

The CCIR,

CONSIDERING

(a) that the current definition of deep space includes the region in the neighbourhood of the Moon;

(b) that Report 986 indicates that difficulties can arise if spacecraft in the neighbourhood of the Moon, in highly elliptic earth orbits, or in halo orbits around the L_1 ot L_2 Sun-Earth Lagrangian points, share frequency bands with spacecraft engaged on missions to much greater distances, e.g. to the planets;

(c) that the maximum distance from Earth to spacecraft in L_1 or L_2 halo orbits or in highly elliptic earth orbits, is less than 2×10^6 km;

(d) that spacecraft in these orbits or in the neighbourhood of the Moon can more readily share frequency bands with spacecraft on missions nearer the Earth;

(e) that some earth satellites in highly elliptic orbits repeatedly enter and exit deep space as currently defined;

(f) that there is a potential for interference as a result of band sharing between satellites in low earth orbits and satellites operating beyond the Moon but at distances less than 2×10^6 km from the Earth,

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* This Recommendation should be brought to the attention of Study Group 4 and the CMV.

UNANIMOUSLY RECOMMENDS

1. that, where possible under the current Radio Regulations, the use of frequencies specifically allocated for deep-space missions be avoided for spacecraft which remain within 2×10^6 km of the Earth;

2. that the next competent Administrative Radio Conference consider the re-definition of deep space, taking into account frequency allocation and usage by the various space services.

SECTION 2F: EARTH EXPLORATION SATELLITES

Recommendations and Reports

RECOMMENDATION 514

TELECOMMUNICATION LINKS FOR EARTH EXPLORATION SATELLITES

Frequencies, bandwidths and criteria for protection from interference

(Question 12/2)

(1978)

The CCIR,

CONSIDERING

(a) that suitable operating frequencies, required radio frequency bandwidths, and limiting interference criteria for Earth exploration satellite telecommunication links are determined by the technical considerations set forth in Reports 540 and 692;

(b) that two-way communication is required for Earth exploration satellite missions;

(c) that precision tracking is required for many Earth exploration satellite missions;

(d) that bandwidths up to 100 MHz are required by currently planned Earth exploration satellites for transmission of wideband data both direct to earth stations as well as via data relay satellites;

(e) that future bandwidth requirements may be as high as 800 MHz for data readout from a single spaceborne sensor;

(f) that bandwidths of the order of 50 MHz are required for transmission of wideband data to low cost earth stations;

(g) that transmission of wideband data to low cost earth stations results in high power flux densities;

(h) that for many Earth exploration missions the typical noise temperature of earth station receivers at frequencies above 1 GHz will be of the order of 100 K, equivalent to -148 dB(W/MHz) and that for reception at frequencies less than 1 GHz cosmic noise increases the system noise temperature approximately as the inverse of the square of the frequency;

(j) that typical operating noise temperatures for receivers in Earth exploration spacecraft are approximately 600 K (-171 dB(W/kHz)), but that measures can be taken to protect the spacecraft receiving system against interference approximately 10 dB greater than this noise level;

(k) that for some frequency sharing situations between Earth exploration satellites and certain representative terrestrial services, separations of several hundreds of kilometers between the Earth terminals may be required and that, in many parts of the world, separations of this magnitude are not readily attainable;

(l) that frequency sharing among Earth exploration satellites is desirable and feasible;

(m) that difficulties can be expected when frequencies are shared between Earth exploration satellites and stations in other services, due to the technical problems of furnishing the required protection against interference from terrestrial services,

UNANIMOUSLY RECOMMENDS

1. that frequencies for Earth exploration satellite telecommunication links be located in the frequency band between 100 MHz and 30 GHz;

2. that the band between 100 MHz and 1 GHz is generally more suitable for narrow band telemetering, tracking and telecommand;

3. that the band between 1 GHz and 20 GHz is generally more suitable for wideband telemetering, precision tracking and telecommand utilizing direction transmission to and from earth stations;

4. that the band between 1 GHz and 30 GHz is generally more suitable for wideband telemetering, precision tracking and telecommand via data relay satellites;

5. that the special needs for high power flux-densities for wideband data transmissions to low cost earth stations should be considered in selection of frequencies for Earth exploration satellites;

6. that spectrum bandwidth of the order of 50 MHz per link (due account being taken of the dependence of the radio-frequency bandwidths on the type of modulation used) is technically suitable for the transmission of wideband information to low cost earth stations;

7. that spectrum bandwidth of the order of 200 to 800 MHz per link is technically suitable for transmission of wideband information direct to major data acquisition facilities and to data relay satellites;

8. that note be taken of the difficulties to be expected in frequency sharing between Earth exploration satellites telecommunication links and passive microwave sensors operating on the same spacecraft, for example, in frequency bands such as that around the water vapour line at 22.235 GHz;

9. that frequency sharing be accomplished to the maximum extent feasible among earth exploration satellites;

10. that the protection criteria for Earth receiving sites be established as follows: for frequencies between 1 and 10 GHz, the power spectral density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands shall not exceed -154 dB(W/MHz) at the receiver input for more than 1% of the time; for frequencies less than 1 GHz, the permissible interference may increase at the rate of 20 dB per decreasing frequency decade;

11. that the protection criteria for near-Earth spacecraft receivers be established as follows: for frequencies between 300 MHz and 10 GHz, the power spectral density of noise-like interference or the total power of CW-type interference in any single band or in all sets of bands 1 kHz wide shall not exceed -161 dB(W/kHz) at the receiver input for more than 0.1% of the time; for frequencies less than 300 MHz, the permissible interference may increase at the rate of 20 dB per decreasing frequency decade;

12. that note be taken of the difficulties to be expected in frequency sharing between Earth exploration satellites and stations in other services.

REPORT 535-3

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR THE EARTH EXPLORATION-SATELLITE SERVICE

(Study Programme 12A/2)

(1974–1978–1982–1986)

1. Introduction

The World Administrative Radio Conference (Geneva, 1979) defined the Earth exploration-satellite service as follows: A radiocommunication service between earth stations and one or more space stations, which may include links between space stations, in which:

- information relating to the characteristics of the Earth and its natural phenomena is obtained from active sensors or passive sensors on earth satellites;
- similar information is collected from air-borne or earth-based platforms;
- such information may be distributed to earth stations within the system concerned;
- platform interrogation may be included.

This service may also include feeder links necessary for its operation.

This Report discusses some of the technical and operational parameters of earth resources and earth observation systems which will operate within the earth exploration satellite service; it is based upon the characteristics of systems in the United States of America, Europe, Japan and Canada.

2. Earth exploration satellites

Earth exploration information can currently be categorized according to the following headings:

- agriculture and forestry,
- hydrology and water resources,
- geology and mineral resources,
- geodesy and geodynamics,
- geography and cartography,
- oceanography,
- environmental quality.

Although all of these represent well established disciplines, it is generally recognized that their full potential has not yet been reached. One of the reasons for this has been the lack of technology enabling scientists to acquire data from sufficiently broad regions of the Earth. As satellites offer this capability, they will play an important role in the future. The main advantages offered by satellites are the synoptic view and repetitive coverage of the Earth's surface. Other advantages include the acquisition of real-time or near real-time data, the use of uniform equipment and methods of calibration and measurements, and the possible reduction in costs of data gathering.

It should be noted that the basic objective of earth exploration satellite systems is the extraction of information for improved decision making in resource and environmental management and not data collection as such. To accomplish this, spacecraft, aircraft and ground systems must play complementary roles. Other important features of an earth exploration system are automated information extraction, the development and utilization of models of the environment and its resources, models with built-in decision capability which can make effective use of data collected by satellite and aircraft.

The application of satellite data collection to earth exploration disciplines is still in its early stages; however, significant strides have been made with the information gathered by Landsat-1 and 2 (previously known as the Earth Resource Technology Satellite) [NASA, 1973] and Skylab. Results obtained from Landsat-1 are described in the references. In the years to come, many different types of system will come into use [University of Michigan, 1971a and b] and the characteristics of these systems may differ significantly from one another.

The technical characteristics of the systems discussed in this Report are only to be considered representative of earth exploration satellites now existing or envisaged in the United States of America, Europe, Japan and Canada.

The application of satellite techniques to geodesy and geodynamics is described in Report 988.

3. Present and near future Earth exploration systems

3.1 *Earth exploration systems*

Earth exploration-satellite systems developed and being considered by the United States of America are discussed in Annexes I and II to this Report. The low-orbit systems comprise the two experimental satellites Landsat-1 and Landsat-2, launched respectively in 1972 and 1975, and Landsat-3 launched in 1977. The operational versions of these Earth resources satellites began with the launches of Landsat-D in 1982 and Landsat-D′ in 1984.

The SPOT Earth observation satellite was launched by France in February, 1986. In Japan, the Marine Observation Satellite-1 (MOS-1) is under design with target date for its launch in 1987. The European Space Agency is presently designing its remote sensing satellite ERS-1 which will be essentially devoted to ocean and coastal zone observation using active and passive sensors; the target launch date is mid-1989. Canada is planning to place an Earth exploration satellite (RADARSAT) in orbit in 1990.

Most of these future satellites are designed to supply local direct and playback read-out of sensor data and may also be capable of forwarding information to earth stations via geostationary data relay satellites (see Report 982).

SPOT, MOS-1, ERS-1 and RADARSAT are described more fully in Annexes III, IV, V and VI.

3.2 *Spectrum considerations for Earth exploration-satellite systems*

Earth exploration-satellite systems comprise passive and active sensors sometimes accommodated on board a common space platform. Both use large bandwidths which may occupy several hundreds of megahertz in the case of spaceborne altimeters.

Earth exploration satellites are also characterized by the very high data rates generated by many of their sensors. Sensors are currently being developed which will have data rates of the order of 120 Mbit/s. These and other sensors are listed in Table I. Projections by Earth resources scientists indicate that the need for increased swath width may ultimately result in sensors which produce data rates up to five times that of the present thematic mapper. Such an increase would result in data rates up to 600 Mbit/s from a single sensor.

TABLE I – *Typical sensors and parameters for Earth exploration satellites*

Instrument	Swath width (km)	Resolution	Data rate (bit/s)
Television	185	30 m	15×10^6
Multi-spectral scanners	185	83 m	15×10^6
High resolution pointable imager	48	10 m	1.2×10^8
Visible and infra-red radiometers	2870	2 km	3.3×10^5
Radar scatterometer	1000	50 km	4×10^3
Microwave radiometer	1350	20-60 km	5×10^3
Synthetic aperture radar	100	25 m	50×10^6
Radar altimeter	2	10 cm (1)	8.2×10^3

(1) Vertical resolution.

In addition, the need to acquire sensor information on Earth by low-cost user data acquisition facilities involves concepts requiring high power flux-densities.

3.2.1 *Passive sensors*

Passive sensors obtain data on surface or atmospheric phenomena by reception of either emitted or reflected energy. Initially, passive sensing was accomplished at visible and infra-red wavelengths. More recent research and experiments have indicated that passive sensing is effective in the microwave region. One significant advantage of microwave sensors is that the longer wavelengths are much less affected by clouds and precipitation, and can be used to determine brightness temperatures to within 1° in overcast conditions.

Passive earth exploration sensors may utilize bands allocated for radioastronomy and/or for space research (passive). However, it has been found that for certain functions the optimum frequency for a passive sensor does not coincide with allocations for these services. Therefore, studies have been undertaken on the feasibility of sharing frequency bands between passive sensors and services other than radioastronomy and space research (passive). Frequency of operation and bandwidth requirements of passive sensors currently under development are described in Report 693.

3.2.2 *Active sensors*

Active microwave sensors have two features not found in passive microwave sensors. These are:

- topographic features of land and sea surface can be determined, and
- greater spatial resolutions can be obtained by utilizing a synthetic aperture radar.

As examples of the first feature, petroleum exploration and mineral deposit mapping are two applications for which the capability of active microwave sensors to penetrate surface vegetation could be extremely valuable.

As for the second feature, the resolution expected from the best passive microwave imaging radiometer is of the order of 1 km, while the synthetic aperture radar carried on Seasat had a resolution capability of 25 m.

The capabilities of active microwave sensors have been demonstrated at frequencies ranging from 1.4 GHz to above 30 GHz.

Report 695 shows that frequency bands allocated to the radiolocation service may be shared with active microwave sensors without harmful interference to either the radiolocation service or to the active sensor. This result is reflected in Recommendation 516. Design frequencies and bandwidths of active sensors currently under development and a set of preferred frequencies are contained in Report 693.

3.2.1 *Power flux-densities for data communications*

Power flux-density limits which are at present in effect may restrict the applications planned for earth exploration satellites. Specifically:

- small, low cost data acquisition facilities are an integral part of the designs of several earth exploration satellite systems. These terminals will be used in order to provide real-time data delivery to the user community. The primary design constraint for these terminals is economic. Costs must be held to a minimum in order to make the facility available to a maximum number of users. Accordingly small antennas must be used for those terminals with a consequent requirement for high power flux-density;
- for certain geometries, a link from an Earth exploration satellite to a tracking and data relay satellite may also require power flux-densities which exceed the currently prescribed limits.

As low orbit satellites provide an inherent method for time sharing, and as studies show that sharing may be feasible between services even with higher power flux-densities, it may be desirable to increase the power flux-densities permitted in the bands to be used by Earth exploration satellites.

3.2.4 *Techniques for data communications*

3.2.4.1 *Transmission modes and data rates*

The data will be transmitted from many of the planned satellites to the Earth via three modes:

- direct real-time and playback read-out to major data acquisition facilities;
- direct real-time and playback read-out to local users having lesser data acquisition facilities; and
- through geostationary data relay satellites which will provide a continuous real-time data read-out capability.

The high data rate requirements of existing and planned Earth exploration-satellite programmes (described in the Annexes to this Report) have led to the need to use the 8025 to 8400 MHz frequency band for space-to-Earth links. The LANDSAT programme and future Earth exploration satellites of the United States of America also use the 14.4 to 15.35 GHz frequency band to transmit high rate data through the tracking and data relay satellite (TDRS).

The earth station configuration, together with the high data rates, the expected number of Earth exploration satellites and the characteristics of the atmosphere, should be considered when selecting appropriate regions of the spectrum for the spacecraft-to-Earth data link. It should be noted that actual transmission rate requirements will depend upon the degree of development in the techniques of on-board information extraction.

3.2.4.2 *Bandwidth compression*

In a data acquisition link for an Earth exploration satellite, the principal requirement for a wide frequency bandwidth is the transmission of two- and three-dimensional observation image data. A number of studies have been made on bandwidth compression techniques with regard to image transmission. Two approaches are possible to reduce the bandwidth required for transmission of earth resource data:

– data compression;
– new modulation techniques.

Application of these techniques can assist in accommodating the very high data rates expected from future Earth exploration sensors.

a) *Data compression*

Data compression (or source encoding) may play a significant future role in each step of the data acquisition and dissemination chain. The data rate required for transmission to the ground can be reduced by using statistical properties of the image data.

The practicability of applying data compression techniques to earth resource data will depend on a number of factors, including:

– mean squared errors between original and compressed/reconstructed scenes;
– effect on classification accuracy;
– hardware implementation requirements;
– computational requirements;
– subjective image quality.

For geostationary Earth exploration satellites, the transmission rate of image data could be reduced by using the technique of slow scanning or inter-frame coding which is used in data compression of colour television signal transmission [Iijima *et al.*, 1975]. However, a very large spacecraft memory would be required.

b) *Modulation techniques*

Bandwidth compression can be obtained by the appropriate choice of a modulation system for transmitting the signal. For example, the use of a four-phase PSK modulation system, as in the Landsat-D thematic mapper and SPOT high-resolution visible data, reduces the required bandwidth by a factor of about two in comparison with two-phase modulation systems [Chakraborty, 1975].

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ANNEX I

LANDSAT PROGRAMME

1. Landsat-1, Landsat-2 and Landsat-3

The United States LANDSAT-1, LANDSAT-2, and LANDSAT-3 satellite programme (formerly known as the Earth Resource Technology Satellite) designated as a research and development tool to demonstrate that remote sensing from space is a feasible and practical approach to efficient management of the resources of the Earth. The knowledge gained from the application of data acquired by the three satellites has pointed the way towards development of fully operational and more effective systems for earth resources management. Landsat-1 (launched in 1972), Landsat-2 (launched in 1975), and Landsat-3 (launched in 1977) are no longer operating.

2. LANDSAT follow-on programme

The United States LANDSAT follow-on programme (formerly known as the Earth Observatory Satellite) is intended to continue the research initiated by the LANDSAT-1, LANDSAT-2, and LANDSAT-3 series. Landsat-D and Landsat-D′ were launched in 1982 and 1984 respectively. The objectives of the programme are, firstly, to define advanced remote sensing instrumentation, Earth observation systems and missions required for:

- surveying and monitoring of Earth's resources;
- identification and monitoring of surface and atmospheric pollutants;
- understanding the physical behaviour of the oceans, water/atmosphere interaction and coastal processes;

and secondly, to support requirements of user organizations by providing data on these topics.

2.1 *Initial mission payloads*

The initial mission in the LANDSAT follow-on programme has application to the disciplines of earth resources survey and pollution measurement. Sensors include a six-channel thematic mapper (TM) scanning a 185 km swath with 30 m resolution, and a five-channel multi-spectral scanner. Coverage of the Earth survey function is real-time, direct data transmission only, with no on-board recording capability.

2.2 *Orbit considerations and attitude control*

Systematic, repetitive Earth coverage is required to maximize the utility of the multi-spectral images collected by the different sensors. The nominal LANDSAT orbit is circular, Sun-synchronous, and near-polar at an altitude of 705 km. The orbital period is 99 min, resulting in an entire Earth scan every 16 days.

During normal operation, the attitude control sub-system (ACS) is capable of pointing the observatory continuously to the Earth's centroid to an accuracy of better than 0.01°. Attitude perturbation is less than 2 s and the rate of attitude drift is less than 2×10^{-6} degrees/s.

2.3 *High-data-rate communications*

Landsat follow-on satellites contain the thematic mapper (TM) and the multi-spectral scanner (MSS) sensors and produce a composite data rate of approximately 84 Mbit/s.

Three wideband data communications links are:

- the primary wideband data link to the ground is via the TDRS. The composite data at 84 Mbit/s are transmitted to the TDRS on a frequency of 15.0034 GHz;
- the 84 Mbit/s TM data are transmitted directly to Earth at a frequency of 8215.5 MHz. Quadriphase modulation is utilized with a resultant bandwidth of approximately 100 MHz. A wide-angle spacecraft antenna designed to produce maximum gain in the direction of maximum slant range is used to maximize data acquisition by participating earth stations;
- MSS data are transmitted directly to Earth at a rate of 15 Mbit/s. This sub-system operates in band 9 and is identical to the wideband telemetering sub-system utilized on Landsat-1, Landsat-2 and Landsat-3. This data link is included in the LANDSAT follow-on programme in order to provide continuity of data for existing earth stations that are currently acquiring MSS data from Landsat.

2.4 *Communications and data handling (CDH) sub-system*

The CDH sub-system provides means for ground and on-board control of all spacecraft and instrument functions and for retrieval of low-rate telemetry data. This sub-system contains communication equipment composed of the RF transmitters and receivers, and data handling equipment composed of a command group, a telemetry group, and an on-board computer.

For more detailed information, see Annexes I and II to Report 535 (Geneva, 1982).

ANNEX II

SEASAT PROGRAMME

The primary objective of the SEASAT programme was to determine the applicability of satellite-borne remote sensing techniques to oceanographic problems. The Seasat spacecraft was launched in 1978 into a near-polar orbit. It circled the Earth 14 times daily collecting data from 95% of the Earth's oceans every 36 h. Although planned for a year's flight, a catastrophic failure occurred in the satellite power sub-system which resulted in communications with the satellite being terminated after three months of its operation. However, a thorough evaluation of all the data acquired during the mission has met virtually all the programme objectives and, in particular, the concept of microwave measurements of oceanographic features has been demonstrated.

The Seasat spacecraft was the first major step in developing and demonstrating a global ocean dynamics monitoring system using relevant measurement techniques from a space platform. It carried an experimental instrumentation payload intended to validate concepts for monitoring and measuring ocean features, in particular for predicting general ocean circulation, for synoptic monitoring and the predicting of transient surface phenomena. The objectives also included measurements of the geoid, earthquake damage monitoring, charting ice fields, and measuring precise sea-surface topography as well as the global monitoring of wave height, surface wind speed and direction, ocean current patterns and ocean surface temperature.

The satellite instrument complement included three active sensors: a radar altimeter, a wind field scatterometer and a synthetic aperture radar, all of which normally operated full-time over the ocean and were switched off over land. A scanning radiometer operated in the visible and infra-red regions of the spectrum.

The spacecraft was placed into a nearly circular orbit at an altitude of approximately 800 km. The orbit was inclined 108° to the equator with a period of 6045 s, resulting in about 14 1/3 revolutions per day. The orbit was not Sun-synchronous and was designed to precess during a day/night cycle in approximately 3.5 to 5.5 months.

The Seasat spacecraft control, tracking and data transmission complement included a receiver and four transmitters. The dual redundant receiver operated in band 9. Two of the transmitters, although used for tracking, were primarily utilized for data transmission. The wideband data transmitter required a 20 MHz bandwidth in band 9 for the data stream from the synthetic aperture radar. The narrow-band data transmitter required a 5 MHz bandwidth in band 9. Real-time or recorded data from the other sensors were transmitted over this link.

Two other transmitters operated in band 8 and band 9 and transmitted stable signals containing no modulation. The signals from these transmitters were used for range-rate tracking measurements. The use of two separate frequencies permits compensation for ionospheric effects.

The radar altimeter operated in band 10 and transmitted peak power of 2.5 kW. The scatterometer operated in band 10, separated by about 1000 MHz from the radar altimeter, with 100 W peak power. The synthetic aperture radar operated in the middle of band 9 with a peak power of 800 W.

The normal mode of operation for the radar altimeter and scatterometer was only over seas. Illumination of any one spot on Earth would occur a maximum of 2.4 s per day and 2 min per day for the altimeter and scatterometer respectively.

The illumination of any one spot on Earth from the synthetic aperture radar occurred a maximum of 2 s per day.

For more detailed information, see Annex III to Report 535 (Geneva, 1982).

ANNEX III

SPOT PROGRAMME

1. Introduction

The SPOT-1 satellite is the first of a generation of Earth observation satellites that France brought into operation in 1986. The main objective of this first satellite is to establish, store and make available a high-resolution, remote-sensing data base for a large part of the world, in order to:

– study soil utilization and the evolution of the environment;
– evaluate renewable natural resources (agriculture-forests);
– contribute to the exploration of mineral resources;
– carry out medium-scale (1/100 000) mapping, revise maps having scales of about 1/50 000, and prepare new types of maps.

Two sensors operating in the visible portion of the spectrum, have been designed to attain these specific objectives:

- a 3-channel multiband sensor,
- a high resolution panchromatic sensor.

Two identical picture-taking instruments are equipped with these two sensors, each instrument being capable of taking multiband and panchromatic pictures independently of the other. These HRV (High Resolution Visible) instruments are mounted on a platform designed not only for the initial mission but also for future missions.

2. Satellite and orbit characteristics

The spacecraft is so designed that the payload constitutes an independent entity, with the result that the platform design can be re-used for future missions. In addition, the general structure of the spacecraft is modular, thus providing a certain flexibility of use.

SPOT-1 has been designed for a circular Sun-synchronous near-polar orbit at a nominal altitude of 822 km and will circle the Earth in 101.3 min, completing an entire Earth scan every 26 days. Moreover, the HRV instruments are equipped with a device enabling them to observe the Earth's surface on either side of the local vertical in a plane perpendicular to the absolute velocity vector of the satellite. The repetition of observations over a selected area can thus be increased considerably. For example, the lateral boresight device makes it possible to observe the same equatorial Earth zone 8 times in 26 days.

3. Communications and data handling system

A system of communications and data handling provides for all the flow of information between the spacecraft and the earth stations. It comprises three separate sub-systems:

- localization, telecommand and telemetering: a platform sub-system;
- wideband telemetering: a payload sub-system;
- wideband video tape recorders: another payload sub-system.

3.1 *Telemetering, telecommand and tracking sub-system*

This sub-system collects telemetering maintenance data from the spacecraft and transmits them to the earth stations. It retransmits tracking data and receives orders from the earth stations which it executes on board the spacecraft.

The telemetering maintenance data are PCM signals, NRZ-M coded, with biphase modulation of the carrier. The data are transmitted in the band 2200-2290 MHz at 2048 bit/s.

The telecommand orders are PCM signals, coded in NRZ-L or M, also with biphase modulation of a carrier. They are transmitted in the band 2025-2110 MHz at 2 kbit/s.

Tracking is effected:

- by two-way range measurements, obtained by measuring phase differences on sinusoidal modulations, allowing for sequential sense finding;
- or by range-rate measurement as between the transmitted frequency and the received frequency after an earth station-spacecraft round trip;
- or by a combination of both types of measurement in accordance with orbit recovery requirements.

3.2 *Wideband telemetering*

The wideband telemetering sub-system receives and processes data supplied by the two HRV instruments or by the two wideband video tape recorders. This sub-system consists of a transmitter with a power of 20 W operating in the band 8025-8400 MHz. It allows for the simultaneous transmission of data coming from the HRV instruments, either directly or via the recorder in the replay mode. When one of the two instruments is not operating, the missing data are replaced by a pseudo-random code without any particular significance.

Each information channel associated with an HRV instrument consists of a PCM signal, NRZ-L coded, and transformed by Gray differential coding. The bit rate per channel is 25 Mbit/s. The two channels are multiplexed, so that the data transmission rate is 50 Mbit/s. After multiplexing, the data are either recorded or transmitted to earth. The data are transmitted to earth by quadriphase modulation of a carrier.

The transmitting antenna diagram is shaped so as to compensate for the dynamic range of the signal between 5° and 90° elevation as far as possible.

3.3 *Wideband video tape recording*

Two wideband video tape instruments record and reproduce the data coming from the two sensors. When working, one of the recorders is always in the replay mode, while the other is in the recording mode. The data stream from the two instruments is therefore always recorded or retransmitted by one and the same recorder. The maximum recording duration is 22 min per recorder. The recording and replay speeds are the same (50 Mbit/s).

ANNEX IV

MARINE OBSERVATION SATELLITE (MOS-1)

1. Introduction

Japan's first Earth observation satellite MOS-1 is an experimental satellite to collect information on earth surface (colour and temperature of sea surface, land use, etc.) and to establish the fundamental technologies.

The conceptional design and the preliminary design of MOS-1 were completed in 1979 and 1981 respectively. The satellite is now under development with target date of launch in 1987 and a design lifetime of two years.

1.1 *Mission objectives*

The mission objectives of the MOS-1 programme are as follows:

- establishment of fundamental technologies which are common to both marine and land observation satellites;
- observation of the state of sea surface and atmosphere using visible, infra-red and microwave radiometers and verification of the performance of these sensors.

1.2 *Mission equipment*

1.2.1 *Sensors*

In MOS-1, a Multispectral Electronic Self-Scanning Radiometer (MESSR), the Visible and Thermal-Infra-red Radiometer (VTIR) and a Microwave Scanning Radiometer (MSR) are to be installed.

MESSR is a high resolution, visible and near-infra-red radiometer with push-broom scanning method using charge coupled devices (CCD's).

VTIR is a mechanical scanning type of radiometer to measure sea surface temperature etc.

MSR is a Dicke type radiometer to measure the content of water vapour in the atmosphere.

The anticipated characteristics of these radiometers are summarized in Table II.

1.2.2 *DCS (Data Collection System) transponder*

In order to perform the fundamental experiments concerning collection of the data acquired by many DCP's (Data Collection Platforms) via a satellite and locating the DCP's, MOS-1 is to carry a transponder for the experimental DCS.

2. Launch and orbit

MOS-1 will be launched by the N-II vehicle from Tanegashima Space Center.

The envisaged operational orbit of MOS-1 is Sun-synchronous, with a 17-day recurrent period. The nominal altitude is 909 km. The local time of the descending node will be kept between 1000 h and 1100 h.

3. Communication system

A schematic diagram of the communication system is shown in Fig. 1. The 8 GHz band has been selected for transmission of the data obtained by MESSR and VTIR, and the data rate is about 9 Mbit/s. MSR data are transmitted by the 2 GHz link. Characteristics of the communication system are shown in Table III.

TABLE II – *Characteristics of MOS-1 sensors*

Item \ Sensor	MESSR	VTIR		MSR	
Measurement objective	Sea-surface colour	Sea-surface temperature		Water content of atmosphere	
Wavelength (μm)	0.51 to 0.59 0.61 to 0.69 0.72 to 0.80 0.80 to 1.1	0.5 ≈0.7	6 to 7 10.5 to 11.5 11.5 to 12.5	–	
Frequency (GHz)	–	–	–	23.8	31.4
Geometric resolution (IFOV (¹) in km)	0.05	0.9	2.7	32	23
Radiometric resolution	39 dB (²)	55 dB (²) (Albedo = 80%)	0.5 K	1 K	1 K
Swath (km)	100 (one optical element) × 2	1500		320	
Scanning method	Electrical	Mechanical		Mechanical	

(¹) Instantaneous field of view.

(²) Signal-to-noise ratio excluding quantization noise.

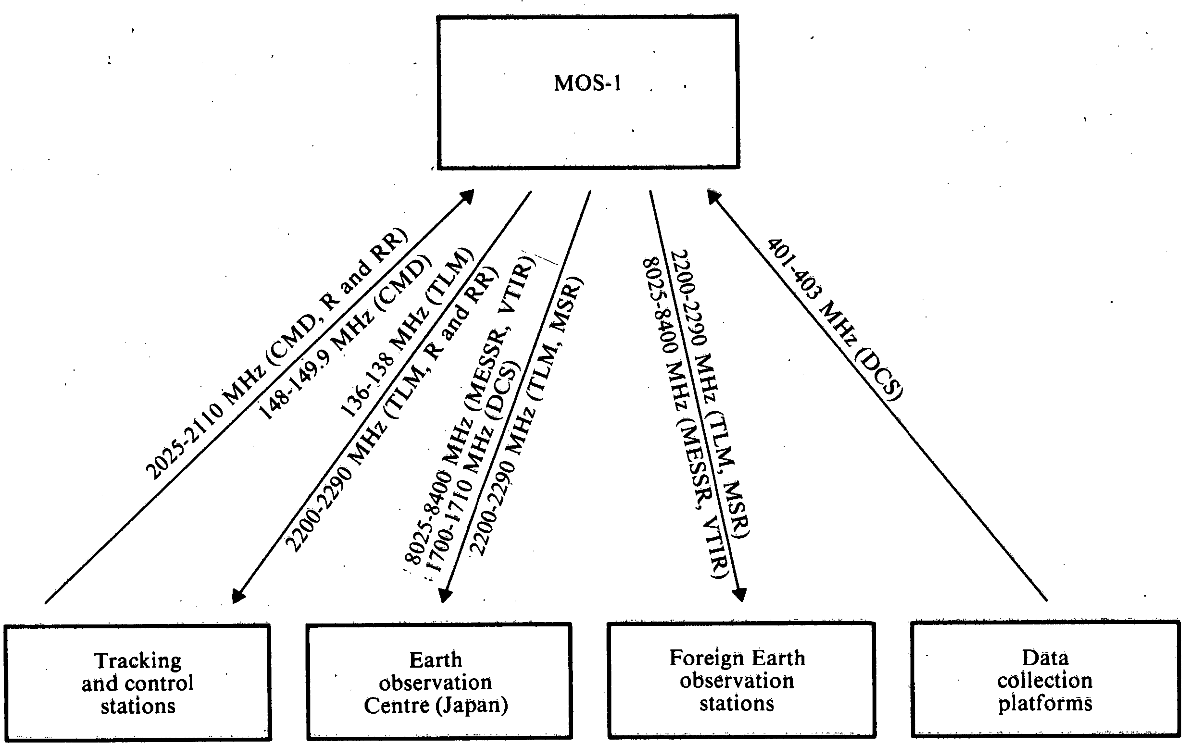

FIGURE 1 – *Communication system of MOS-1*

TABLE III – *Characteristics of communication system of MOS-1*

Link / Function / Item	Space-to-Earth					Earth-to-space		
	MESSR and VTIR	MSR	DCS	R and RR	TLM	DCS	CMD	R and RR
Frequency	8025-8400 MHz	2200-2290 MHz	1700-1710 MHz	2200-2290 MHz	2200-2290 MHz and 136-138 MHz	401-403 MHz	2025-2110 MHz and 148-149.9 MHz	2025-2110 MHz
Modulation	MSK	PCM-PSK-PM	PM	Tone AM-PM	Real time: PM Stored: PSK-PM	PSK or MSK	FSK	Tone AM-PM
Data rate	8.78 Mbit/s	2 kbit/s	100 bit/s	–	Real time: 1024 bit/s Stored: 26 624 bit/s	100 bit/s	128 bit/s	–

ANNEX V

ERS REMOTE SENSING SATELLITE PROGRAMME

1. Introduction

ERS-1 is the first of a family of remote sensing satellites of the European Space Agency (ESA) and is planned to be launched by mid-1989. It is planned to develop derived satellites later for operational applications in meteorology, oceanography and advanced land observations.

ERS-1 is mainly an oceanographic mission, aiming at:

– the development and promotion of applications related to a better understanding of ocean, sea and ice parameters and their status;

– improvement of scientific knowledge about coastal zones and ocean processes.

2. Orbit

ERS-1 will be launched into a Sun-synchronous circular orbit at a nominal altitude of 777 km and with a descending node at 1015 local time. The accuracy of the ground track repetition is expected to be within ± 1 km across track.

During the 3-year mission, the baseline repeat cycle can be altered for experimental purposes, which will cause some orbit parameters to change.

3. ERS-1 payload

Priority in the payload has been given to a comprehensive set of radar instruments designed mainly to observe the oceans. They consist of:

– an active microwave instrument (AMI) combining a synthetic aperture radar (SAR) and a wind scatterometer; and

– a radar altimeter (RA).

In addition, the following instruments are included in the payload:

– an along track scanning radiometer and microwave sounder (ATSR-M);

– a precise range and range rate experiment (PRARE);

– a laser retro-reflector.

3.1 *The active microwave instrument*

3.1.1 *SAR imaging and wave modes*

The synthetic aperture radar of the AMI uses much common equipment for both the imaging and wave modes. Table IV summarizes the relevant SAR characteristics.

TABLE IV – *ERS-1 SAR characteristics*

Frequency (MHz)	5300
Bandwidth (MHz)	15.5
PRF (Hz)	1620-1720
Pulse duration (μs)	37.1
Peak power (kW)	5.8 (at power amplifier output)
Polarization	linear vertical

This Table applies to both the SAR imaging and wave modes. When in the imaging mode, data are collected from nearly 100 km wide swaths for no more than 10 min per orbit. In the wave mode, data are collected from 5 km wide swaths (anywhere within the imaging swath capability) for 5 km along track, every 200 or 300 km.

3.1.2 *Wind scatterometer*

In the wind scatterometer mode, the AMI uses a 3-beam antenna, which is described in Table V.

TABLE V – *ERS-1 wind scatterometer characteristics*

Frequency (MHz)	5300		
Peak power (kW)	5.8 (at power amplifier output)		
Polarization	linear vertical		
Beam	*Forward*	*Centre*	*Backward*
Pulse duration (μs)	130	70	130
Pulse repetition interval (ms)	10.2	8.7	10.2
Orientation (degrees)	45	90	135

Data collection is made over a 500 km swath. It is expected that the wind speed can be determined with 10% accuracy over the range 4 m/s to 24 m/s and wind direction with 20° accuracy. The wind scatterometer and the wave modes are operated alternately.

3.2 *Radar altimeter*

The ERS-1 radar altimeter will have the characteristics described in Table VI below.

TABLE VI – *ERS-1 radar altimeter characteristics*

Frequency (GHz)	13.8
Bandwidth (MHz)	330
Pulse duration (μs)	20
RF peak power (W)	50
Pulse repetition frequency (Hz)	1020
Antenna gain (dBi)	42

The expected accuracy of the altitude measurement is 10 cm over water and 40 cm over ice. The significant wave height measurement is expected to have an accuracy of 10% over the range 1 to 20 m.

3.3 *Along track scanning radiometer and microwave sounder*

The ATSR-M is a purely passive instrument for the following observations:

- sea surface temperature;
- images of land surface temperature; and
- clouds, aerosols, haze and total water vapour content of the atmosphere.

The instrument consists of an infra-red radiometer and a microwave radiometer, the latter operating at 23.8 GHz and 36.5 GHz.

3.4 *Precise range and range rate experiment (PRARE)*

This equipment extends the ERS-1 mission to geodetic and geodynamic applications: PRARE aims at determining the satellite orbit radial component to a precision of the order of 10 cm. Table VII summarizes its RF characteristics.

TABLE VII – *ERS-1 PRARE characteristics*

Up link	
Frequency (MHz)	7225.296
Bandwidth (MHz)	20
System noise figure (dB)	3.9
Down link 8 GHz	
Frequency (MHz)	8489
Bandwidth (MHz)	20
Power transmitted (W)	1
Modulation rate (PSK) (Mbit/s)	10 (PRN)
Maximum antenna gain (dB)	5.7
Down link 2 GHz	
Frequency (MHz)	2248
Bandwidth (MHz)	2
Power transmitted (W)	1
Modulation rate (PSK) (Mbit/s)	1 (PRN)
Maximum antenna gain (dBi)	5.7

The 7/8 GHz band is used for range measurement and the 2 GHz band for ionospheric correction.

Further information on geodetic and geodynamic satellites is contained in Report 988.

4. Communication and data handling system

4.1 *Telemetry tracking and command*

The housekeeping data have a bit rate of 2048 kbit/s and uses PCM-PSK-PM to modulate a 2225 MHz carrier.

The telecommand uses a 2048.85 MHz carrier with PCM-PSK-PM modulation at a 2000 bit/s data rate.

4.2 *Payload data transmission*

The AMI SAR imaging mode data are transmitted in real-time to the ground by means of a 105 Mbit/s 4-PSK link in the 8 GHz band, called link I. This link will operate for only about 10 min per orbit.

All other instrument data are either transmitted in real time or recorded on board, for subsequent play-back using link II. The overall instrument data rate is 800 kbit/s. The real-time data are convolutionally encoded which results in a data rate of 3.2 Mbit/s. In addition, over the prime stations, the on-board recorder is played back at 15 Mbit/s and modulates together with the real-time data the link II carrier.

Table VIII summarizes the transmission characteristics.

TABLE VIII – *ERS-1 8 GHz band transmission*

Link I	
Carrier frequency (MHz)	8140
Modulation	4-PSK differentially encoded
Bit rate (Mbit/s)	105
Radiated power (dBW)	11.9
Maximum antenna gain (dBi)	8.5
Polarization	Right hand circular
Link II	
Carrier frequency (MHz)	8040
Modulation ([1])	a) SPL/2-PSK b) U4-PSK (with unbalance factor 1/4)
Bit rate ([1])	a) 3.2 Mbit/s b) SPL 3.2 Mbit/s and NRZ 15 Mbit/s
Radiated power (dBW)	11.9
Maximum antenna gain (dBi)	8.5
Polarization	Right hand circular

([1]) Either a) or b) are operated, exclusively.

ANNEX VI

RADARSAT

1. Introduction

Canada has embarked on a national programme to develop and operate RADARSAT, a remote sensing satellite system. Radarsat will be a 3-axis stabilized polar orbiting satellite with a payload consisting of a synthetic aperture radar, a scatterometer and an optical instrument. The payload will be mounted on a low-orbit derivative of a platform which was conceived for the geostationary Olympus satellite. The satellite is designed for a 5-year life in orbit following a launch by the NASA Space Shuttle in mid-1991. The operational life is expected to be extended to more than 8 years after in-orbit servicing during the fifth year.

2. Objectives

The mission objectives of Radarsat are to monitor and to predict the location and type of sea ice; to provide scientific information for sea-ice analysis; to aid ship-route planning, off-shore drilling and production, and fishing fleet and oil slick monitoring; to manage agriculture, forestry and hydrology resources; and to update geological maps.

3. Orbit

Radarsat will be placed in a Sun-synchronous, near-polar, circular orbit with a descending node local time of 0944. The period will be 105.21 min at a mean height of 1004 km. The entire Earth scan is repeated every 16 days.

4. Payload

The RADARSAT payload will consist of the following instruments.

4.1 *Synthetic aperture radar (SAR)*

The SAR will provide raw data for high-resolution imagery from a swath width greater than 100 km. This swath will be one of four selectable swaths in a 500 km accessible swath. The fully-calibrated SAR system will generate 500 W mean RF power at 5.3 GHz which will be used to coherently illuminate a swath to the left of the nadir by means of a planar array antenna. The characteristics of the SAR are listed in Table IX. The SAR instrument will be operated up to 20 min in sunlight and 8 min in eclipse during each orbit.

4.2 *Scatterometer (RSCAT)*

The RSCAT instrument will be a modified Navy remote ocean sensing system (N-ROSS) scatterometer. The Radarsat version will generate 35 W mean RF power at 14 GHz which will be used to illuminate 670 km swaths on each side of nadir. The RSCAT characteristics are listed in Table IX. This instrument will be operated over oceans and large inland waters but may be operated continuously, if desired.

TABLE IX – *Radarsat SAR and RSCAT characteristics*

	SAR	RSCAT
Azimuth resolution (m)	7	
Range resolution (m)	25	
Incidence angle range (degrees)	20-45	20-56
Accessible swath (km)	500	
Swath width (km)	140	670
Number of swaths	4	
Operating frequency (GHz)	5.3	13.995
Bandwidth (MHz)	11.3	1
Peak transmitted power	10 kW	110 W
Pulse width	55 μs	5 ms
Pulse repetition rate (p/s)	1160-1360	62
Raw data rate (Mbit/s)	120	
Antenna polarization	vertical	4 vertical, 2 horizontal
Antenna length (m)	14	
Antenna height (m)	1.8	
Antenna gain (dBi)		32
Antenna beamwidth (degrees)		0.5 × 25
Wind speed accuracy		2 m/s or 10%
Wind direction (degrees)		20
Spatial resolution (km)		50
Sampling interval (km)		25

4.3 *Optical imaging sensors*

Radarsat will have two optical sensors on board. The advanced very high resolution radiometer (AVHRR) will have a resolution of 1.1 km in each of six optical and infra-red bands. In addition the modular opto-electronic multi-spectral system will have four optical channels with a swath width of 400 km and a pel size of 30 m.

5. Communications and data handling

The Radarsat communications and data handling systems consist of telemetry, telecommand and tracking, low data rate and high data rate sub-systems.

5.1 *Tracking telemetry and telecommand sub-systems*

This, sub-system collects spacecraft and payload instrument status data and transmits them to earth stations. This sub-system also receives, decodes and distributes telecommand data and retransmits tracking data.

The telemetry data are NRZ coded PCM signals at 2048 bit/s. These signals phase-shift-key sub-carrier oscillators which phase-modulate a down-link carrier in the 2200 to 2290 MHz band.

The telecommand data are NRZ coded PCM signals phase-shift-keying a sub-carrier oscillator which phase modulates an up-link carrier in the 2025 to 2110 MHz band.

A tracking station acquires spacecraft range data by measuring the phase differences of returned sinusoidal tones (maximum frequency of 100 kHz) which phase modulate the up and down links. Range-rate data are acquired by measuring the 2-way Doppler shift of the up and down links using a coherent transponder in the spacecraft.

5.2 *Low data rate sub-system*

The 3.2 kbit/s RSCAT data will be down-linked via a transmitter in the 1.7 GHz band. On-board recording devices will permit acquisition of these data when Radarsat is out of the range of a data acquisition station.

5.3 *High data rate sub-system*

The 120 Mbit/s SAR and the optical imaging data will be down-linked via two transmitters in the 8.025 to 8.400 GHz band, each with a bandwidth of 75 MHz. In addition, on-board tape recorders will permit the acquisition of some of these data when out of range of a data acquisition station.

REPORT 692-2

PREFERRED FREQUENCY BANDS AND POWER FLUX-DENSITY CONSIDERATIONS FOR EARTH EXPLORATION SATELLITES

(Questions 11/2 and 12/2, Study Programme 12A/2)

(1978–1982–1986)

1. Introduction

In recognition of the potential usefulness of Earth exploration satellites, frequency bands have been allocated in the Radio Regulations for telemetering data from Earth exploration satellites in Bands 9 and 10 (2200 to 2290 MHz and 8025 to 8400 MHz) for direct read-out and 25.25 to 27.5 GHz for acquisition of data via data relay.

Applications planned for Earth exploration satellites may be restricted by the power flux-density limits which apply to the frequency bands used by the satellites' radiocommunication systems.

The purpose of this Report is to present the factors which influence the selection of frequencies for transmissions of wideband data from Earth exploration satellites as well as to present the power flux-density levels needed by Earth exploration satellite applications.

This Report does not deal with selection of operating frequencies for satellite housekeeping telemetry. It also does not deal with frequency selection for microwave sensors or with power flux-densities produced by active microwave sensors which are discussed in Report 693.

2. Frequency selection criteria

There are several important criteria which must be satisfied in choosing frequencies for transmission of wideband data from Earth exploration satellites.

- Adequate bandwidth must be available for present and future sensor data requirements.
- Harmful interference must not exist either to or from services sharing common frequency bands.
- Power flux-densities must be permitted which are sufficiently high that Earth exploration satellite applications are not significantly compromised.
- Spacecraft and ground station data acquisition systems must be technically and economically viable.

3. Sensor data rate requirements

Basic to the problem of frequency selection is the need to provide sufficient bandwidth for the data output of the spacecraft sensors. The data rates produced by Earth exploration satellite sensors are extraordinarily high, and hence bandwidth requirements are much greater than for many other space systems.

It is also necessary to ensure that there is no overlap between the frequencies used in the spacecraft communications system and the spectral region covered by the sensors.

Sensors include a thematic mapper which produces data at a rate of 84 Mbit/s. This sensor is used in the LANDSAT programme.

Future sensors under consideration include a High Resolution Pointable Imager (HRPI) which will have a data rate of around 120 Mbit/s.

It will be necessary to multiplex data when a satellite carries two or more sensors. A satellite carrying a thematic mapper and an HRPI will generate a composite data rate of 204 Mbit/s. The bandwidth required for this signal, a guard band, and a 20 Mbit/s signal for transmission to low cost data acquisition facilities is approximately 350 MHz.

Earth resources scientists predict that data rate requirements for optical type sensors may ultimately reach rates five times that of the present thematic mapper. This could result from either increased scan width or resolution. Such an increase would produce data rates up to 600 Mbit/s from a single sensor, requiring bandwidths of the order of 800 MHz.

4. Spacecraft and ground station consideration

4.1 *Major data acquisition facilities*

Among the factors influencing design of Earth exploration satellites are the availability and the costs of data acquisition facilities to operate the satellites. Earth exploration satellite communication links in the United States have been designed for 9 m diameter data acquisition antennas. In addition to the economic advantage of using existing data acquisition antennas, there are technical reasons why 9 m diameter antennas are near optimum for Earth exploration satellites. Communication link requirements can be satisfied using available, convenient components on board the satellite. Above 10 GHz, the surface accuracy and the control system accuracy of the data acquisition antenna, become limiting factors on the design of the communications link. At frequencies near 20 GHz, 9 m approaches the limiting size for an economical antenna constructed using conventional techniques. For these reasons, 9 m will be used as a given parameter for the size of the data acquisition antenna in determining power flux-density requirements for the radiocommunications link from Earth exploration satellite to major data acquisition facility.

With the technology available today, a viable communications link cannot be accommodated above 20 GHz because of the required data rates. At low elevation angles, link losses under moderate rain conditions are about 28 dB greater near the 20 GHz band than in the 8025 to 8400 MHz band. Existing ground station antenna designs provide insufficient gain and control systems accuracy to satisfy the communications requirement with available spacecraft components. On the other hand, technology is available to provide the spacecraft e.i.r.p. required to meet mission requirements in the 8025 to 8400 MHz Earth Earth exploration-satellite allocation. At the present time, the upper limit of technically suitable frequencies for transmission of Earth exploration-satellite data to Earth is approximately 20 GHz.

Another problem would occur if frequencies near sensor operating frequencies were used for data communications. For example, one of the sensors developed by earth resources scientists is a microwave radiometer which utilizes frequencies near the 22.235 GHz water vapour line to measure atmospheric water vapour. Technology does not exist to shield the radiometer from interference from the communications transmitter if it were to operate just above 20 GHz. It would not be possible to operate the radiometer and the data communications system simultaneously.

4.2 *Low cost data acquisition facility*

Small, low-cost data acquisition facilities are under consideration for future Earth exploration-satellite systems. These terminals will be used in order to provide real-time data delivery to the user community. The satellites will transmit selected data to these terminals at reduced data rates. Twenty Mbit/s data rates are contemplated for these communications links.

Since local users will acquire data over limited regions, receiving antenna angles will never be less than 30° above the horizon. Data error ratios are required to be no greater than 10^{-5}.

The primary design constraint for these terminals is economic. Costs must be held to a minimum in order to make the facility available to a maximum number of users.

Cost can be minimized by increasing the satellite e.i.r.p. to reduce the required ground antenna size and quality of the preamplifier. Impact of costs for these components is assumed to be negligible if they comprise less than 10% of the total cost of the low cost data acquisition facility. This criterion can be achieved if the ground antenna is limited in size to a 0.3 m diameter parabola and a preamplifier noise temperature of 200 K is used for the frequency bands being considered.

These two parameters (0.3 m diameter ground antenna, 200 K preamplifier noise temperature) will determine the power flux-density required at the Earth's surface for the communications link from Earth exploration satellites to low cost data acquisition facilities.

4.3 *Tracking and data relay satellite*

A research tracking and data relay satellite (TDRS) designed by the United States of America provides two-way radiocommunications to and from experimental Earth exploration satellites and other research Earth satellites. The system relays these communications and data to one or more fixed earth stations within view of the relay satellites. At the same time, the research satellites which receive communications relay support from the TDRS, may require communication of some of the data directly to and from fixed earth stations not associated with the TDRS.

Operational Earth exploration satellites may require a similar data relay satellite for data acquisition. Preferred frequencies and sharing aspects of an operational relay satellite system in the Earth exploration satellite service are discussed in Report 982.

The design of the TDRS is such, that user satellite data rates up to 300 Mbit/s will be accommodated. Equivalent isotropically radiated power (e.i.r.p.) of 60 dBW will be required from the user for 300 Mbit/s data rates. A 2.5 m parabolic antenna having -10 dBi median backlobe and sidelobe pattern which follows the CCIR equation, $32 - 25 \log \theta$, is representative of the antenna that will be needed on the Earth exploration satellite.

5. Power flux-density (pfd) analysis

Radiocommunication link parameters contained in Table I were used to determine power flux-density levels commensurate with Earth exploration satellite applications. The analysis was carried out for the allocated frequency bands of 8025 to 8400 MHz as well as in the vicinity of 20 GHz.

Values given in Table I are based on 120 Mbit/s quadriphase shift keyed data on the path from the Earth exploration satellite to the major data acquisition facility and 20 Mbit/s bi-phase shift keyed data on the path from Earth exploration satellite to low cost data acquisition facility. These signals were chosen as representative of systems currently being designed in the United States. A change of data rate, however, would not affect the requirements for pfd. The analysis assumed an error ratio requirement of 10^{-5} during moderate rainfalls of 4 mm per hour. Appropriate link design and pfd limits should be considered for regions of the world with higher rainfall rates to maintain satisfactory performance.

Values determined for satellite e.i.r.p. are contained in Table I.

TABLE I – *Radiocommunication link parameters*

Radiocommunication link	Frequency bands			
	8025 to 8400 MHz Major facility	8025 to 8400 MHz Low-cost facility	20 GHz Region Major facility	20 GHz Region Low-cost facility
System temperature (K)	266	292	477	420
System noise (dBm)	−93.6	−100.9	−91.1	−99.4
System margin (dB)	−3.0	−6.0	−3.0	−6.0
Required S/N (dB)	12.0	12.0	12.0	12.0
Required receive signal (dBm)	−78.6	−82.9	−76.1	−81.4
Nominal ground antenna gain (dB)	55.5	26.0	63.1	33.2
Antenna surface tolerance loss (dB)	−0.3	–	−1.8	–
Antenna pointing loss (dB)	−0.5	−0.5	−2.6	−2.6
Receive circuit loss (dB)	−0.5	−1.0	−0.9	−1.7
Free space loss (dB)(1)	−181.0	−174.7	−188.8	−181.9
O_2/H_2O absorption loss (dB)	−0.6	−0.4	−3.2	−0.5
Precipitation loss (4 mm/h) (dB)	−0.8	–	−8.1	−2.1
Cloud loss (dB)	−1.9	−0.3	−8.1	−1.7
Satellite antenna pointing loss (dB)	−3.0	−3.0	−3.0	−3.0
Satellite required e.i.r.p. (dBm)	53.9	71.2	76.9	78.9

(1) Calculation based on a 1000 km orbit. Loss calculated at 5° elevation angle link to major data acquisition facility and at 30° elevation angle for link to low cost data acquisition facility. Elevation angle of low cost acquisition facility angle is restricted to values above 30°.

The calculation for the resultant pfd is performed for the maximum value, ignoring variable increases in propagation losses as well as pointing error of the satellite antenna:

$$\text{pfd}_{max} = 10 \log (4 \text{ kHz}) + \text{e.i.r.p.} - 10 \log BR/2 - 10 \log 4\pi D^2 \qquad (1)$$

for quadriphase modulation, and

$$\text{pfd}_{max} = 10 \log (4 \text{ kHz}) + \text{e.i.r.p.} - 10 \log BR - 10 \log 4\pi D^2 \qquad (2)$$

where:

BR : bit rate
D : distance

for bi-phase modulation. Both equations assume phase-shift keying (PSK) transmission and non-return to zero (NRZ) coding format.

Since the Earth exploration satellite may have a mode of transmission where one wideband sensor is turned off and therefore the data rate is reduced by a factor of 2 while the same power will be radiated within only half the bandwidth, the calculated pfd must be increased by 3 dB for the link to the major data acquisition facility.

The results of the analysis are shown below:

	8025 to 8400 MHz	In the region of 20 GHz
pfd max (major data facility)	– 145.8 dB(W/(m² · 4kHz)) (at 90°)	– 98.9 dB(W/(m² · MHz)) (at 90°)
pfd max (low cost facility)	– 123.8 dB(W/(m² · 4 kHz)) (at 90°)	– 92.1 dB(W/(m² · MHz)) (at 90°)
Present pfd limits *	– 140 dB(W/(m² · 4 kHz)) (25° to 90°)	– 105 dB(W/(m² · MHz)) (25° to 90°)

Due to increased path length attenuation at low elevation angles from low orbit satellites, the pfd limit above 25° determines the allowable satellite e.i.r.p. Present pfd limits as given in the Radio Regulations and Report 358, and discussed in Report 387, are derived from detailed analyses of interference to the fixed service, based essentially on the use by the fixed-satellite service of geostationary satellites. Further detailed examination may be required to verify an extension of their applicability to include non-geostationary satellites.

The maximum pfd generated at the Earth's surface for an Earth exploration satellite transmitting data to a TDRS, occurs when the satellite is at the Earth's horizon with respect to TDRS as shown in Fig. 1. The distance from the satellite to the point on the Earth where maximum pfd occurs is 3080 km for a 705 km orbit as is planned for the LANDSAT programme. The pfd for this worst-case condition would be – 102.6 dB(W/(m² · MHz)). In practice, transmission paths to TDRS closer to the surface of the Earth than 50 km will not be used. The worst pfd which would occur in this case, would be – 124.2 dB(W/(m² · MHz)).

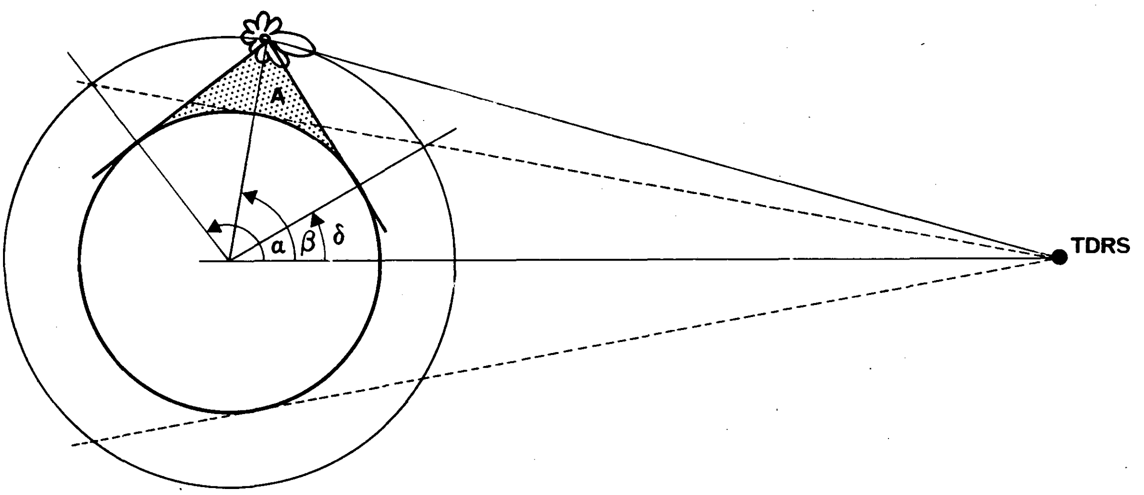

FIGURE 1 – *Earth, user satellite, TDRS geometry*

The results show that the pfd in the 8025 to 8400 MHz band is within the pfd limit for the link to the major data acquisition facility but exceeds the limit by 16.2 dB for the link to the low cost data acquisition facility. In the region of 20 GHz, the pfd limit for the link to a major data acquisition facility would be exceeded by 6.1 dB and on the link to a low cost data acquisition facility by 12.9 dB.

6. Conclusion

The 8025 to 8400 MHz band is well suited for telemetering data from near-future Earth exploration satellites directly to major data acquisition facilities. The 8025 to 8400 MHz band has insufficient bandwidth to accommodate future developments in satellite borne sensors. In addition, the power flux-density limit in the 8025 to 8400 MHz band will severely restrict the use of low cost data acquisition facilities which are needed for real time distribution of satellite data to the user community.

* There is no proposal to increase the present pfd limits. The calculations above merely compare those limits with the pfd that would be required for low-cost facilities.

Increased atmospheric and precipitation losses at frequencies above 20 GHz preclude configuration of a satisfactory radiocommunications down link with current spacecraft and ground data acquisition technology for the high data rates generated by Earth exploration satellites. The power flux-density limit imposed on the band also prevents a satisfactory link. Mutual interference would preclude use of a radiometer operating at the 22.235 GHz water vapour line on a satellite whose data communications system operated just above 20 GHz.

The practical economic upper limit of frequencies useful for telemetering wide-band data from Earth exploration satellites directly to Earth is approximately 20 GHz. Above this frequency, technology is not available at low cost to overcome high atmospheric and precipitation losses. The power flux-density limit at 20 GHz would constrain the design of the link to major data acquisition facilities and would severely restrict the use of low cost data acquisition facilities.

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REPORT 540-1 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN AN EARTH EXPLORATION-SATELLITE (EES) SYSTEM AND FIXED SATELLITE, METEOROLOGICAL SATELLITE AND TERRESTRIAL FIXED AND MOBILE SERVICES

(Study Programme 12A/2)

(1974–1982)

1. Introduction

According to the Radio Regulations, the frequency band 8025 to 8400 MHz is allocated on a shared basis to the Earth exploration-satellite service (space-to-Earth).

However, the allocation in Regions 1 and 3 is made only on a secondary basis, with the exception of a number of countries whose names are included in a footnote and which may have primary status subject to an agreement reached in accordance with the procedure envisaged in Article 14 of the Radio Regulations.

The band is shared in the three Regions with the terrestrial fixed and mobile services and with the fixed-satellite service (Earth-to-space). The sub-band 8175 to 8215 MHz is further shared with the meteorological-satellite service (Earth-to-space).

The technical feasibility of frequency sharing between Earth exploration satellite and terrestrial fixed and mobile services, fixed satellites and meteorological satellites is discussed in this Report. The basic conclusions that can be drawn from the analyses of the sharing possibilities are:

1.1 Sharing between an Earth exploration satellite system and a line-of-sight radio-relay system is feasible provided that the power flux-density produced at the surface of the Earth by the satellite is limited to the Radio Regulation values (see Article 28, Section IV) for a fixed-satellite service sharing with a line-of-sight radio relay; and provided that the earth resources system earth station is coordinated with line-of-sight radio-relay transmitters according to established procedures.

1.2 Frequency sharing between space-to-Earth links of an Earth exploration satellite system using a low orbit and the Earth-to-space links of either a geostationary fixed satellite or a geostationary meteorological satellite is feasible, provided that the power flux-density produced at the geostationary orbit by any Earth exploration satellite does not exceed -174 dB(W/m^2) in any 4 kHz band and that the earth station of the Earth exploration satellite is coordinated with the Meteorological and Fixed Satellite Service earth stations according to established procedures.

* This Report should be brought to the attention of Study Groups 4, 5, and 9.

2. Interference potentiality from EES space stations to line-of-sight radio-relay receivers

For the purposes of evaluating the technical feasibility of this aspect of sharing, the applicable technical characteristics of a planned United States Earth exploration satellite are given in Table I.

TABLE I – *Technical characteristics of an Earth exploration satellite (EES)*

Characteristic	R (km)	Numerical value
P_t, space station (dBW)		+ 16
Max. G_t, space station ([1]) (dB)		+ 6
Max. e.i.r.p. ([1]) (dBW)		+ 22
Spreading loss, $1/4\pi R^2$ (dB) ([5])	5400 ([2]) 3600 ([3])	145.6 142.0
Power flux-density at surface of the Earth (dB(W/m^2))	5400 3600	– 123.6 – 120.0
Spectral power flux-density ([4]) (dB(W/m^2) in 4 kHz)	5400 3600	– 157.6 – 154.0

([1]) Objective of EES antenna design is to provide constant flux density within the field-of-view of the satellite.

([2]) Horizon distance for 1800 km orbit altitude.

([3]) Horizon distance for 900 km orbit altitude.

([4]) Assuming a 100 MHz emission bandwidth and a maximum "peaking factor" of 10 dB above mean spectral distribution level.

([5]) If this expression is used for calculating spreading loss, R is expressed in metres.

The values of power flux-density in 4 kHz given above, allowing 10 dB for non-uniform spectral distribution, still allow margins of 5.6 and 2.0 dB, respectively, without exceeding -152 dB(W/m^2) in 4 kHz at low elevation angles.

Characteristics for the French SPOT satellite are given in Annex I.

3. Interference from EES space station transmitters to fixed service satellite or meteorological satellite receivers

For the purpose of evaluating the technical feasibility of sharing with other space stations, applicable technical characteristics of the projected Earth exploration satellite are given in Table I.

The geometrical relationship between the near-polar (100° retrograde) orbit of the Earth exploration satellite and the geostationary satellite orbit is shown in Fig. 1.

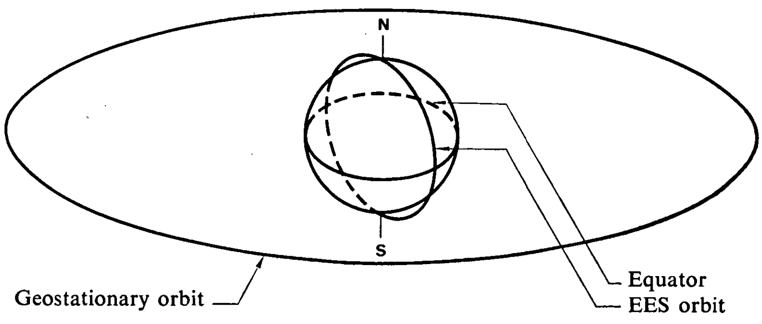

FIGURE 1 – *Geometric relationship between geostationary satellite orbit and circular-inclined orbit of altitude 1800 km, inclination 100°*

Since the Earth exploration satellite will direct its maximum e.i.r.p. at the horizon of its coverage, it follows that this maximum e.i.r.p. will be directed at the corresponding part of the geostationary satellite orbit.

The interference potential of the Earth exploration satellite can be evaluated by comparing its e.i.r.p. with that of earth stations operating with meteorological and communication satellites in this band.

The general case is defined by the equation for the carrier-to-interference ratio of the fixed or meteorological service receiver:

$$C/I = P_{TW} + G_{TW} - (P_{TU} + G_{TU}) + \Delta L_p + 10 \log (B_U/B_W) \qquad \text{dB} \qquad (1)$$

where:

P_{TW}, G_{TW}: transmitter power and antenna gain of wanted earth station,

$(P_{TU} + G_{TU})$: e.i.r.p. of the earth resources satellite in the direction of the interfered-with satellite,

ΔL_p: differential path loss between the desired and undesired signals,

B_U and B_W: emission bandwidths of the unwanted and wanted signals.

As an example, we assume that the minimum earth station e.i.r.p. anticipated for an earth station in the Fixed Satellite Service, $(P_{TW} + G_{TW})$, is +45 dBW in an emission bandwidth of the order of 0.25 MHz(B_W). Thus, the C/I ratio at the fixed service satellite is, to a reasonable approximation:

$$C/I = 45 - (P_{TU} + G_{TU} + \Delta L_p + 10 \log (B_U/0.25)) \qquad B_U \text{ in MHz} \qquad (2)$$

If the maximum undesired e.i.r.p. is +22 dBW,

ΔL_p, the differential path loss between the desired and undesired signals, is $\leqslant$ 3 dB,

B_W, the receiver bandwidth required for the desired signal, is $\approx$ 0.25 MHz,

B_U, the bandwidth of the EES transmission is 100 MHz, the minimum acceptable C/I becomes:

$$45 - 22 - 3 + 26 = 46 \text{ dB}$$

The factor 10 log $(100/B_W)$ assumes uniform spectral distribution for both signals; if actual spectra are known, they should be used in determining the bandwidth factor. Allowing 10 dB for non-uniform spectral distribution of EES emission, C/I min = 36 dB.

When $\Delta L_p \approx -3$ dB, the earth exploration spacecraft is directly beneath a geostationary or near-geostationary satellite. However, at that point, the e.i.r.p. in the direction away from the Earth will be less than +22 dBW, and C/I will therefore be greater than 36 dB.

$(P_T + G_T)$ will in general be considerably greater than +45 dBW, so that the minimum value of C/I is expected to exceed 36 dB.

For meteorological satellites, typical minimum values of C/I are tabulated in Table II.

TABLE II – *Technical characteristics of meteorological satellite earth stations*

Meteorological satellite earth stations	e.i.r.p. (dBW)	B_W (MHz)	Minimum C/I (1) (dB)
CDA (2) (stretched data)	73·4	3·5	52·9
CDA (facsimile)	73·4	0·026	74·3
CDA (command link)	56·4	0·03	56·5
CDA (ranging data)	64·4	1	49·4
TARS (3) (ranging data)	45·0	1	30·0

(1) Values of C/I are based on:

$P_{TU} + G_{TU} = +22$ dBW

$\Delta L_p = -3$ dB

and 10 log $B_U/10\ B_W$, to account for non-uniform spectral distribution of B_U.

(2) CDA: Command and data acquisition (station).

(3) TARS: Turn-around ranging station.

The foregoing analyses of interference in terms of protection ratios (C/I) lead to the conclusion that meteorological and fixed satellite receivers in the geostationary satellite orbit can tolerate the power flux-density which results when the full e.i.r.p. of the low-altitude EES satellite is directed toward the geostationary orbit. This can be translated to a power flux-density limit as follows:

$$\text{Power flux-density} = P_t + G_t - L_p - 10 \log B_U \qquad \text{dB(W/(m}^2 \cdot 4\text{ kHz))} \tag{3}$$

where:

$P_t + G_t$: EES e.i.r.p. +22 dBW,

L_p: the spreading loss at minimum range of EES is 162 dB,

B_U: the equivalent emission bandwidth of EES for interference purposes, expressed in kHz; for this case $B_U = 10$ MHz $= 10^4$ kHz,

therefore:

$$\text{Power flux-density} = +22 - 162 - 34 = -196 + 22 = -174 \qquad \text{dB(W/(m}^2 \cdot 4\text{ kHz))}$$

4. Interference from terrestrial fixed service transmitters to EES earth station receivers

The sharing criterion for this interference path is the coordination distance required to ensure adequate separation between the terrestrial service transmitters and the EES earth station receivers.

The minimum permissible basic transmission loss to protect the earth station can be stated as:

$$L_b\,(1\%) = P_t + G_t - (P_i - G_R) \qquad \text{dB} \tag{4}$$

where:

P_t: terrestrial service transmitter power (dBW),

G_t: terrestrial service antenna gain in the direction of the earth station (dB),

G_R: gain of the earth station antenna in the direction of the terrestrial station (dB),

P_i: maximum permissible interference level at the earth station receiver input (dBW),

$L_b\,(1\%)$: the value of minimum acceptable basic transmission loss to be exceeded for all but 1% of the time along the interference path between the terrestrial transmitter and the earth station receiver. The value 1% is derived from the service probability requirement of the EES system, and from the statistical variability of G_R in the case of an earth station tracking a low-altitude inclined-orbit satellite, and the fact that the earth station would not be active 100% of the time.

The minimum value of L_b is derived as follows, using as an example a frequency of 8 GHz and the following parameters:

Space station e.i.r.p. (dBW)	+22
Free space path loss, L_p, (D = 5400 km) (dB)	185
Receiving antenna gain, G_R (8 m parabola, 55% eff) (dB)	53.8

With such a low value of C/N, the maximum tolerable value of interference, P_r, at the EES earth station receiver is assumed to be 6 dB below kT_sB, or -132.6 dBW; therefore:

$$L_b\,(1\%) = P_t + G_t + G_R + 132.6 \qquad \text{dB} \tag{5}$$

5. Interference from fixed satellite or meteorological satellite earth station transmitters to EES earth station receivers

For purposes of evaluating the technical feasibility of sharing, the applicable technical characteristics of a proposed USA Earth exploration-satellite earth station are given in Table III using a frequency of 8 GHz as an example.

TABLE III – *Technical characteristics of the proposed earth exploration satellite earth station receiver*

T_s (K)	150
Receiver bandwidth, B (MHz)	100
kT_sB (100 MHz) (dBW)	−126·6
Power flux-density (1) (dB(W/m^2))	−123·6
Effective area of receiving antenna, A_R (m^2) 10 log A_R (2)	+14·4
Miscellaneous losses (dB)	2·0
P_r (dBW)	−111·2
C/N (dB)	15·4

(1) For e.i.r.p. of +22 dBW at a range of 5400 km.
(2) For a parabolic reflector having a diameter of 8 m and an efficiency of 55%.

The procedure presently used for ensuring protection of a fixed-satellite service earth station receiver from a terrestrial line-of-sight radio-relay transmitter operating in shared bands, is to establish a coordination distance. This procedure can be applied to determine the required separation between up-link earth station transmitters and down-link earth station receivers, as outlined below.

The minimum permissible basic transmission loss to protect the earth station receiver can be stated as:

$$L_b\,(1\%) = P_t + G_t - (P_i - G_R) \qquad \text{dB} \tag{6}$$

where:

P_t : space service up-link transmitters power (dBW),

G_t : space service up-link antenna gain in the direction of the EES earth station (dB),

G_R : gain of the EES earth station antenna in the direction of the interference (dB),

P_i : maximum permissible interference level at the EES earth station receiver input (dBW),

L_b (1%) : the value of minimum basic transmission loss to be exceeded for all but 1% of the time along the interference path between the terrestrial transmitter and the earth station receiver. 1% derives from the service probability requirement of the EES system, and from the statistical variability of G_R in the case of an earth station tracking a low-altitude inclined-orbit satellite.

As indicated in Table III, the noise power in the earth station receiver is −126.6 dBW, and the carrier-to-noise ratio, C/N is 15.4 dB. With such a low value of C/N, the maximum tolerable value of interference, P_i, at the EES earth station receiver is 6 dB below kTB, or −132.6 dBW. If we assume that the maximum gain in the horizontal direction of the EES earth station antenna at a minimum elevation angle of 5° will be +15 dB,

$$L_b\,(1\%) = P_t + G_t + 147.6 \qquad \text{dB} \tag{7}$$

ANNEX I

POSSIBILITIES OF FREQUENCY SHARING BETWEEN THE EARTH EXPLORATION-SATELLITE SERVICE AND THE FIXED SERVICE (LINE-OF-SIGHT RADIO RELAY SYSTEMS) AROUND 8 GHz

1. Introduction

The following calculation method does not replace the method given in Appendix 28 to the Radio Regulations. It is not intended to be used in evaluating coordination distances. It allows the *a priori* evaluation of an order of magnitude for acceptable separation distances between an earth station and a terrestrial station, on the basis of a number of parameters. For this purpose, the calculation of the attenuation over the interference path is based not on the worst case but on an average case, with reference exclusively to diffraction caused by an obstacle situated between the two stations. The separation distance thus calculated gives a realistic idea of practical sharing possibilities between the space service and the terrestrial service.

2. Technical characteristics

2.1 *Characteristics of the space stations concerned*

For the purposes of this analysis, the characteristics of the SPOT Earth observation satellite project developed by France have been taken as the basis.

These are as follows:

– frequency:	8.25 GHz
– e.i.r.p. (equivalent isotropically radiated power):	+14.5 dBW
– modulation:	4-phase PSK
– passband:	50 MHz
– polarization:	circular
– orbit altitude:	822 km

These characteristics result in power flux-density values conforming to the limitations imposed by the Radio Regulations in this band.

2.2 *Characteristics of the radio-relay systems concerned*

The standard characteristics are as follows:

– power emitted per channel:	9 dBW
– number of channels in 100 MHz:	3
– P_T = Maximum power emitted in 100 MHz:	14 dBW
– G_T = Antenna gain less losses:	see Fig. 2

2.3 *Characteristics of the earth station concerned*

The SPOT Earth observation satellite project developed by France has the following characteristics:

Bandwidth:	100 MHz
P_i = Maximum permissible interference power for less than 1% of the time: (value in accordance with Recommendation 514)	−134 dBW
G_r = Antenna gain of the earth station:	The gain in the axis is 55.4 dBi; the gain values at more than 1° from the axis are given by the formula $G_r = 32 - 25 \log \varphi$ (in accordance with Recommendation 509).

3. Method of calculation

3.1 *Principle*

3.1.1 The minimum permissible transmission loss for protecting the earth station receiver is given by the relation:

$$L(1\%) = P_T + G_T - P_i + G_r = 148 + G_T + G_r \tag{8}$$

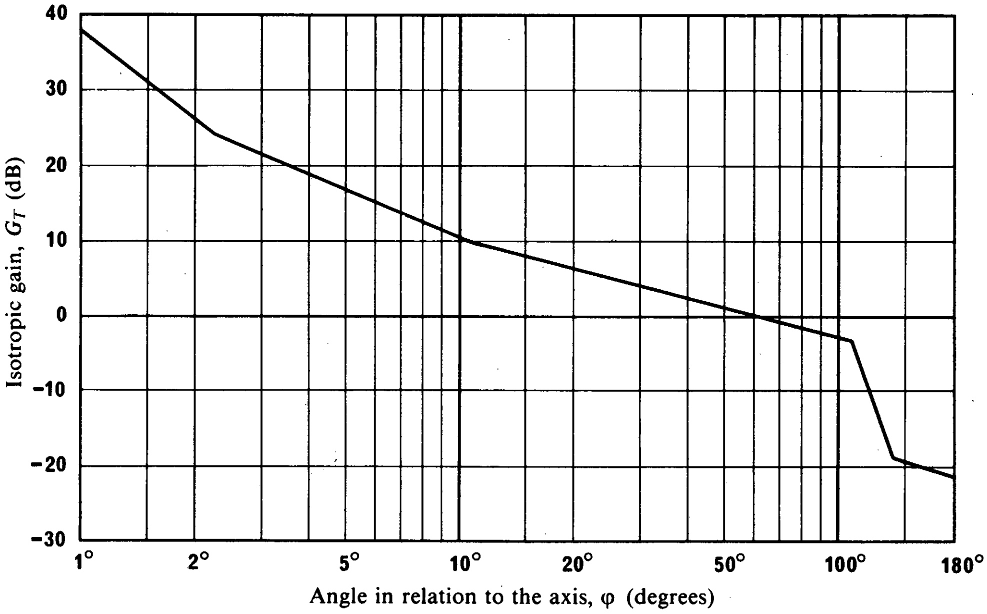

FIGURE 2 – *Radiation diagram of the radio-relay system antenna*

Parabolic antenna 3.60 m in diameter
Frequency: 8.25 GHz
Gain in the axis: 43 dBi

Since the earth station operates exclusively above an angle of elevation of 5°, the antenna gain must be as at $\theta = (5 - \varepsilon)°$ in elevation when the physical horizon is at $\varepsilon°$ in elevation, less 10 dB to allow for the diversity of the angular positions occupied by the satellite in sight of the earth station (see Fig. 3).

$$L(1\%) = 148 + G_T + 32 - 25 \log (5 - \varepsilon) - 10 = 170 + G_T - 25 \log (5 - \varepsilon) \qquad (9)$$

3.1.2 The calculation of the loss on the interference path takes the following into account:

– free space propagation loss : A_d
– loss due to diffraction by an obstacle between the two stations : A_h.

The value of the first loss coefficient expressed in dB is obtained by calculating the relation:

$$A_d = 20 \log \left(\frac{4\pi d}{\lambda}\right) \qquad (10)$$

where:

d: distance between the earth station and the terrestrial station (m)

λ: wavelength of the terrestrial station transmitting frequency (m).

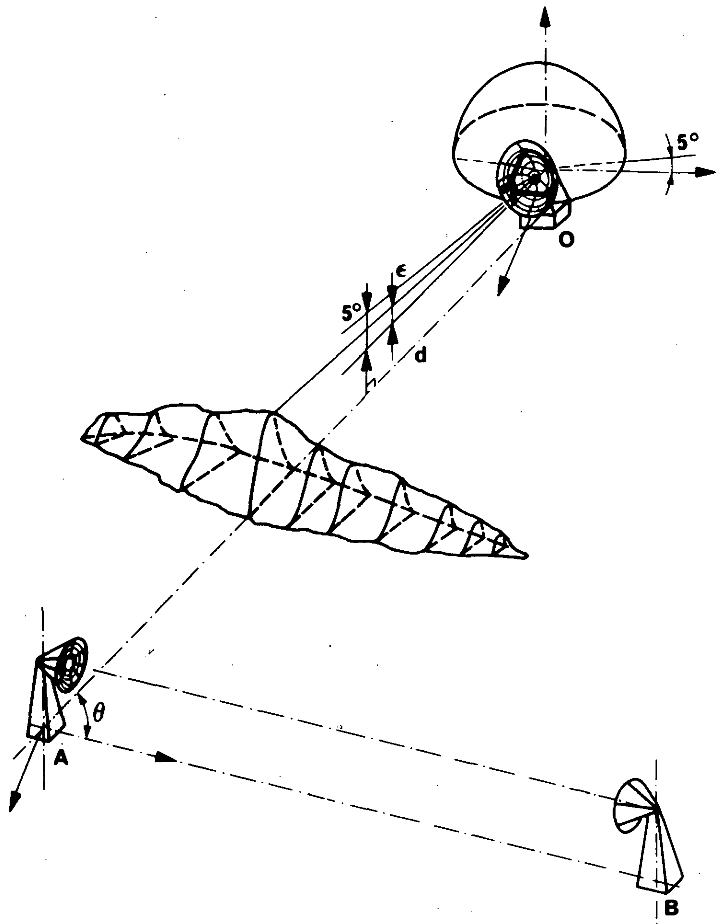

FIGURE 3 – *Configuration of terrestrial stations in relation to the earth station for the study of practical sharing possibilities*

d : distance OA

ε : angle of elevation of the earth station's physical horizon

O : earth station

AB : line-of-sight radio-relay link

θ : offset angle

The value of the second loss coefficient expressed in dB is obtained by calculating the relation:

$$A_h = 20 \log [1 + (4.5 f^{1/2} \varepsilon)] + f^{1/3} \varepsilon \tag{11}$$

(see Report 724 (Geneva, 1982))

where:

f: terrestrial station transmitting frequency (GHz)

ε : the elevation of the earth station's physical horizon in the direction of the terrestrial station.

3.1.3 The interference level of the earth station is then considered to be below the permissible level provided the minimum permissible transmission loss $L(1\%)$ is smaller than the loss on the interference path $(A_d + A_h)$. The condition which must be met is expressed by the following inequality:

$$L(1\%) \leqslant A_d + A_h \tag{12}$$

3.2 *Construction of a nomogram*

The practical possibilities of sharing between the space service and the terrestrial service are analyzed with the aid of a nomogram (Fig. 4). The nomogram is based on observance of the inequality referred to in the preceding paragraph.

If, for example, the special technical characteristics described above are taken into account, it is interesting to convert that inequality and to use it in the following form for the construction of the nomogram:

$$G_T(\theta) \leqslant 25 \log (5-\varepsilon) + 20 \log \left(\frac{4\pi d}{\lambda}\right) + 20 \log [1 + (4.5 f^{1/2}\varepsilon)] + f^{1/3}\varepsilon - 170 \quad (13)$$

3.2.1 *First stage*

The free space propagation loss A_d, is calculated for a particular arbitrarily chosen distance:

$$A_d = 20 \log \left(\frac{4\pi d}{\lambda}\right) = 144.75 \text{ dB} \quad (d = 50 \text{ km}, \lambda = 0.0364 \text{ m}, f = 8.25 \text{ GHz})$$

such that:

$$G_T(\theta) \leqslant 25 \log (5-\varepsilon) + 20 \log [1 + (4.5 f^{1/2}\varepsilon)] + f^{1/3}\varepsilon - 25.25$$

3.2.2 *Second stage*

The two elements of the second term of the inequality which depend on ε (angle of elevation of the earth station's physical horizon in the direction of the terrestrial station) are calculated.

TABLE IV

ε	0.5°	1°	2°	3°	4°
$A_h = 20 \log [1 + (4.5 f^{1/2} \varepsilon)] + f^{1/3} \varepsilon$ (dB)	18.47	24.9	32.62	38.05	42.52
$A = 25 \log (5 - \varepsilon)$ (dB)	16.33	15.05	11.9	7.53	0
$(A_h + A)$ (dB)	34.8	39.95	44.55	45.58	42.52

It will be found that the sum of these two terms $(A_h + A)$ presents a maximum value equal to 45.58 dB for a value of ε equal to 3°.

3.2.3 *Third stage*

In the circumstances we may, for a particular value of the distance between the earth station and the terrestrial station associate a value of the terrestrial station gain in the direction of the earth station with a value of the angle of elevation of the earth station's phsyical horizon.

Table V shows this correspondence in the particular case under study:

TABLE V

ε	0.5°	1°	2°	3°	4°
$G_T(5 - \varepsilon)$ (dB)	9.55	14.7	19.30	20.33	17.27

To obtain the slope of the lines represented in Fig. 4 the arbitrarily chosen distance used in the calculations is doubled. The new value of the terrestrial station gain in the direction of the earth station is obtained from the values already calculated to which 6 dB is added.

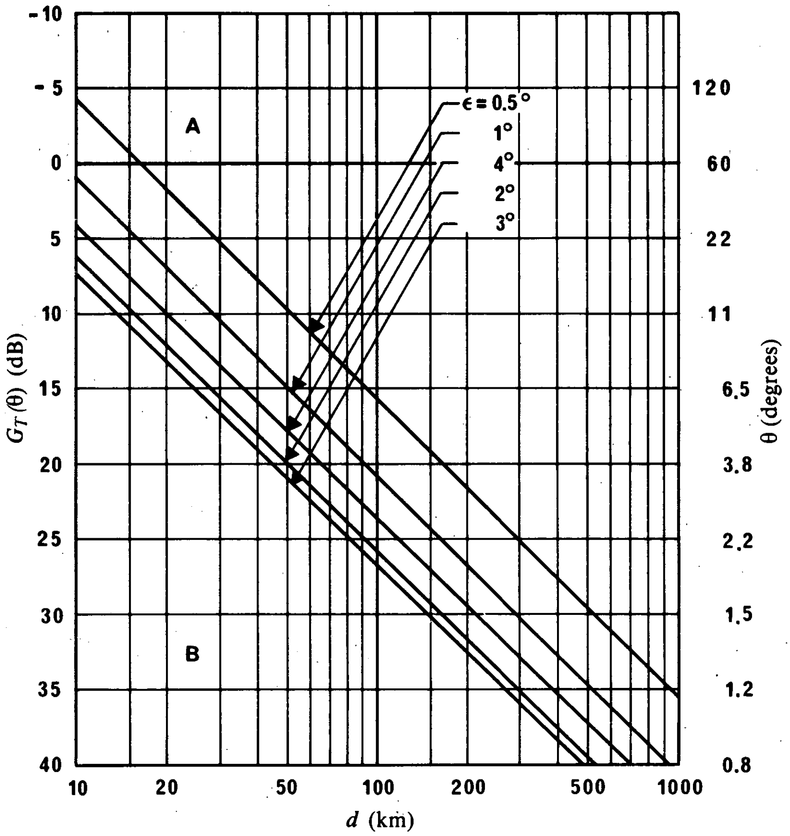

FIGURE 4 – *Field of interference to the Earth station by a radio-relay system in line-of-sight*

d : distance between the earth station and the terrestrial station

$G_T(\theta)$: gain of the terrestrial station in the direction of the earth station

ε : angle of elevation of the earth station's physical horizon in the direction of the terrestrial station

A : area in which interference is improbable

B : area in which interference is probable

Characteristics of the earth station

- Maximum permissible interference power for less than 1% of the time : –134 dBW
- Bandwidth : 100 MHz
- Reception : digital

Characteristics of the radio-relay systems

- Interfering power emitted in 100 MHz : 14 dBW
- Transmission : analogue

3.3 *Use of the nomogram*

The nomogram shows, for example, that the interference level of the earth station is below the permissible level if:

- the relief around the earth station offers a protection of 0.5° to 4° in elevation;
- the distance between the two stations is above 50 km;
- the axis of the radio-relay system is more than 10° out of line with the direction joining the terrestrial station to the earth station.

4. Conclusion

Without prejudice to the coordination procedure described in Appendix 28 to the Radio Regulations, it is often necessary to make a swift analysis of the practical conditions for siting an earth station in an already existing radio-relay network. There is a simple graphical method (Fig. 4) for making such analyses and provisionally determining the best sites for the earth station in relation to those of terrestrial stations in the radio-relay system.

Applied specifically to the French SPOT Earth observation satellite, the method used quickly reveals that application of the coordination procedure in Appendix 28 to the Radio Regulations should not involve intolerable constraints as regards the siting of the earth station.

RECOMMENDATION 515

PREFERRED FREQUENCIES FOR PASSIVE SENSING MEASUREMENTS

(Question 12/2)

(1978)

The CCIR,

CONSIDERING

(a) that passive microwave sensor technology is being applied to remote measurements made by Earth exploration and meteorological-satellites;

(b) that protection from interference on certain frequencies is essential to the advancement of passive sensing measurements and applications;

(c) that for measurements of known spectral lines, certain bands at specific frequencies are of particular importance;

(d) that, for other types of passive sensor measurements, a certain number of frequency bands are in use, the exact positions of which in the spectrum are not of critical importance so long as the centre frequencies fall in particular regions of the spectrum;

(e) that the sensitivity of passive sensor receiving equipment is still steadily improving, and already greatly exceeds the sensitivity of communications and radar equipment;

(f) that information related to selection of preferred frequency bands for passive sensing measurements is contained in Report 693,

UNANIMOUSLY RECOMMENDS

1. that the preferred frequency bands for passive sensor measurements of properties of the Earth's land, oceans and atmosphere are:

Frequency (GHz)	Suggested Bandwidth (MHz)	Measurements
Near 1.4	100	Soil moisture, salinity
Near 2.7	60	Salinity, soil moisture
Near 5	200	Estuarine temperature
Near 6	400	Ocean temperature
Near 11	100	Rain, snow, lake ice, sea state
Near 15	200	Water vapour, rain
Near 18	200	Rain, sea state, ocean ice, water vapour
Near 21	200	Water vapour, liquid water
22.235	300	Water vapour, liquid water
Near 24	400	Water vapour, liquid water
Near 30	500	Ocean ice, water vapour, oil spills, clouds, liquid water
Near 37	1000	Rain, snow, ocean ice, water vapour
Near 55	250 (multiple)(1)	Temperature
Near 90	6000	Clouds, oil spills, ice, snow
100.49	2000	Nitrous oxide
110.80	2000	Ozone
115.27	2000	Carbon monoxide
118.70	2000	Temperature
125.61	2000	Nitrous oxide
150.74	2000	Nitrous oxide
164.38	2000	Chlorine oxide
167.20	2000	Chlorine oxide
175.86	2000	Nitrous oxide
183.31	2000	Water vapour
184.75	2000	Ozone
200.98	2000	Nitrous oxide
226.09	2000	Nitrous oxide
230.54	2000	Carbon monoxide
235.71	2000	Ozone
237.15	2000	Ozone
251.21	2000	Nitrous oxide
276.33	2000	Nitrous oxide
301.44	2000	Nitrous oxide
325.10	2000	Water vapour
345.80	2000	Carbon monoxide
364.32	2000	Ozone
380.20	2000	Water vapour

(1) several bands each of 250 MHz bandwidth.

RECOMMENDATION 577-1

PREFERRED FREQUENCY BANDS FOR ACTIVE SENSING MEASUREMENTS

(Question 12/2 and Study Programme 12B/2)

(1982-1986)

The CCIR,

CONSIDERING

(a) that spaceborne active microwave sensors can provide unique information on physical properties of the Earth as discussed in Report 693;

(b) that the sensing of different physical properties requires the use of different frequencies;

(c) that the spatial resolution of the measurement determines the necessary bandwidth;

(d) that simultaneous measurements at a number of frequencies may be needed to distinguish between the various properties;

(e) that sharing is feasible between some spaceborne active microwave sensors and terrestrial radars in some bands of the radiolocation service (Recommendation 516),

UNANIMOUSLY RECOMMENDS

1. that the preferred frequency bands for active sensing measurements of the Earth are:

- near 1 GHz,
- near 3 GHz,
- near 5 GHz,
- near 10 GHz,
- near 14 GHz,
- near 17 GHz,
- near 35 GHz,
- near 76 GHz;

2. that bandwidths of 100 MHz are sufficient for active sensor applications except for altimeter measurements having spatial resolution requirements greater than 50 cm;

3. that bandwidths of 600 MHz are required for some applications with altimeters;

4. that the following measurements using active sensors can be made by use of the preferred frequencies in RECOMMENDS 1:

- soil moisture;
- vegetation mapping;
- snow distribution, depth and water content;
- geological mapping;
- land use mapping;
- ice boundaries, depth, type and age;
- ocean wave structure;
- ocean wind speed and direction;
- mapping of ocean circulation (currents and eddies);
- geodetic mapping;
- rain rates;
- cloud height and extent;
- surface pressure.

REPORT 693-2

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR THE EARTH EXPLORATION-SATELLITE SERVICE

Preferred frequency bands for active and passive microwave sensors

(Question 12/2 and Study Programme 12B/2)

(1978-1982-1986)

1. Introduction

In the area of Earth exploration for earth resources, meteorology and oceanography, new satellite programmes currently developed in Europe, Canada and the United States are expected to extend the useful remote sensing spectrum into the microwave region, using both passive and active devices. Based on this work, the purpose of this Report is to present the preferred frequency bands and the expected characteristics of microwave sensors under development for these satellites.

2. Passive microwave radiometry

Energy at microwave frequencies is emitted and absorbed by the surface of the Earth and by the atmosphere above the surface. The transmission properties of the absorbing atmosphere vary as a function of frequency, as shown in Fig. 1. This figure depicts calculated one way zenith (90° elevation angle) attenuation values for oxygen and water vapour [Crane, 1971]. The calculations are for a path between the surface and a satellite. These calculations reveal frequency bands for which the atmosphere is effectively opaque and others for which the atmosphere is nearly transparent. The regions or windows that are nearly transparent may be used to sense surface phenomena; the regions that are opaque are used to sense the top of the atmosphere.

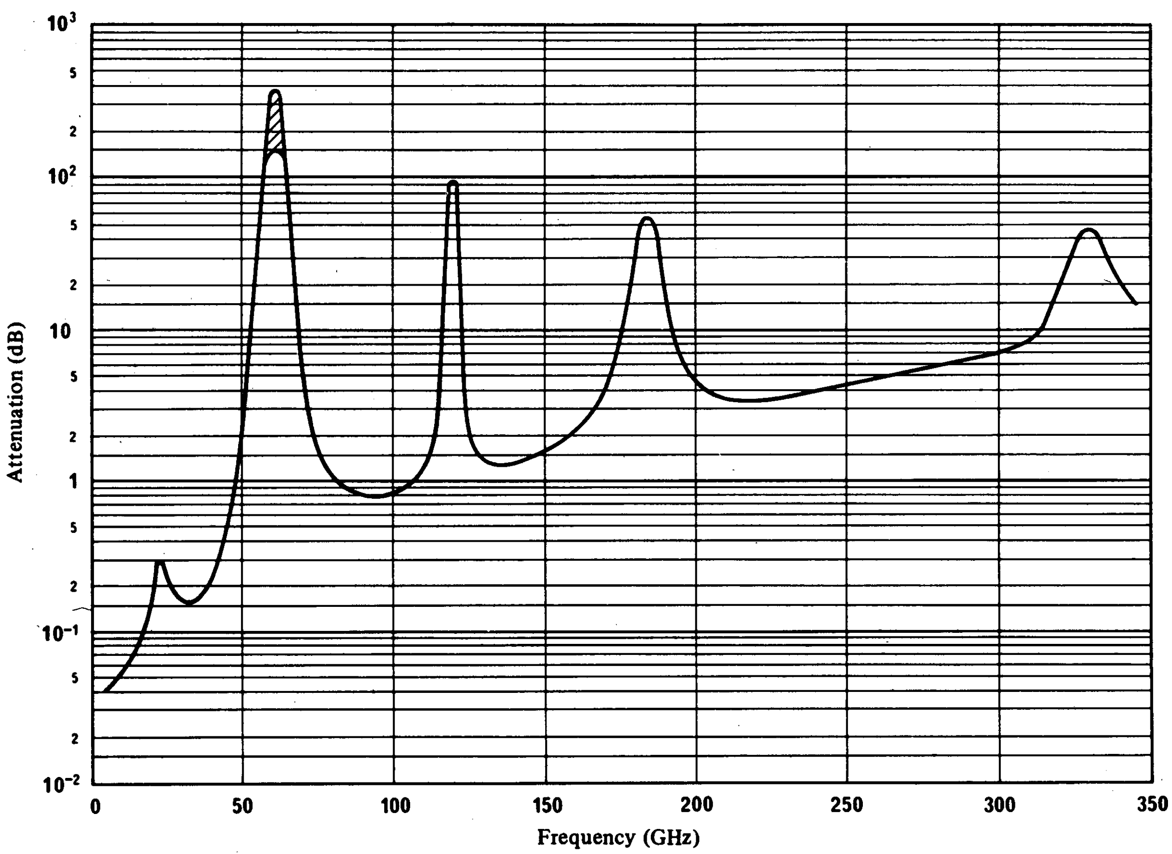

FIGURE 1 – *Zenith attenuation versus frequency (January, mid-latitude 7.5 g/m³ surface water vapour density)*

The power received by a radiometer on a satellite looking down at the Earth may be calculated from the equations of radiative transfer, [Crane, 1971; Staelin, 1969]. For a nonscattering medium,

$$T_A(\nu) = \frac{p(\nu)}{kB} = \frac{1}{4\pi}\int_0^{4\pi} g(\Omega)\left[T_0(\nu)\,\mathrm{e}^{-\tau(L)} + \int_0^L T(s)\,\beta(s)\,\mathrm{e}^{-\tau(s)}\,\mathrm{d}s\right]\mathrm{d}\Omega \tag{1}$$

where:

T_A : antenna temperature (K)

p : received power (W)

ν : centre frequency (Hz)

B : receiver bandwidth (Hz)

k : Boltzmann's constant (J/K)

g : antenna gain (numeric ratio)

Ω : solid angle about the antenna (steradian)

T_0 : surface brightness temperature (emission plus scattering) (K)

τ : optical depth (nepers)

β : absorption coefficient (nepers/km)

L : path length from satellite to ground (km)

s : position along the path (km)

and $T(s)$: atmospheric temperature at point s along the path (K)

The optical depth is simply related to the attenuation as follows:

$$\tau(s) = \int_0^s \beta(x)\,\mathrm{d}x = \int_0^s \left(\frac{a(x)}{4.34}\right)\mathrm{d}x = \frac{A(s)}{4.34} \tag{2}$$

where

A : attenuation (one way) (dB)

and a : specific attenuation (dB/km).

Equations (1) and (2) display the essential features of remote sensing using microwave frequencies. The surface brightness temperature, the atmospheric temperature at points, s, along the path and the absorption coefficients are unknown and to be determined from measurements of the antenna temperature, T_A. The surface brightness temperature and the absorption coefficients in turn, depend upon the physical properties of the surface or atmosphere that are to be sensed. A single observation at a single frequency cannot be used to estimate a single physical parameter. Observations must be made simultaneously at a number of frequencies and combined with models for the frequency dependence and physical parameter dependence of the surface brightness temperature and of the absorption coefficient, before the integral equation (1), may be solved.

The equation may be simplified for application at frequencies in the atmospheric windows where the attenuation is less than 1 dB. For an antenna system with a narrow beam and for an absorber at a constant temperature, T_s the equation reduces to:

$$T_A(s) = T_0\,\mathrm{e}^{-\tau(s)} + T_s(1 - \mathrm{e}^{-\tau(s)}) \tag{3}$$

$$T_A(s) \simeq T_0(1 - \tau(s)) + T_s\,\tau(s) \tag{4}$$

This result shows that even in the windows, the effect of the atmosphere above the surface must be considered.

Radiometric receivers sense the noise-like thermal emission collected by the antenna and the thermal noise of the receiver. By integrating the received signal the random noise fluctuations can be reduced and accurate estimates can be made of the sum of the receiver noise and external thermal emission noise power. Expressing the noise power per unit bandwidth as an equivalent noise temperature, the effect of integration in reducing measurement uncertainty can be expressed as given below, [Kraus, 1966]:

$$\Delta T_e = \frac{\alpha\,(T_A + T_N)}{\sqrt{B\tau}} \tag{5}$$

where:

ΔT_e : r.m.s. uncertainty in the estimation of the total system noise, $T_A + T_N$

T_A : antenna temperature

T_N : receiver noise temperature

B : bandwidth

τ : integration time

α : receiver system constant.

The sensitivity of microwave receivers is improving rapidly due to the development of improved solid-state components. At wavelengths longer than 3 cm, receiver noise temperatures of less than 150 K can be obtained with solid-state parametric amplifiers. At wavelengths shorter than 3 cm, the most common type of receiver is the superheterodyne with noise temperatures ranging from several hundred degrees at 3 cm wavelength to perhaps 20 000 K at 3 mm wavelengths. Improvements in Schottky-barrier diodes show promise of reducing superheterodyne noise temperature to a few hundred degrees for wavelengths as short as 5 mm.

With the receiver noise temperatures that can be obtained with current technology, significant reductions in the ΔT_e values (or increased sensitivity) can only be accomplished in spaceborne radiometers by increased system bandwidths. Low orbit spaceborne radiometers are limited to integration times on the order of seconds or less, due to the spacecraft relative velocity and high spatial resolution requirements.

3. Active sensors

Active sensors differ from passive sensors in that they illuminate the object under observation and respond to the reflected energy.

There are three basic types of active sensors:

- scatterometers
- altimeters
- imagers

Radar scatterometers are useful for determining the roughness of large objects. When operating at frequencies higher than 300 MHz, the scatterometer measures the amount of backscatter from the surface roughness in broad categories ranging from smooth to very rough. At frequencies around 200 MHz, reflectivity depends upon the dielectric constant of the object; at lower frequencies, reflectivity depends primarily upon electrical conductivity. These lower frequencies can be used to penetrate the surface of the earth to detect subsurface structures.

Radar altimetry has yielded three possible operational concepts for practical systems. One of these techniques is based upon the use of a very narrow beamwidth (2 mrad) and a very short transmitted pulse (2 ns). Timing of the round-trip delay of the transmitted pulse leading edge, is used to provide altitude information. A technique that is similar to the short pulse system, is the pulse compression technique. A short impulse pulse generates a longer frequency modulated pulse and the return, which has a wide bandwidth, is compressed back to a short pulse which is then leading edge detected. The third technique requires moderate antenna size and spacecraft stabilization, with radar return from the nadir point obtained by a time-gating technique. In this system, altitude information is extracted by measuring the centroid of the early portion of the radar waveform rather than the leading edge of a very short pulse.

Radar imaging systems are employed to produce high resolution images required by users in such fields as geology, oceanography, and agriculture. To achieve reasonable resolution from space, synthetic aperture focused radars will be employed for many applications as they have resolutions independent of range. In the area of meteorology scanning Doppler radars may also be employed.

4. Present and near future microwave sensors

Characteristics of passive and active sensors currently in use and under development are shown in Tables I and II respectively.

TABLE I – *Passive microwave sensor parameters*

Sensor	Frequency (GHz)	Bandwidth (MHz)	Sensitivity ΔT_e (K)	Sensitivity (dBm)	Operation date
Radiometer (L-band)	1.4	27	1	– 124	1972
Nimbus-5 microwave spectrometer	22.23 ; 31.4 ; 53.65 ; 54.9 ; 58.8	220	1	– 115	1972
Scanning microwave spectrometer	22.23 ; 31.65 ; 52.85 ; 53.85 ; 55.45	220	1 to 1.5	– 115	1975
Tiros-N microwave sounding unit	50.3 ; 53.74 ; 54.95 ; 57.95	200	0.3	– 121	1978
Electronic scanning microwave radiometer	37 (Nimbus-6) 19.35 (Nimbus-5)	250 300	1 1	– 114 – 114	1975 1972
Scanning multi-channel microwave radiometer	6.6 ; 10.69 ; 17.96 ; 21.0 ; 37.0	250	0.9 to 1.5	– 113	1978
Microwave limb sounder (UARS)	63, 119, 183, 205, 231	To be determined	To be determined	To be determined	1986
Radiometer (S-band)	2.65	100	0.1	– 129	1970
Microwave temperature sounder	53.331 52.85 53.85 55.45	600 120 120 120	1 1 1 1	– 111 – 118 – 118 – 118	1975
Radiometer (L-band)	1.43	60	0.1	– 130	1975
Swept frequency radiometer	4.5 to 7.2	2000	0.1	– 116	1976
Passive microwave imaging system	10.69	150	1.2	– 115	1970
Multi-frequency microwave radiometer	1.4135 18.0 22.05 37.0	27.5 200 200 500	1 1 1 1	– 124 – 115 – 112 – 112	1970

TABLE I *(end)*

Sensor	Frequency (GHz)	Bandwidth (MHz)	Sensitivity ΔT_e (K)	Sensitivity (dBm)	Operation date
Large antenna multi-frequency microwave radiometer (ICEX)	1.4 ; 4.3 ; 5.1 ; 6.6 ; 10.7 ; 18.5 ; 21.5 ; 36.5 ; 92	100 MHz-1 GHz	≈ 1	– 109 to – 119	To be determined
Advanced microwave moisture sensor	91, 65, 183, 15	1 GHz, 2-9 GHz	2, 6	– 106 – 91 to – 98	1979
Advanced microwave sounding unit	18.5 ; 22.23 ; 31.65 ; 50.30 ; 52.85 ; 53.40 ; 54.35 ; 54.90 ; 55.50 57.968 (6 channels) ; 90, 150, 183.311 (3 channels)	2.5-7000	0.25 (chan. 1-12) 0.40 (chan. 13) 1.0 (chan. 14) 2.2 (chan. 15) 0.5 (chan. 16) 0.6 (chan. 17-20)	– 141 to – 103	1986-1987

TABLE II – *Active microwave sensors parameters*

Sensors	Frequency (GHz)	Beamwidth (degrees)	Sensitivity (dBm)	E.i.r.p. (dBW)	Operation date
Skylab altimeter	13.9	1.4	– 88	72	1972
Skylab scatterometer	13.9	1.4	– 88	52	1972
GEOS-C altimeter	13.9	2.6	– 80	73	1975
Seasat synthetic aperture radar	1.275	5 × 1	– 98.5	64	1978
Seasat scatterometer	14.6	25 × 5.5	– 128	55	1978
Seasat altimeter	13.5	1.5	– 81	75	1978
AAFE multispectral active microwave imaging system	3.0 13.9	6 6	– 98 – 98	67 63	1977
Surface contour radar	35.7 36.3	1.2 1.2 × 40	– 82 – 82	45 45	1977
Radiometer/scatterometer	13.9	1.5	– 90	41	1970
Radar pulse compression experiment	13.9	15	– 107	21	1977
Shuttle imaging radar	10 1	1.3 × 8 0.15 × 8		75 79	1982 1982
Microwave pressure sounder	29.25 ; 26.55 ; 44.87 ; 50.80 ; 67.51 ; 73.01	1.3 × 0.17 to 0.52 × 0.07			
Spacelab SAR/scatterometer :					
– SAR	9.65	2.4 × 1.25	– 90	60	1983
– scatterometer	9.65	2.4 × 1.25	– 90	64	1983
ERS-1 wind scatterometer	5.3	3.3 × 0.8	– 134.5	49 (max = 56)	1989
ERS-1 SAR/wave scatterometer :					
– wave scatterometer	5.3	5 × 0.3	– 98.5	62.4 (max = 72)	1989
– SAR	5.3	5 × 0.3	– 100	67.2 (max = 76.8)	1989
ERS-1 altimeter	13.7	1.6	– 83.2	48 (max = 68)	1989

5. Preferred frequency bands

5.1 *Passive sensors*

Operating frequencies for passive microwave sensors are primarily determined by the phenomena to be measured. For certain applications, such as those requiring measurements of microwave emissions from atmospheric gases, the choice of frequencies is quite restricted and is determined by the spectral line frequencies of the gases. Other applications have broad frequency regions where the phenomena can be sensed.

5.1.1 *Atmospheric measurements**

Atmospheric attenuation does not occur within a single atmospheric layer of constant temperature. Figure 2 (see Report 719 (Geneva, 1982)) displays the variation of attenuation with frequency and height. Equation (1) indicates that the measured antenna temperature depends mostly upon the temperature in the region along the path where the attenuation (total to the satellite) is less than 10 dB, and little upon temperatures in regions where the attenuation is very small, or the total attenuation to the satellite is large. The temperature values can be sensed at different heights or distances along the path by selecting frequencies near the edges of the opaque regions with different attenuations, which provide different weighting functions or multipliers of $T(s)$ in equation (1). The broad opaque region between 50 and 70 GHz is composed of a number of narrow absorption (opaque) lines and observations may be made either at the edges of the complex of lines or in the valleys between the lines. The range of attenuation values, peak to valley for the complex of lines, are indicated as shaded areas on Figs. 1 and 2.

A number of different frequencies may be chosen to provide a reasonable set of weighting functions for atmospheric temperature, water vapour, ozone, chlorine oxide, nitrous oxide and carbon monoxide profile measurements. For the last four molecular measurements, each individual line does not have enough fine structure, as in the O_2 temperature profiling band, or enough width, as in the water vapour band about 22.235 GHz, to allow for profile measurements about a line, given the satellite constraints on integration time. Hence, in order to achieve profiling information on these constituents, multiple line measurements will be necessary.

Sample calculations for a set of frequencies in the oxygen line complex are given in Fig. 3. Calculations for the channels corresponding to the lowest five frequencies in Fig. 3, performed using a statistical procedure for inverting equation (1), show that for a 0.3 K radiometer sensitivity the expected r.m.s. uncertainty in the estimated temperatures is less than 2 °C for heights above 1 km at mid-latitudes over the ocean.

Clouds and rain can provide additional attenuation when they occur along the path. Both rain and clouds may be sensed in the atmospheric windows between 5 and 150 GHz. Multiple observations over a wide frequency range are required to separate rain from cloud and to separate these effects from surface emission.

5.1.2 *Land and ocean measurements*

Emission from the surface of the Earth is transmitted through the atmosphere to the satellite. When the attenuation values are high, this emission cannot be sensed. When it is low, as required to sense the temperature of the lowest layer of the atmosphere, both the surface and atmospheric contributions are combined. Additional measurements within the window channels are required to separate the two types of contributions. Surface emission is proportional to the temperature and emissivity of the surface. The latter are related to the dielective properties of the surface and to the roughness of the surface. If the emissivity is less than unity, the surface both emits and scatters radiation. The scattered radiation originates from downward atmospheric emission from above the surface. In a window channel with very small attenuation values this latter contribution is negligible; otherwise it must be considered in the solution of equation (1).

* See also the sections on Radiometeorology (5C), Space Telecommunications (5F) and Interference (5G) of Volume V.

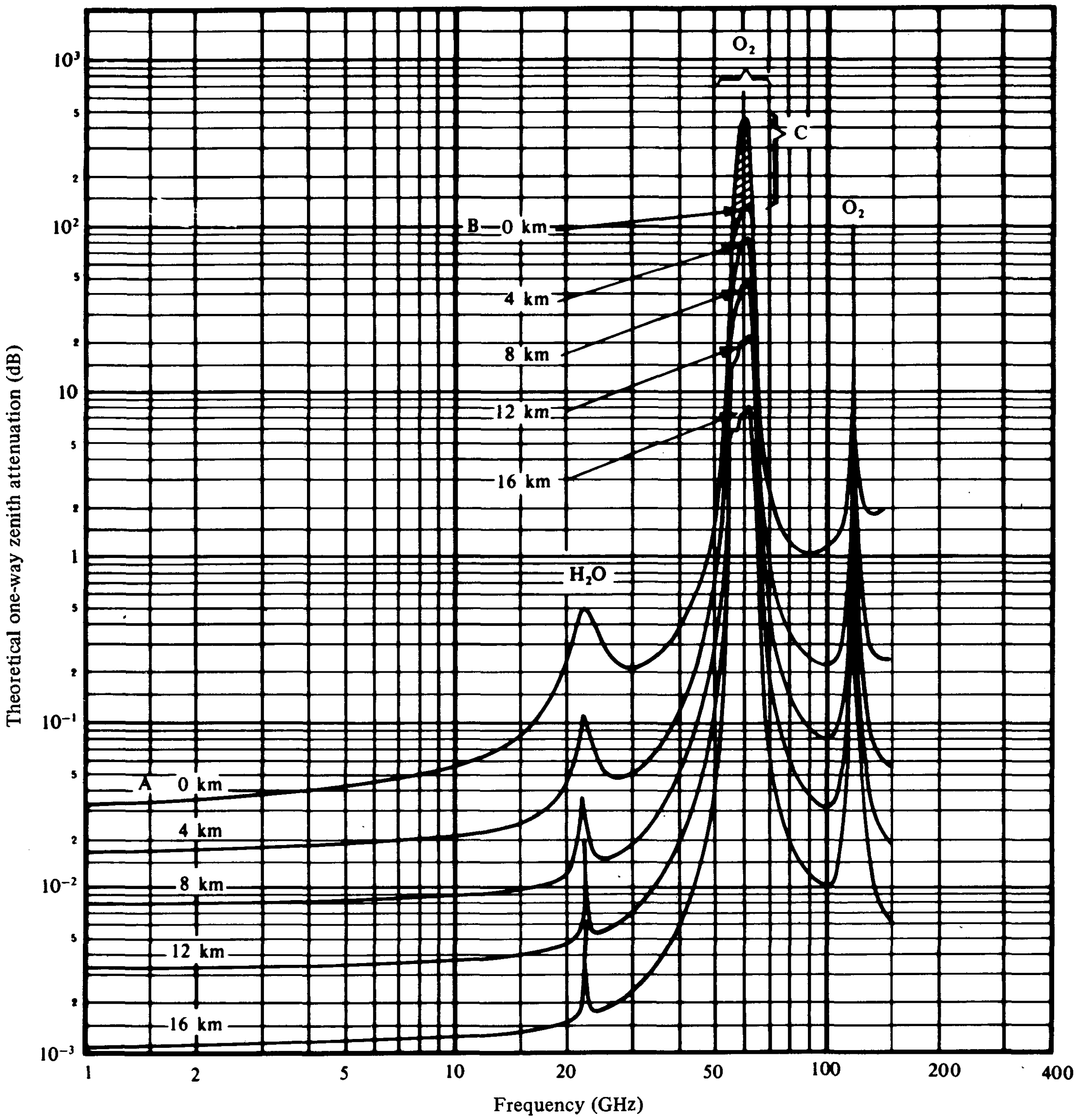

FIGURE 2 – *Theoretical vertical one-way attenuation from specified height to top of the atmosphere for a moderate humid atmosphere (7.5 g/m³ at the surface)*

A: Starting heights (km)

B : Minimum values for paths starting at indicated heights (km)

C : Range of values for the path from the surface to 80 km

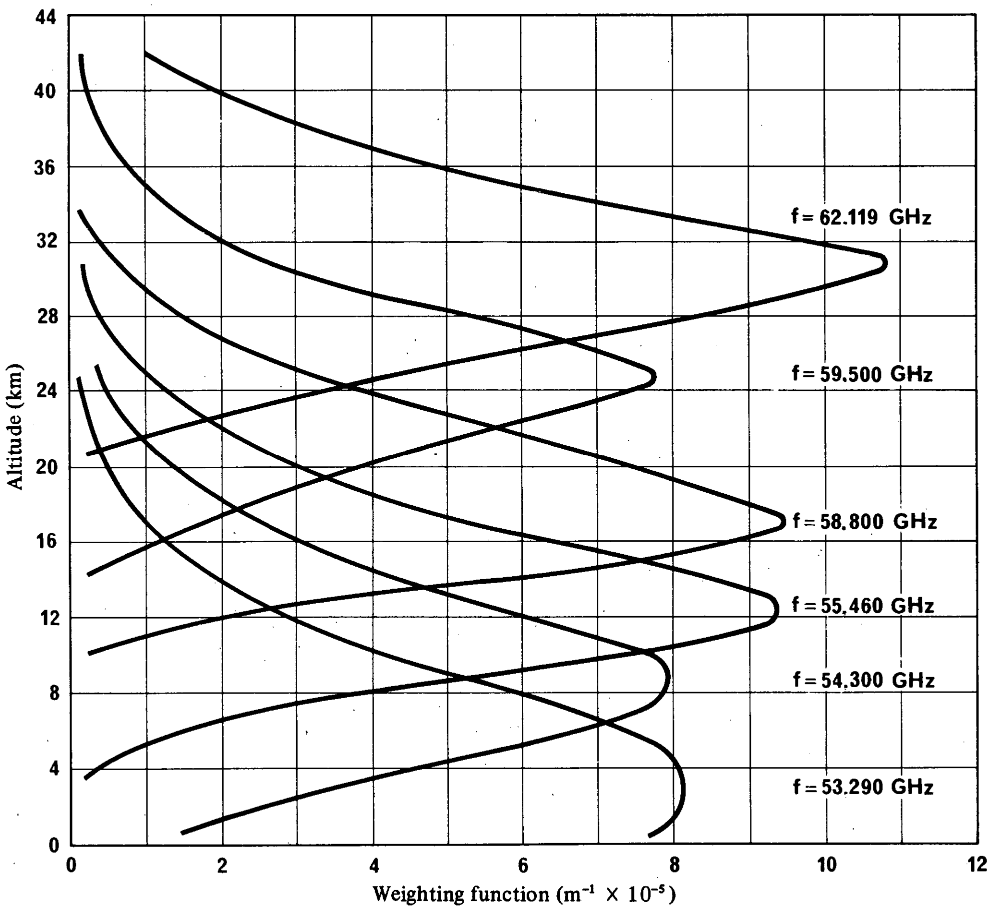

FIGURE 3 – *Temperature weighting functions (zenith θ = 40°, polarization = 90°)*

(Clear sky)

Surface brightness temperatures do not show the rapid variation with frequency exhibited by emission from atmospheric absorption lines. The relatively slow frequency variations of the effects of surface parameters requires simultaneous observations over a broad frequency range within the atmospheric windows to determine their values. Separation of the parameters can only be accomplished when the parameters have different frequency dependences. Figures 4, 5, and 6 depict the frequency dependence of the several parameters affecting the brightness temperature of the ocean surface, salinity, temperature, and wind. The wind affects the brightness temperature by roughing the surface and by producing foam which has dielectric properties different from the underlying water. These figures show that salinity is best sensed at frequencies below 3 GHz and, if extreme measurement accuracy is required, at frequencies below 1.5 GHz. Sea surface temperature is best sensed using frequencies in the 3 to 10 GHz range, with 5 GHz being near optimum. Wind affects observations at all frequencies but is best sensed at frequencies above 15 GHz.

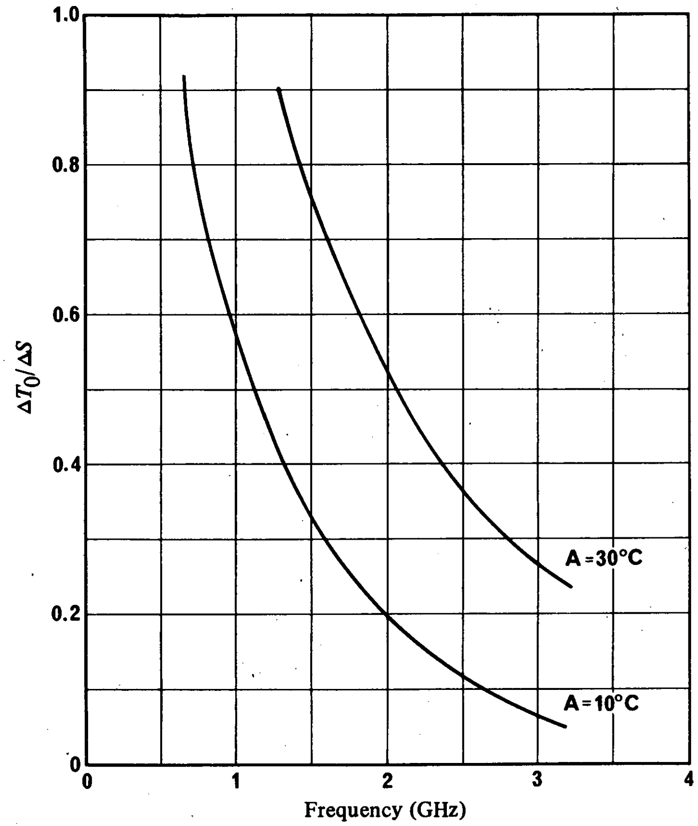

FIGURE 4 – *Change in brightness temperature with salinity*

A : Surface temperature

ΔS : Salinity change in parts per thousand (‰)

ΔT_0 : Temperature change (K)

Surface layers of ice or oil floating on the ocean surface have dielectric properties different from water and can be sensed due to the resultant change in brightness temperature. Oil slicks can change the brightness temperature above 30 GHz by more than 50 K [Hollinger and Mennella, 1973] and ice can change the brightness temperature by more than 50 K at frequencies from 1 to 40 GHz. Although ice and oil spills can provide a large change in brightness temperature, a number of observations in each of the atmospheric windows are required to separate the effects of ice and oil from rain and clouds.

The moisture content of the surface layers can be detected at microwave frequencies [Schmugge *et al.*, 1974]. The brightness temperature of snow and of soil both change with moisture content and with frequency. In general, the lower the frequency, the thicker the layer that can be sensed. Since the moisture at the surface is related to the profile of moisture below the surface, observations at higher frequencies can also be useful. In sensing the melting of snow near the surface, observations at 37 GHz and higher, provide the most information. For sensing soil, especially soil under a vegetation canopy, frequencies below 3 GHz are of most interest. In practice, a number of frequencies are required, first to classify the surface as to roughness, vegetation cover, sea ice age, etc., and, second, to measure parameters such as ice thickness or moisture content. Figures 7 and 8 present sensitivity curves versus frequency for ice and soil moisture. In particular, Fig. 7 presents actual measurements over ice for various frequencies and polarizations.

Table III presents the preferred frequency bands for passive microwave sensing measurements. The primary measurements which require each frequency band are also listed as well as necessary bandwidths to provide sufficient measurement accuracy and usable areas of coverage.

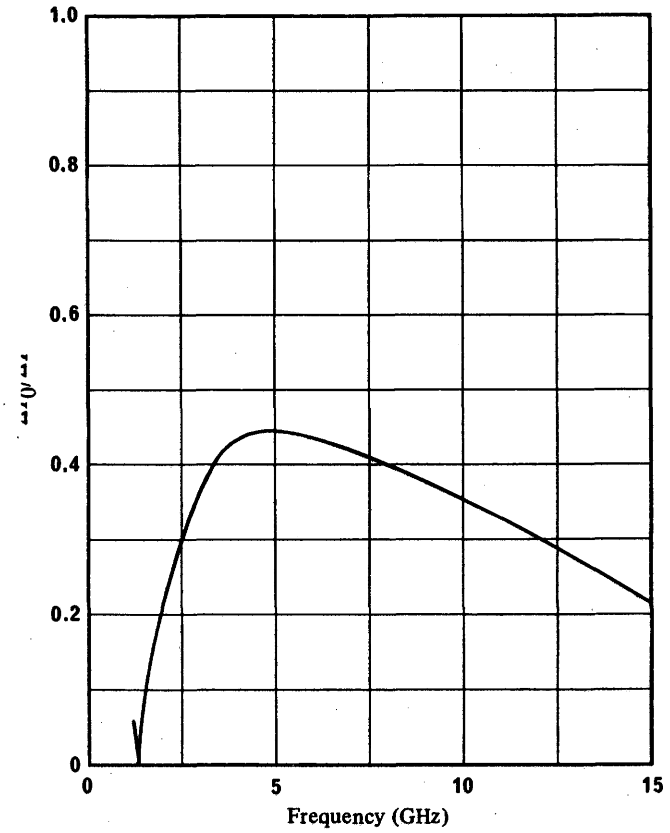

FIGURE 5 – *Change in brightness temperature with surface temperature (salinity 36 parts per thousand)*

ΔT : Physical surface temperature change (K)

ΔT_0 : Brightness temperature change (K)

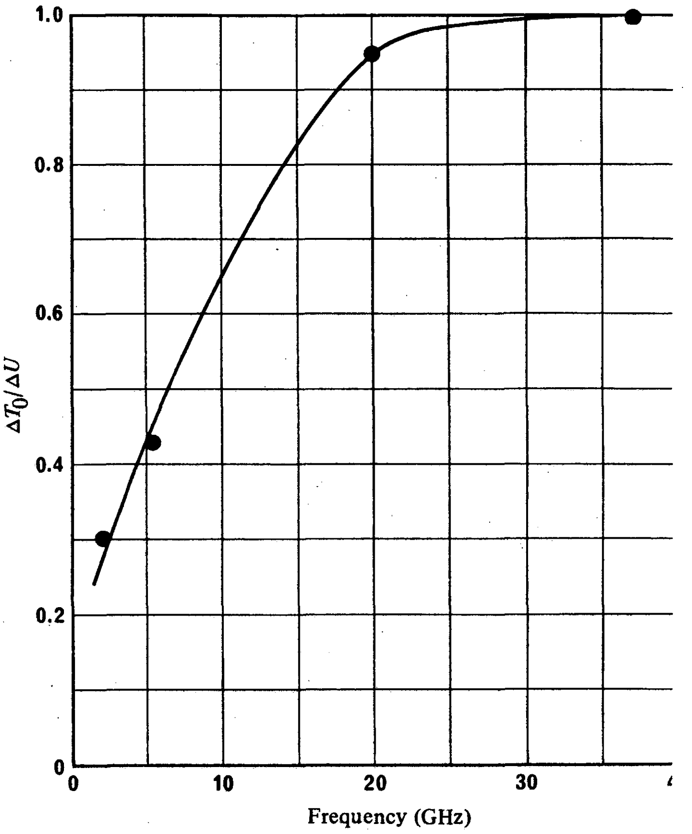

FIGURE 6 – *Change in brightness temperature with wind speed (nadir)*

ΔU : Wind speed change (m/s)

ΔT_0 : Brightness temperature change (K)

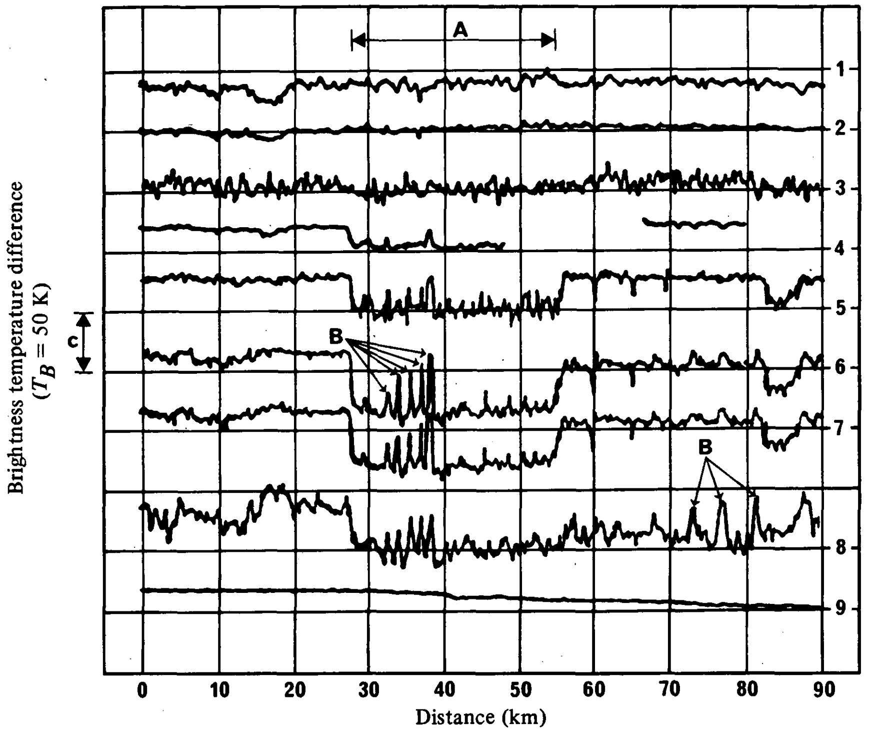

FIGURE 7 – *Brightness temperatures of ice at various wavelengths and polarizations*

A: Large multiyear ice floe
B: Refrozen leads
C: Temperature difference range indication

Curve	λ (cm)	Pol.	Curve	λ (cm)	Pol.
1:	21.1	V,H	6:	0.81	V
2:	11.2	V,H	7:	0.81	H
3:	6.01	V,H	8:	0.32	H
4:	2.81	V,H	9:	10 μm (Infra-red)	
5:	1.55	V,H			

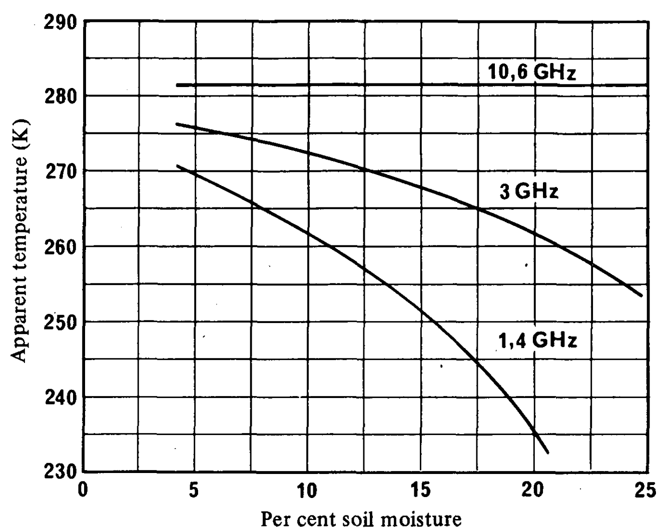

FIGURE 8 – *Apparent temperature of a smooth surface uniform vegetation for various frequencies*

40° Incidence
Vertical polarization
Density = 5.0%
Canopy height = 50 cm

5.1.3 *Technical parameters of passive sensors*

Studies have been performed to determine sensor sensitivity requirements, spatial resolution requirements, and non-scanning bandwidth requirements [NASA 1976a and 1976b]. The results of the studies are summarized in Table IV for each of the preferred frequencies contained in Table III. Also presented in Table IV is the coverage width that can be achieved with the suggested bandwidths in Table III by use of scanning sensors. It should be noted that 185 km coverage widths result in total Earth coverage in about 18 days for a typical EES orbit such as that used by the Landsat series of satellites. Updating at a period of less than every 18 days is required to fully satisfy the requirements of environmental scientists and meteorologists.

5.2 *Active sensors*

Since the 1940's, it has been apparent from ground-based and airborne experiments and operations, and recently from experiments aboard satellites, that active microwave sensing of atmosphere, ocean and land parameters is feasible and economically useful. Active remote sensing in the microwave region offers several advantages over visible region sensors and passive microwave sensors. Besides being uniquely sensitive to several land/ocean/atmosphere variables (e.g., plant moisture and cloud height), active sensing can, for instance, penetrate the surface and vegetation, operate on an all-weather, day/night basis, attain high spatial resolution (synthetic aperture radar, SAR), enhance features by changing the illumination angle, and operate over broad spectral ranges independent of emissions from narrow-band phenomena.

Active sensors illuminate the object under observation and respond to reflected energy. In order to gather information concerning the Earth's surface from space, the transmitted signal must traverse the atmosphere twice. As a result the electromagnetic absorption and scattering properties of the atmosphere play an important role in determining the spectral regions suitable for active remote sensors.

Severe atmospheric attenuation is confined to the shorter wavelengths, and for this reason, active sensors usually operate below the 60 GHz oxygen absorption region and also avoid the spectral region near the 22 GHz water vapour line.

Electromagnetic scattering by precipitation and clouds can present a more serious problem than atmospheric absorption. Echoes from water droplets increase with droplet diameter and decrease with increasing wavelength. Thus, at longer wavelengths clouds give little echo, but precipitation can give somewhat stronger echoes because of the larger particle diameters of the raindrops.

Seasat, launched by the United States in 1978, had an active sensor complement (see Table II) designed to study ocean dynamics and physical properties on a global basis.

The Canadian SURSAT programme [Department of Energy, Mines and Resources, 1980] was begun in April, 1977 as a step towards the utilization of satellite microwave remote sensors to provide oceanographic data. One consequence of this programme has been the proposal for the satellite Radarsat as described in Annex VI to Report 535.

5.2.1 *General frequency considerations for active sensor measurements*

The following have been identified as being of prime importance for the application of spaceborne radar:

- soil moisture;
- vegetation mapping;
- snow distributions, depth and water content;
- geological mapping;
- land use mapping;
- ice boundaries, depth, type and age;
- ocean wave structure;
- ocean wind speed and directions;
- mapping of ocean circulation (currents and eddies);
- geodetic mapping;
- rain rates;
- cloud height and extent;
- surface pressure.

Studies [NASA, 1974] have identified a number of frequency bands that are needed in order to obtain the measurements listed above.

TABLE III – *Preferred frequency bands for passive microwave sensors*

Frequency (GHz)	Bandwidth (MHz)	Measurement(s)
Near 1.4	100	Soil moisture; salinity
Near 2.7	60	Salinity; soil moisture
Near 5	200	Estuarine temperature
Near 6	400	Ocean temperature
Near 11	100	Rain; snow; lake ice; sea state
Near 15	200	Water vapour; rain
Near 18	200	Rain; sea state; ocean ice; water vapour
Near 21	200	Water vapour; liquid water
22.235	300	Water vapour; liquid water
Near 24	400	Water vapour; liquid water
Near 30	500	Ocean ice; water vapour; oil spills; clouds; liquid water
Near 37	1000	Rain; snow; ocean ice; oil spills; clouds
Near 55	250 multiple(1)	Temperature
Near 90	6000	Clouds; oil spills; ice; snow
100.49	2000	Nitrous oxide
110.80	2000	Ozone
115.27	2000	Carbon monoxide
118.70	2000	Temperature
125.61	2000	Nitrous oxide
150.74	2000	Nitrous oxide
164.38	2000	Chlorine oxide
167.20	2000	Chlorine oxide
175.86	2000	Nitrous oxide
183.31	2000	Water vapour
184.75	2000	Ozone
200.98	2000	Nitrous oxide
226.09	2000	Nitrous oxide
230.54	2000	Carbon monoxide
235.71	2000	Ozone
237.15	2000	Ozone
251.21	2000	Nitrous oxide
276.33	2000	Nitrous oxide
301.44	2000	Nitrous oxide
325.10	2000	Water vapour
345.80	2000	Carbon monoxide
364.32	2000	Ozone
380.20	2000	Water vapour

(1) Several bands each of 250 MHz bandwidth.

TABLE IV – *Technical considerations for passive spaceborne sensors*

Frequency (GHz)	Primary application	Required ΔT_e (K)	Resolution (km)	System noise temp. (K)	Non-scan bandwidth (MHz)	Suggested bandwidth (MHz)	Coverage width (km)
Near 1.4	Soil moisture, salinity	0.1	20	450	42	100	48
Near 2.7	Salinity, soil moisture	0.1	2	450	60	60	2
Near 5	Estuary surface temperature	0.3	2	450	45	200	9
Near 6	Sea surface temperature	0.3	20	450	5	400	1600
Near 11	Rain,(1) snow, ice, wind	1.0	1	1000	60	100	2
Near 15	Water vapour, rain	0.2	2	1000	180	200	2
Near 18	Rain, snow, ice, wind, water vapour(1)	0.2	2	1000	180	200	2
Near 21	Water vapour, liquid water	0.2	2	1000	180	200	2
22.235	Water vapour, liquid water	0.4	2	1000	45	300	13
Near 24	Water vapour, liquid water	0.2	2	1000	180	400	4
Near 30	Ice, oil spills, clouds	0.2	2	1000	180	500	6
Near 37	Rain, snow, ice	1.0	1	2300	230	1000	4
Near 55	Atmospheric temperature profiling	0.3	10	2300	235	Multiple(2)	10
Near 90	Clouds, oil spills, ice, snow	1.0	1	2300	230	6000	26
Above 100	Nitrous oxide, O_3, CO, H_2O, CLO, temperature	0.2	1	4300	1850	2000	1

(1) Parameters given for this application.

(2) Several bands around 55 GHz.

Several aspects of active sensor research, particularly as it relates to the choice of frequencies for measuring Earth-oriented variables from a space platform, are presented below. It should be noted in determining optimal frequencies that, due to the broad frequency response range of various phenomena of interest, there is often a need for simultaneous measurements at several frequencies so that contributions of the radar return from different sources can be separated.

The radar return from any surface is a function of radar frequency, surface roughness, surface dielectric properties, angle of incidence and aspect, and sub-surface microstructure. In each of the applications listed earlier, the energy reflected back to a radar sensor is strongly affected by at least one backscattering mechanism related to the measured phenomenon. In general, these are: oceanic roughness (used in the study of ocean structure and winds over sea surfaces); O_2 absorption (used in determining surface pressure over oceans); and surface roughness and dielectric constant variations (used in studies of ice, snow and land parameters).

5.2.2 *Active sensing of ocean and ocean winds*

Oceanic active sensor studies are dominated by wave structure determination, sea-surface wind measurements and ocean current investigations. Generally the reflected microwave energy is due to ocean roughness; specifically, the radar return is a function of diffraction effects from both large gravity waves and small capillary, surface-tension ripples riding the large-scale waves, and foam. The amount of reflected radiation due to each of these effects observed by an active sensor depends on the sea state and the particular active measurement technique.

Theoretical, laboratory, and pre-satellite field work at several frequencies in band 10 have shown that the effects of large gravity waves dominate at near-normal incidence and those of capillary waves at incidence angles greater than 20° [Wright, 1968]. Thus to sense sea roughness (a function of the very breeze-dependent ripples) and the size and direction of long-lived gravity waves (coarse sea structure), a two-component concept is used. In the study of ocean surface winds (important in weather prediction models), the underlying principle is that ocean roughness is a gauge by which wind variables can be inferred, since the small roughness elements which convey the transfer of momentum from the wind to the sea are in at least near equilibrium with the wind. Using variable frequencies, polarizations and incidence angles, investigators were able to infer details of ocean surface wind, significant wave height and mean square wave slopes, an accomplishment beyond the capabilities of passive sensing [Claasen *et al.*, 1973; Price, 1976; Weissman and Johnson, 1977]. Table V illustrates the history of wind studies using scatterometers which infer ocean roughness from backscatter measurements.

The Skylab S-193 radiometer/scatterometer/altimeter (RADSCAT) experiment was the first attempt to gather data using spaceborne, active microwave systems. Following this, the GEOS-3 altimeter provided measurements of mean sea level and ocean wave heights and the Seasat scatterometer provided data on the relationship between radar backscatter, ocean surface roughness, wind speed and incidence angle. The Seasat scatterometer (14.6 GHz) was able to provide wind estimates by taking pairs of orthonormal measurements [Price, 1976]. Experiments have shown that good wind speed sensitivity is obtained at the Seasat scatterometer frequency of 14.6 GHz and that there is a reduced sensitivity to wind speed at 1.3 GHz. The Seasat scatterometer used a Doppler filtering technique, and both the peak power (100 W) and bandwidth (800 kHz) requirements were moderate.

SARs are now showing promise in coarse ocean structure measurements (average significant wave height). An advanced SAR program (ASAR) will employ four frequency bands in the 1 to 10 GHz range and three polarizations with wide-swath and multiple-incidence angle capabilities as a further step in the development of SARs. The Seasat SAR collected data on ocean wave length and direction, which are currently being processed [Frost *et al.*, 1980].

While the first generation of operational radars will probably utilize a bandwidth comparable to that used by the Seasat SAR (19 MHz), it is probable that greater bandwidths will be required in the future to improve the range resolution. Also, because of the desirability of larger incident angles and higher resolution, it is possible that higher peak power output will be required than that used by the Seasat SAR (800 W).

TABLE V – *Compendium of experiments concerning the active sensing of ocean/water surface structure and winds*

Type of measurement and organization	Frequency (GHz)	Polarizations ([1]) combinations	Approximate range of angles of incidence (degrees)	Range of winds or waves
Space borne experiments:				
NASA	13.9	VV, VH, HV and HH	0 to 53	2.1 m/s to more than 28.3 m/s
Airborne experiments:				
Naval Research Laboratory	1.2; 4.4; 8.9	VV, VH, HV and HH	0 to 89	2.1 m/s to 24.7 m/s
NASA	13.3	VV	0 to 60	3.1 m/s to more than 28.3 m/s
NASA	13.9	VV, VH, HV and HH	0 to 50	3.1 m/s to 20,6 m/s
CRPE ([2])	5.3	VV, VH, HV and HH	0 to 60	0 to 25 m/s
From platform bridges:				
Naval Research Laboratory	9.4; 35	VV	0 to 80	0 to 12.9 m/s
CNES	3 to 18	HH, VV, HV and VH	0 to 60	0 to 25 m/s
Wave tank measurements:				
Naval Research Laboratory	9.375	VV and HH	10 to 86	Millimetre waves of wavelengths from 1.6 to 6 cm

([1]) VV: vertical transmit/vertical receive
VH: vertical transmit/horizontal receive
HH: horizontal transmit/horizontal receive
HV: horizontal transmit/vertical receive.

([2]) Centre de recherches en physique de l'environnement terrestre et planétaire.

Altimeters have been used successfully from a number of satellites over the world's oceans. The Seasat altimeter was designed to operate at 13.5 GHz and to measure ocean wave heights on a track directly beneath the satellite. A very large bandwidth (360 MHz) and relatively high peak power ($\approx$ 2.5 kW) were required in order to achieve a precision of 10 cm. For oceanographic satellites such as TOPEX, under study in the United States of America, an altimeter system having an overall range measurement precision better than 2 cm is required. To achieve 2 cm precision will require removal of the range errors due to ionospheric electron content which cause errors as great as 22 cm at 13.5 GHz [Goldhirsh and Rowland, 1982]. A two-frequency altimeter system [Goldhirsh and Rowland, 1982] can eliminate the range uncertainty due to the ionosphere. A two-frequency altimeter system can also provide accurate measurements of continuous swaths of the ionospheric electron content, measurements which are not available today over large regions of the Earth's oceans. A region of the spectrum, separated by more than an octave from the 13.4-14 GHz band, would be a suitable choice for the second frequency. The second frequency could be selected around 5 GHz, with the main frequency remaining near 14 GHz. It is thought that in the longer term, higher frequencies around 35 GHz could be used.

It can thus be seen that several frequencies have proven useful for the remote active sensing of ocean-wave structure. Due to high wind speed dynamic range and the relative absence of atmospheric effects, wind speed measurement technology is converging on the 10 to 15 GHz region.

5.2.3 *Active sensing of ice-covered surfaces*

Airborne investigations of Arctic ice fields at 400 MHz, and 1.2, 9.4, 10, 13.3 and 34.9 GHz [Anderson, 1966; Parashar, 1974] have found that ice variables which most affect radar return are surface roughness, material microstructure, ice liquid content, temperature and brine volume. A summary of all these investigations indicates that the following types of ice variables are amenable in varying degrees to active microwave sensing: ice-type (young, old, etc.), surface roughness, concentration, floe size and number, water openings, drift, surface topography, pressure characteristics, thickness and changes in nature and in distribution of types. Based on these studies, a frequency in band 10 appears to be the best for determining sea-ice types. Band 9 radar is useful in resolving ambiguities resulting from measurements of thin ice, especially when utilized in conjunction with band 10 radars. Higher frequencies are under study.

The most important spaceborne active microwave sensors for sea-ice application are the SAR, radar altimeter and radar scatterometer. Satellite research on sea-ice has been primarily carried out by Seasat. Airborne synthetic aperture radar imagery (1.3 GHz and 9.1 GHz) has shown that in some cases, including sea-ice mapping, the higher frequency channel is preferable. However, there are currently technical problems and risks associated with the development of a 9 GHz spaceborne synthetic aperture radar and the most probable frequency for the near-term development of spaceborne radars is near 1.3 GHz or 5 GHz with the possibility of future development at 9 GHz or even higher frequency. Although the interpretability of sea-ice imagery does improve with higher frequencies, there is no question of the usefulness of the product at 1.3 GHz. Altimeters have been used to map sea-ice parameters and the height of the Greenland ice-cap.

The usefulness of active microwave sensing of ice-cover parameters will be better understood as Seasat data continue to be analyzed.

5.2.4 *Meteorological observations*

The knowledge gained in ground-based and airborne measurement of rainfall, storm features and pressure fields in weather prediction models is being extended to spaceborne systems. The techniques are based upon changes in clear atmosphere refractive index due to rain-related features or differential reflectivities of multi-frequency echoes. Studies carried out with orthogonally polarized radars and multiple, narrow-beam coverage at several frequencies between 2 and 37.5 GHz [Skolnik, 1974; Goldhirsh and Katz, 1974; Atlas and Ulbrich, 1973; Okamoto *et al.*, 1982] have been able to measure precipitation rate, intensity, spatial distribution, drop size and surface pressure over oceans, and wind movements within storms. The results of flight experiments for rain-rate measurements by an airborne microwave scatterometer/radiometer system suggest the potential of spaceborne sensors for global mapping of rain rate [Okamoto *et al.*, 1982]. In the estimation of rain rate, it is desirable to complement radar measurements by data from radiometers [Masuko *et al.*, 1981]. There are several factors constraining frequency choices. A combination of bands must be chosen to match minimum rainfall sensitivity, yet not be swamped by Earth echo at needed viewing angles. Only downward-looking scanning pencil beams (as opposed to azimuthal or cross-track fan beams) have the capacity to infer rainfall intensity from altimeter estimates of the freezing layer. In the multi-frequency approach to rainfall measure, the correct comparison of attenuating/non-attenuating bands is called for to detect reflectivity changes.

5.2.5 *Active sensing of vegetation cover and soil moisture*

Interest in active sensing of soil moisture arose due to the limited spatial resolution of passive sensors. The amount of reflected radar power from the soil depends on soil roughness and dielectric constant, vegetation cover and incidence of the transmitted microwave beam. Early laboratory studies showed that soil moisture affects reflectivity of the soil due to changes in soil dielectric constant [Lundien, 1966]. Aircraft measurements of backscatter coefficient which show the effect of irrigation on the backscatter coefficient are plotted in Fig. 9. Usually, incidence angles less than 45° help distinguish roughness returns from moisture returns, whereas polarization regimens appear to offer little prospect of improving these results. Research, which utilized 4.7, 5.9 and 13.3 GHz [King, 1973; Ulaby *et al.*, 1974, 1975; Ulaby and Batlivala, 1976] indicates that a satellite scatterometer system operated at 4.7 GHz with 5° to 17° incidence angles could adequately distinguish soil moisture returns from those of vegetation cover and roughness. However, additional frequencies are needed when vegetation cover is a factor or when sub-soil measurements are required.

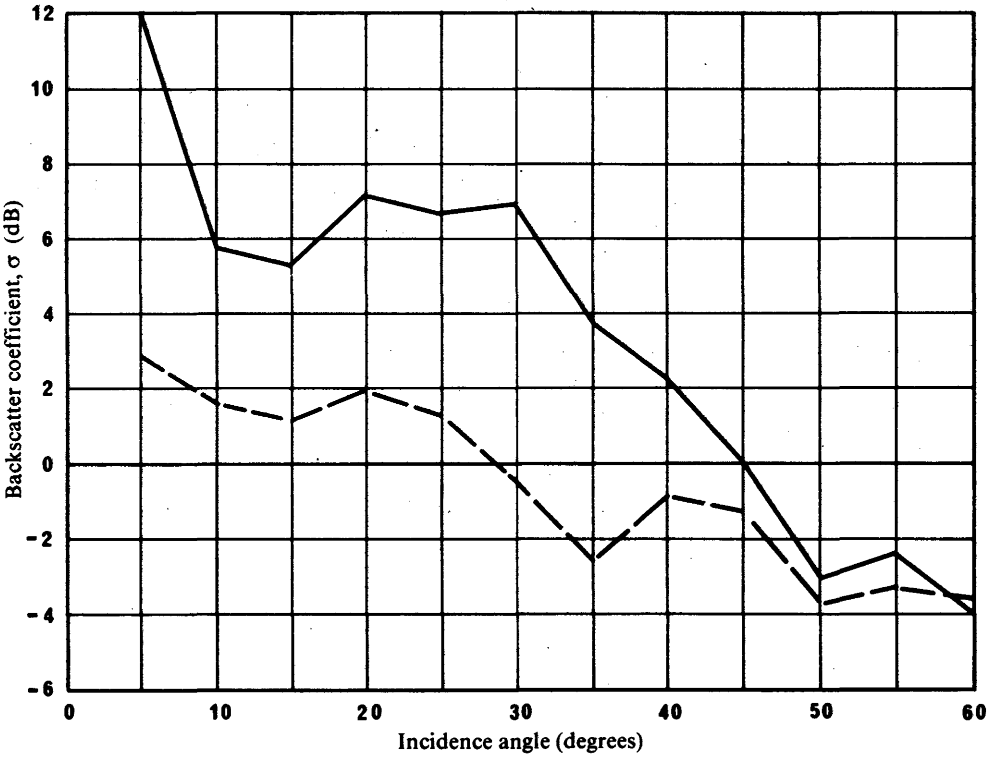

FIGURE 9 – *Dependence of radar backscatter on soil moisture at various incidence angles [King, 1973]*

Frequency: 13.3 GHz

Polarization: VV

——— After irrigation

– – – Before irrigation

On the other hand, vegetation cover has been studied as an objective, particularly in crop identification experiments, where soil returns become an obscuring factor. Both imagers and scatterometers have been used with the reflected power from vegetation being related to vegetation roughness, moisture and dielectric constant, and viewing angle. Results of these investigations indicate that satellites can be useful in active sensor identification of crops and forests, of land use patterns (range, forest, etc.) and of watershed parameters. Multi-spectral, multi-polarization, multi-temporal schemes of observation at high incidence angles (to minimize soil returns) have yielded promising results in research at 1.3, 5.9, 9.0, 9.4, 13, 16 and 35 GHz [De Loor *et al.*, 1974; Havalick *et al.*, 1970; Schuchman and Drake, 1974; Ulaby and Moore, 1973]. In crop studies in the 8 to 18 GHz range [Ulaby and Bush, 1975; Ulaby, 1976], crop classification was improved by taking growing periods into account, by employing several frequencies and by repeating measurements over several weeks. It can be seen in Fig. 10 that HH polarization yielded improved results over VV and a combination of HH and VV polarizations gave the best single-frequency results. The identification statistics can be improved to 91% using a combination of three frequencies (8.6, 13.3 and 16.6 GHz).

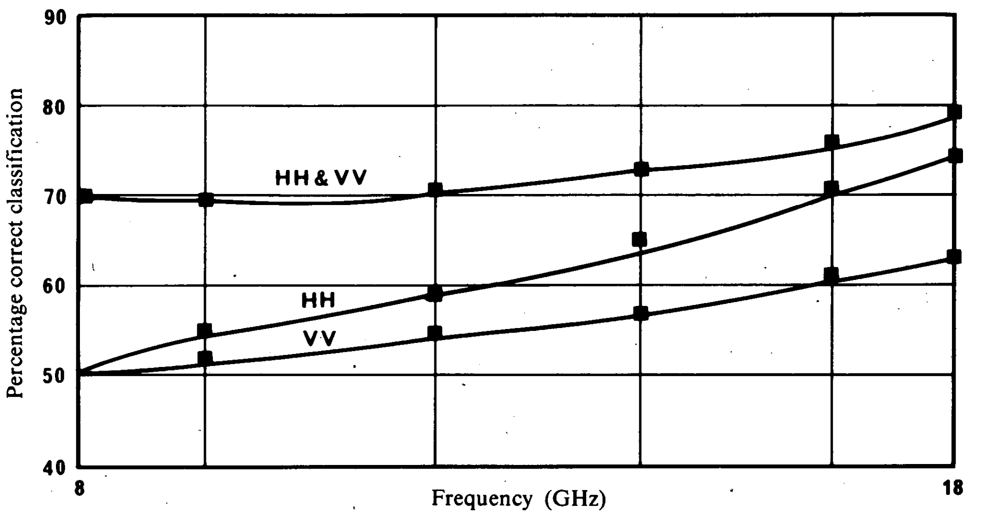

FIGURE 10 – *Crop classification accuracy versus frequency and polarization [Ulaby, 1976]*

(Radar spectrometer results)

Crops: wheat stubble
tall alfalfa
short alfalfa
short milo
tall milo
tall soybeans
green wheat

5.2.6 *Bandwidth requirements for active sensing*

Bandwidth requirements for active sensors vary with the type of sensor, i.e., synthetic aperture radar, real aperture radar, scatterometer or altimeter. In all cases, the bandwidth is determined by the required range resolution and is equal to:

$$B = \frac{1}{\tau} = \frac{c}{2\Delta R} \frac{1}{\cos \theta_d} \tag{6}$$

where:

B: bandwidth (Hz)

ΔR: range resolution (m)

c: speed of light (m/s)

θ_d: depression angle from satellite, or equivalently, arrival angle at Earth

τ: effective pulse duration (equivalent to the inverse of the pulse compression bandwidths) (s).

As an example, the synthetic aperture radar on Seasat had a range resolution of 25 m, a τ of 53 ns and a θ_d of 70°. The required bandwidth was therefore 19 MHz, which is the inverse of the effective pulse duration.

Applications envisaged by scientists using synthetic aperture radars will require greater bandwidth than the active sensors used on Seasat. A bandwidth of 100 MHz would be compatible with a large majority of applications.

Altimeters, used in applications such as geodetic mapping, require a greater bandwidth than do other types of active sensors. For example, the Seasat altimeter had a bandwidth of 360 MHz. Allowing for more precise future measurements, a bandwidth of 600 MHz would be appropriate for use by spaceborne altimeters.

5.2.7 *Summary of preferred frequencies for active sensing*

Although active microwave sensing technology is advancing rapidly and much still needs to be learned, a set of preferred frequencies can be defined which satisfy the specific measurement requirements discussed in § 5.2.2 and provide for multi-frequency measurements needed to separate signal contributions from different sources. Sharing considerations (Report 695 (Kyoto, 1978)) dictate that specific frequency bands for active sensors should be in bands shared with the radiolocation service. Thus, preferred frequencies for active spaceborne sensor measurements of the phenomena discussed in § 5.2.2 to 5.2.5 fall near 1, 3, 5, 10, 14, 17, 35 and 76 GHz. A bandwidth of 100 MHz is appropriate for all applications using active sensor instruments other than altimeters. Altimeter measurements may need up to 600 MHz bandwidth to satisfy accuracy requirements, but, at present, this requirement can be accommodated only in the band allocated near 14 GHz for active sensing. A second frequency band, with 600 MHz bandwidth would achieve 2 cm precision for the application of altimeters to oceanography. Two frequency bands which would be useful for achieving this precision are, for instance, around 5 GHz and 35 GHz. A variety of active microwave sensing instruments is summarized in Table II.

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REPORT 694-2*

SHARING CONSIDERATIONS AND PROTECTION CRITERIA RELATING TO PASSIVE MICROWAVE SENSORS

(Question 12/2 and Study Programme 12B/2)

(1978-1982-1986)

1. Introduction

The purposes of this Report are to evaluate the possibilities of sharing frequency bands between passive microwave sensors and stations of other services, and to develop sharing criteria where sharing is determined to be feasible.

Frequency bands ranging from below 1 GHz to above 300 GHz are needed to carry out microwave sensing applications being developed for earth exploration in earth resources, meteorology and oceanography. The extent to which sharing with other services is feasible will determine the need for dedicated or shared frequency bands and will affect the development of operational remote sensing systems.

Three potential methods for sharing common frequency bands between microwave sensors and other services are:

- simultaneous operations,
- time sharing,
- geographical separation.

Simultaneous sharing requires no operational constraints on the sharing services and is preferred. In bands where simultaneous sharing is not feasible, service characteristics may permit time sharing.

The third technique, geographical separation of interfering stations, may be applicable to certain remote sensing applications which are needed over areas of limited extent, such as estuarine salinity.

2. Microwave sensor factors pertinent to sharing

2.1 *Harmful interference criteria*

Radiometer sensitivities are generally expressed as a temperature differential (Report 224). This sensitivity is given by:

$$\Delta T_e = \frac{\alpha T_s}{\sqrt{Bt}} \qquad \text{(K)} \qquad (1)$$

where:

B: receiver bandwidth (Hz)

t: total time of observation (s)

α: receiver system constant

T_s: operating noise temperature (the sum of the receiver noise referred to the antenna terminal and that noise entering via the antenna) (K).

The radiometer threshold, or minimum discernible power change, is given by:

$$\Delta p = k \Delta T_e B \qquad \text{(W)} \qquad (2)$$

where: k = Boltzmann's constant, 1.38×10^{-23} J/K.

Harmful interference occurs when the unwanted signal at the receiving antenna is on a level comparable with Δp. The criterion used in this analysis is that interfering signal levels of greater than 20% of Δp constitute the threshold interference level (p_H). Therefore:

$$p_H = 0.2 \; k \Delta T_e B \qquad \text{(W)} \qquad (3)$$

* This Report should be brought to the attention of Study Groups 4, 8 and 9.

2.2 *Sensor performance parameters*

Key sensor characteristics which must be known in order to analyze interference potential include:

- interference threshold,
- antenna gain and pattern,
- geographical coverage requirements,
- frequency of measurements,
- spatial resolution,
- orbit.

3. Analysis approach

Preferred frequency bands for passive microwave sensors are listed in Recommendation 515. The potential for sharing between sensors and other services has been analysed for each frequency band. Typical equipment parameters for the stations of other services were used in the analyses. In bands where equipment has not yet been developed potential systems were postulated following applicable CCIR guidelines.

3.1 *Gain range factor analysis* ($g_t g_r / R^2$)

The gain range model is based upon a parametric analysis of potential interference situations. The harmful interference power, p_H, seen at the passive radiometric receiver is given by equation (3).

In relation to the interfering source,

$$p_H = \frac{p_t \, g_t \, g_r}{4\pi R^2} \left(\frac{\lambda^2}{4\pi} \right) \tag{4}$$

where:

g_t : numerical gain of transmitting antenna,

p_t : power of transmitting source (W),

g_r : numerical gain of receiver antenna,

λ : wavelength (m),

R : range (m).

Rearranging equation (4):

$$\frac{p_H \, (4\pi)^2}{p_t \, \lambda^2} = \frac{g_t g_r}{R^2} \tag{5}$$

A computer simulation of the right-hand side of equation (5) can be performed if the characteristics of the interference source are known and the interference threshold and orbit of the sensor are known. The gain range factor ($g_t g_r / R^2$) analysis determines the percentage of time and areas of geographical coverage lost to a spaceborne sensor when in view of a single terrestrial station.

3.2 *Random interference analysis programme*

The random interference analysis programme was developed to determine the cumulative effects of numerous terrestrial stations simultaneously visible to a spaceborne radiometer.

This technique utilizes a random number generator to place terrestrial stations within the field of view of the radiometer. The terrestrial stations are located at random great circle distances from the spacecraft sub-satellite point, and assigned a random pointing direction. Based upon the terrestrial and radiometer antennas and range to the spacecraft, the interference power at the input to the radiometer is calculated.

The random interference analysis programme is used to determine the probability of interference to a sensor as a function of the population of interfering stations.

4. Sharing considerations

Sensor interference thresholds, corresponding to the preferred frequency bands contained in Recommendation 515 together with applicable bandwidths related to the interference thresholds are given in Table I below. The values for the interference thresholds are determined using equation (3), the values for ΔT_e are given in Table IV of Report 693, and the values for bandwidth are given in Table I of this Report and Table III of Report 693.

The following paragraphs consider the feasibility of sharing between passive microwave sensors and stations in other services.

TABLE I – *Sensor interference thresholds*

Frequency (GHz)	Interference threshold (dBW)	Bandwidth (MHz)
Near 1.4	−165	100
Near 2.7	−166	60
Near 5	−158	200
Near 6	−158	400
Near 11	−156	100
Near 15	−160	200
Near 18	−152	200
Near 21	−160	200
22.237	−155	300
Near 24	−157	400
Near 30	−156	500
Near 37	−146	1000
Near 55	−157	250
Near 90	−138	6000
Above 100	−150	2000

4.1 *Sharing between passive sensors and the fixed service*

Each of the preferred frequency bands for passive sensors has been analysed using the gain range factor ($g_t g_r / R^2$) analysis programme and the random interference analysis programme. Annex I contains details of the analysis.

Simultaneous sharing between passive sensors and fixed service systems has been determined to be generally not feasible much below 10 GHz.

Time sharing with the fixed service is generally not feasible since operation of this service is usually continuous. Limited exceptions might be found where the fixed service is limited to day-time hours. In that case, sensors could operate during the night, so time sharing could be used.

Large areas of the Earth are, at present, interference-free for all bands because of the concentrated locations of the fixed stations. However, sensing applications cannot be performed over some major areas of interest, because of fixed service transmitters.

Above 20 GHz frequency sharing between passive sensors and the fixed service appears feasible due to increased atmospheric attenuation and assumptions as to the technical characteristics of the, as yet, undeveloped fixed service, which is expected to use low power wideband modulation techniques. Small areas of interference would occur for a direct overhead pass. Based on the assumptions and analyses performed, the resultant interference would have negligible impact on passive sensor operations.

Frequency sharing with the fixed service at 10 GHz would be feasible provided the maximum e.i.r.p. of a fixed or mobile station does not exceed 38 dBW and that the power delivered by a transmitter to the antenna of the fixed station does not exceed −1 dBW. Near 18 GHz the results of analysis, based on the assumptions used in Report 850 indicate that sharing would be feasible if the fixed service operated with gains greater than 40 dBi (beamwidth less than 1.6°) and powers less than 0 dBW (see Report 850 for details of sharing analysis and criteria near 18 GHz).

It would be necessary for future analyses near 18 GHz to model a high capacity route in a north-south orientation to consider the effects of low capacity distribution systems and to explore the effects at additional values of terrestrial antenna gain.

4.2 *Sharing between passive sensors and the mobile service*

Sharing between passive sensors and the mobile service below 10 GHz is generally not feasible (see Annex II).

Above 10 GHz sharing becomes progressively more feasible as frequency increases. However, in the 10-20 GHz range sharing criteria would be required if mobile systems were to operate in the fixed/mobile allocations jointly shared with passive sensors. See Report 850 for details of sharing analysis, and criteria for 18 GHz.

4.3 *Sharing between passive sensors and the fixed-satellite service (space-to-Earth)*

The feasibility of frequency sharing between sensors and fixed-satellite space-to-Earth transmissions has been analysed in the vicinity of 18 GHz and 37 GHz. Details of the 18 GHz analysis are contained in Report 850, while the 37 GHz analysis appears in Annex III.

The analysis was first performed assuming that the fixed-satellite e.i.r.p. would result in the maximum allowable pfd at the Earth's surface. Under this condition, interference to the sensor at 18 GHz would be 10 dB above the sensor interference threshold when the sensor is in the fixed-satellite main beam. Simultaneous operations at 18 GHz would therefore not be feasible.

An analysis was also performed to determine suitable sharing criteria that would allow frequency sharing between passive sensors and the fixed-satellite space-to-Earth link. It was determined that sharing is feasible provided that the gain of the fixed-satellite antenna is at least 52 dBi (beamwidth less than 0.4°) and the pfd limit is reduced by 10 dB. Other sets of sharing criteria are also possible (see Report 850).

The constraint on the fixed-satellite service to avoid harmful interference to passive sensors appears compatible with requirements of the international carriers, such as INTELSAT, where large size ($27 \leqslant G/T \leqslant 40$) earth stations are employed.

Sharing with the fixed-satellite service (space-to-Earth) at 37 GHz is feasible.

4.4 *Sharing between passive sensors and the fixed-satellite service (Earth-to-space)*

Sharing between passive sensor and fixed-satellite up-links was analysed in the vicinity of 2.6 GHz, 37 GHz and 50 GHz.

Simultaneous sharing at 2.6 GHz is not feasible, since loss of coverage due to interference from each fixed-satellite earth station would be 27% of the visibility sphere. Time sharing might be feasible if it is assumed that the fixed-satellite service uses this band only for thin-route, on-demand, low duty cycle operations.

Loss of coverage from a single fixed-satellite earth station in the vicinity of 37 GHz would be 2% of the visibility sphere and at 50 GHz would be only 0.24%. Results of the random interference analysis programme show that significant loss of data would occur if more than 15 earth stations were within the sensor field of view. Simultaneous operations in these bands are feasible if the fixed-satellite system employs a small number of earth stations.

4.5 *Sharing between passive sensors and the inter-satellite service*

The feasibility of frequency sharing by passive sensors and the inter-satellite service has been analysed in the region of 50 to 70 GHz and near 115 GHz. The analysis considered three possible configurations of inter-satellite link geometry:

– geostationary-to-geostationary satellite links;
– geostationary-to-low-orbit satellite links, and
– low-orbit-to-geostationary links.

Localized areas of interference could be encountered by a spaceborne sensor when:

– passing through the down-link tracking beam of the geostationary satellite,
– in close proximity to an up-link transmitting low-orbit satellite,
– pointing (for a limb sounder) directly at the geostationary satellite.

Cumulative side lobe interference from multiple inter-satellite links is not expected to be an important factor.

The technical characteristics assumed for the inter-satellite service are based on the hypothetical system model presented in Annex IV.

4.5.1 *Interference due to geostationary-to-geostationary satellite links*

Interference could occur only when the geostationary satellites are separated by more than 70 degrees of the geostationary arc. However, orientation of both nadir-pointing and limb sounding sensors will preclude the antenna couplings which would produce interference. No interference to sensor operations would occur.

4.5.2 *Interference due to geostationary-to-low-orbit satellite links*

Interference could occur for a limb sounding passive sensor but not for a nadir-looking passive sensor. In the former case, interference would occur for short periods of time if the sensor antenna were pointed at the main beam or side lobes of the geostationary satellite antenna. This situation would occur infrequently and be of short duration. The loss of data would be negligible; typically, less than 0.02%.

4.5.3 *Interference due to low-orbit-to-geostationary satellite links*

The only potential for large areas of interference would be due to side lobe to side lobe coupling between the passive sensor antenna and the low orbit satellite antenna. Interference would occur only if the two satellites were separated by less than 150 km. The probability of this occurrence is negligible.

4.5.4 *Conclusion*

Sharing on a simultaneous operational basis between passive sensors and the inter-satellite service is feasible.

4.6 *Sharing between passive sensors and the Aeronautical Radionavigation and Radiolocation Services*

Sharing between passive sensors and the Aeronautical Radionavigation and Radiolocation Services has been analysed for frequency bands near 1.4 GHz, 15 GHz, and above 100 GHz. Annex V contains details of methods of this analysis.

Transmitters in the Aeronautical Radionavigation and Radiolocation Services are typically pulse type radars.

The gain range factor analysis programme was used to simulate couplings between the passive sensor and transmitter antennas. The loss of coverage area for the passive sensor was found to be 100 per cent of the visibility sphere around the terrestrial stations. The population of transmitters is typically large in the bands that were analysed resulting in large areas of the Earth where passive sensing would not be possible.

Frequency sharing between passive sensors and either the aeronautical radionavigation service or the radiolocation service is in general not feasible. An exception to this conclusion is discussed in § 4.9.

4.7 *Sharing between passive sensors and the broadcasting-satellite service*

Sharing between passive sensors and the broadcasting-satellite service near 2.6 GHz was analysed.

There are two possible interference paths from a broadcasting-satellite to a low orbit satellite. Interference could either be received through the low-orbiting satellite antenna back lobe, or through reflection from the surface of the Earth into the radiometer main beam.

Calculations for the above cases show that interference to the passive sensor would be 22 to 33 dB above the sensor interference threshold.

Calculations for a broadcasting-satellite with side lobe gain discrimination meeting CCIR Recommendations and operating 3 time zones away from the sensor position show that interference would still exceed the sensor interference threshold. Therefore, time sharing is not feasible.

Sharing between passive sensors and the broadcasting-satellite service is not considered feasible either on a simultaneous operation or on a time sharing basis. Improved side lobe discrimination of the broadcasting-satellite could possibly permit time sharing on a limited scale.

4.8 *Sharing between passive sensors and the Mobile-Satellite Service*

Sharing between passive sensors and Mobile-Satellite Services has been analysed for frequency bands near 20 GHz, 37 GHz, and 50 GHz.

4.8.1 *Space-to-Earth mobile-satellite links*

Sharing calculations were based on a model of a hypothetical mobile-satellite system, using spread spectrum techniques as presented in Annex III.

Interference levels were determined to be below the sensor interference threshold so long as the mobile-satellites do not produce pfd levels at the surface of the Earth, in excess of -128 dB(W/(m^2 · MHz)) at 20 GHz and -117 dB(W/(m^2 · MHz)) at 37 GHz.

Sharing between passive sensors and mobile-satellite sensors is feasible if the mobile-satellites conform to the pfd limits given above.

4.8.2 *Earth-to-space mobile-satellite links*

The maximum interference level at the sensor occurs when the sensor is in the main beam of the mobile earth station. Interference levels of the order of 40 dB above the sensor threshold result.

An analysis of the gain range factor shows that approximately 2 per cent of the visibility sphere would be lost to the passive sensor at 37 GHz due to a single source of interference. At 50 GHz the corresponding loss would be 0.24 per cent.

The loss of data to a passive sensor would depend on the population of mobile-satellite earth stations and the percentage of time that each station may transmit.

Sharing between passive sensors and Earth-to-space mobile-satellite links is feasible for small numbers of mobile-satellite earth stations. Since loss of coverage would result and since the numbers of earth stations is largely unknown, sharing with mobile-satellite Earth-to-space links is undesirable and should be avoided.

4.9 *Sharing between passive sensors and airborne radio altimeters*

Sharing between passive sensors and radio altimeters operating in the aeronautical radionavigation service in the 4.2 to 4.4 GHz band has been analysed.

Both CW and pulsed type altimeters operate in this band. The two systems have average e.i.r.p. levels of approximately 5 dBW. Estimates of future use of the band indicate that of the order of 50 000 units may be in operation by the year 2000. A small percentage of these units may be configured to allow precision range finding as well as radar altimetry (see No. 789 of the Radio Regulations).

The passive sensor interference threshold would not be exceeded unless more than 3000 aircraft were simultaneously in view of the sensor. This is well above the predicted maximum number of 750 in view over coastal and ocean areas. Between 2000 and 4500 radar altimeter/precision range finding systems having characteristics as given in Annex V could also operate without exceeding the interference threshold of -158 dBW.

Simultaneous sharing with radio altimeters is therefore feasible. The criterion for sharing is that transmitters in the Aeronautical Radionavigation Service employ average output powers of the order of -5 dBW.

4.10 *Sharing between passive sensors and radioastronomy*

The only potential for interference to the Radioastronomy Service would be due to local oscillator leakage and emission through the spacecraft antenna. Based on radioastronomy sharing criteria as presented in Report 224, the analysis indicated that no harmful interference would occur to the Radioastronomy Service. Hence simultaneous sharing is feasible.

Radio astronomers have suggested that, if practicable, designers should choose local oscillator frequencies so that they lie on the upper side of those radioastronomy bands in which line emission has been detected from distant galaxies by the use of high gain antennas (Recommendation 314).

5. Conclusions

Frequency sharing between passive sensors and the fixed service appears feasible above 20 GHz.

Frequency sharing with the fixed service at 10 GHz is feasible only provided that the maximum e.i.r.p. of a station in the fixed service does not exceed 38 dBW, and that the power delivered by a transmitter to the antenna of a station in the fixed or mobile service does not exceed about −1 dBW. Other sets of sharing criteria are possible. For example, sharing is feasible for an e.i.r.p. of 40 dBW and a maximum transmitter output power of −3 dBW, the fixed service limits in the 10.6-10.68 GHz band. Near 18 GHz the results of analysis, based on the assumptions used in Report 850, indicate that sharing is feasible with the fixed service if the antenna gain is at least 40 dBi and the transmitter power less than 1 W. Sharing is feasible with the mobile service if the transmitter power is less than −5 dBW. However, there are fixed systems operating in the 10 GHz range, other than the 10.6-10.7 GHz band, which exceed these criteria by at least an order of magnitude. Also, present regulations permit operation of fixed and mobile systems with 10 dBW input power to the antenna except at 10.6-10.68 GHz. If these maximum allowable levels are used, sharing would not be feasible. Further improvement of prototype fixed systems around 20 GHz might also result in parameters which would exceed the criteria. Analysis shows, however, that many fixed and mobile applications are compatible with the stated criteria.

Frequency sharing with the fixed and mobile services much below 10 GHz is generally not feasible. However, large areas of the Earth's oceans will be interference-free for passive sensing in common frequency bands.

Frequency sharing with fixed-satellite and mobile-satellite space-to-Earth links between 15 GHz and 20 GHz is feasible provided the gain of the fixed-satellite antenna is at least 52 dBi and the pfd limit is reduced by 10 dB. Other sets of sharing criteria are also possible (see Report 850).

Sharing with fixed and mobile-satellite Earth-to-space links is of limited feasibility and should be avoided if possible, the amount of data loss being highly dependent upon the number of earth stations in the fixed and mobile-satellite systems (see Annex III).

Sharing with the broadcasting-satellite service is not feasible, except that time sharing may be feasible on a limited basis if the broadcasting-satellite employs state-of-the-art antenna side-lobe control.

Sharing with the radiolocation and aeronautical radionavigation services is feasible only in bands used exclusively for radio altimeters (see Annex V).

Future studies of the feasibility of passive sensor sharing with active services near 18 GHz should include analysis of factors described in the conclusion of Report 850.

ANNEX I

ANALYSIS OF SHARING FEASIBILITY BETWEEN PASSIVE SENSORS AND THE FIXED SERVICE NEAR 1.4 GHz, 10 GHz, AND ABOVE 21 GHz

1. Introduction

This Annex illustrates the techniques used to determine the feasibility of frequency sharing between passive microwave sensors and the fixed service, by performing interference analyses at 1.4 GHz, 10 GHz and above 21 GHz. The results of the 1.4 GHz analysis are typical for bands below 10 GHz, and the results of the 21 GHz analysis are typical for bands above 20 GHz.

2. Sharing feasibility near 1.4 GHz

At a frequency near 1.4 GHz the sensor interference threshold is −165 dBW in a bandwidth of 100 MHz.

The maximum interference level occurs when the sensor is located in the main beam of the interference source. In the fixed service this takes place when the spacecraft is on the horizon as seen from the terrestrial station. The altitude of the satellite is assumed to be 500 km.

The maximum allowable e.i.r.p. of the terrestrial station in order for the interference threshold not to be exceeded, is computed as follows:

Interference threshold	−165 dBW
Spreading loss ($4\pi R^2$, R in m)	−139 dB/m^2
Atmospheric loss	0 dB
Sensor antenna effective area (side lobe −14 dBi), S in m^2; 10 log S =	− 38
Maximum allowable e.i.r.p.	12 dBW

Fixed stations operating near 1.4 GHz, however, typically have an e.i.r.p. in the range 37 to 55 dBW.

The loss of passive sensor coverage area due to a single fixed station is determined, by the gain range factor $g_t g_r / R^2$ analysis, to range from 5% to 94% of the visibility sphere around the terrestrial station.

Results of simulation of the multiple-source interference environment using the random interference analysis programme show that 5 or more transmitters in view of the sensor would produce total loss of data (Fig. 1).

Simultaneous sharing between sensors and fixed and mobile stations in the vicinity of 1.4 GHz is not feasible since more than 5 transmitters would be in view of the sensor over large areas of the Earth.

Time sharing in this frequency band is not feasible because the fixed service stations operating in the band are generally used for common carrier point-to-point service. Such operations are generally continuous in nature.

Operations of sensors over areas of the Earth out of view of fixed and mobile stations is feasible. Figure 2 shows the areas of the world where total loss of data is expected, based on IFRB Master Register entries for transmitter locations operating in a band 100 MHz wide near 1.4 GHz.

3. Sharing feasibility near 10 GHz

The interference threshold of a passive sensor operating near 10 GHz is −156 dBW in a bandwidth of 100 MHz.

There are three potential interference paths that must be analysed:

– interference which occurs when the sensor is located in the main beam of one or more interference sources,
– interference due to additive effects of the side lobe coupling from multiple interference sources, and
– interference caused during a direct pass over an interfering source in the main beam of the radiometer.

Each interference path is analysed below to determine the maximum allowable e.i.r.p. and transmitted power of the terrestrial station, which would permit frequency band sharing with passive sensors. The analyses are based on a population of 10 000 interfering stations within the view of the sensor.

3.1 *Interference contributions from coupling to main beams of interfering sources*

Half the allowable interference level, or −159 dBW, will be assigned as the contribution from main-beam coupling to the radiometer side lobes when the radiometer is located in the main beam of one or more fixed service transmitters.

The permissible e.i.r.p. of the source of interference can then be calculated as follows:

Interference level	−159 dBW
Spreading loss ($4\pi R^2$; R in m)	−139 dB/m^2
Atmospheric loss	− 5 dB
Sensor antenna effective area (side lobe), S in m^2; 10 log S =	− 58
Three sources of interference	+ 5 dB
Maximum allowable e.i.r.p.	+ 38 dBW

The interference level of −159 dBW will be exceeded whenever the sensor is located in the main beam of four or more sources. Assuming uniform distribution of sources, this condition would occur 2% of the time for a population of 10 000 sources.

3.2 *Interference contributions from coupling into side lobes of sources*

Half the allowable interference level, or −159 dBW, will be assigned as the contribution from the additive effects of side-lobe coupling of multiple sources into the radiometer side lobes.

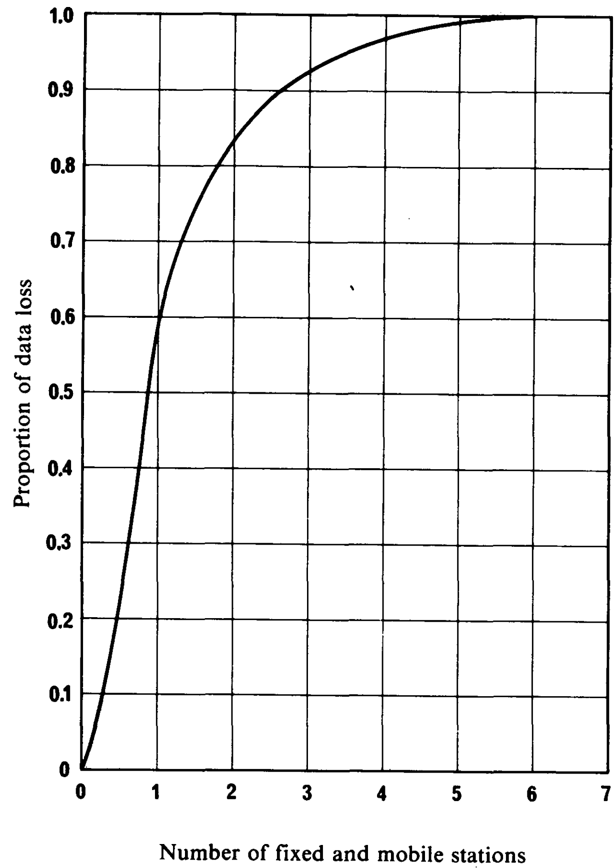

FIGURE 1 – *Data loss versus number of fixed and mobile stations*

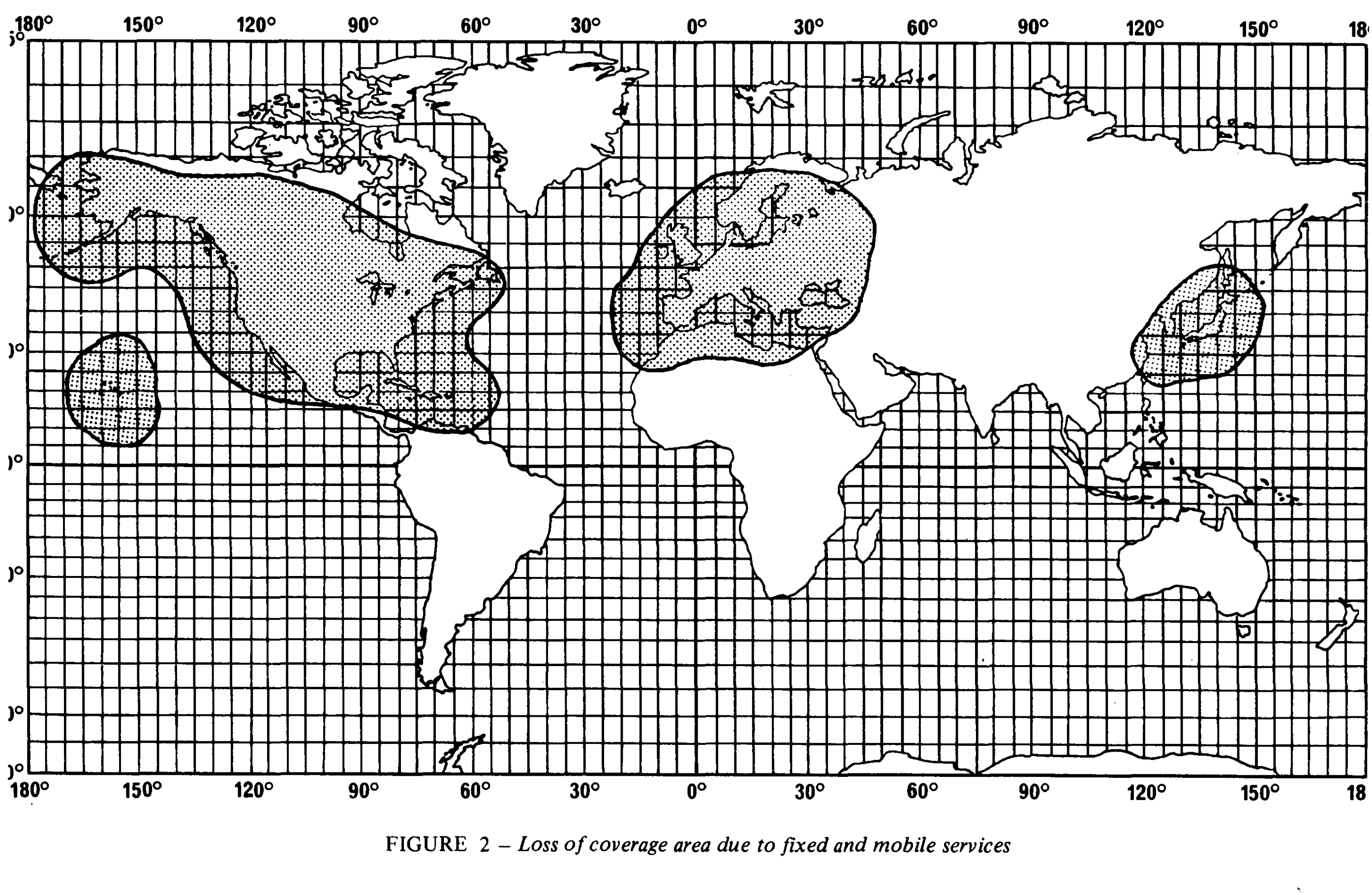

FIGURE 2 – *Loss of coverage area due to fixed and mobile services*

The maximum acceptable power of the interfering transmitter can then be calculated as follows:

Interference level	−159 dBW
Transmitting antenna gain (side lobe)	− 10 dBi
Spreading loss (average) ($4\pi R^2$; R in m)	−130 dB/m^2
Atmospheric loss (average)	− 0.2 dB
Sensor antenna effective area (side lobe), S in m^2; 10 log S =	− 58
10 000 sources	+ 40 dB
Maximum allowable transmitted power	− 0.8 dBW

3.3 *Interference contribution from coupling to main beams of sensors*

Direct pass over of an interfering transmitter will cause interference while the transmitter is in the main beam of the radiometer. This interference level can be calculated as follows:

Transmitted power	− 1 dBW
Transmitting antenna gain (side lobe)	− 10 dBi
Spreading loss ($4\pi R^2$; R in m)	−125 dB/m^2
Sensor antenna effective area, S in m^2; 10 log S =	+ 13
Interference level	−123 dBW

This interference level would exceed the interference threshold by 36 dB and would occur whenever the radiometer antenna main beam axis was aligned within 0.5 degrees of the interferer. Interference would occur over an area of 61 km^2 on the Earth's surface around each interfering source. The percentage data loss, assuming uniform distribution of sources, is:

Area loss from one source	61 km^2
10 000 sources	610 × 10^3
Area within view of sensor	2 × 10^7 km^2
Percentage total area loss	3%

3.4 *Sharing potential*

Frequency sharing near 10 GHz between passive sensors and the fixed service is feasible provided the fixed service is limited to a maximum e.i.r.p. of the order of 38 dBW, and a maximum transmitter output power not exceeding −1 dBW. Other sets of sharing criteria are also possible. For example, sharing is feasible for an e.i.r.p. of 40 dBW and a maximum transmitter output power of −3 dBW.

The above constraints appear compatible with characteristics of fixed equipment using the low power wideband modulation techniques which the fixed service is expected to employ when frequency bands near 10 GHz are developed.

4. Sharing feasibility near 21 GHz and above

Technical characteristics of the as yet undeveloped fixed and mobile services in the 21.2-22 GHz band have been assumed to be based upon information given in Reports 387, 609, and 610. These documents are concerned with broadband, high capacity digital transmission.

In such systems, a high speed digital signal is used to modulate the RF carrier by means of phase-shift-keying. In the United States, the signal is 4-level at 137 MBaud (274 Mbit/s); in Japan, 4-level at 200 MBaud (400 Mbit/s); and in some European countries, a 4-level signal at 70 MBaud (140 Mbit/s) is planned.

The transmitter characteristics modelled in Report 387 were chosen as being representative of a low power system reasonably deserving of satellite power flux-density protection, and which, by their nature are likely to be controlling in the determination of permissible values. These low power system characteristics are given below but eventual transmitter powers for many systems may be substantially higher.

Transmitted power	−13 dBW
Transmitter antenna gain	43.5 dBi
Transmitted e.i.r.p.	30.5 dBW

The system design is based on link lengths of 10 km, a fading margin of about 45 dB, and a transmission bandwidth of 220 MHz.

The interference level in the main beam of a single interference source would occur at the horizon as seen from a fixed or mobile service transmitter. The level of this interference would be:

Transmitted power	– 13 dBW
Transmitter antenna gain	43.5 dBi
Spreading loss	–139 dB
Atmospheric absorption	– 25 dB
Radiometer antenna effective area (side lobe) S in m^2; 10 log S =	– 61.4
Interference level	–194.9 dBW

This is 34.9 dB below the radiometer interference threshold level of –160 dBW. Thus, the radiometer would have to be within the main beam of 3000 fixed-service transmitters in order to reach the interference threshold. The probability of this occurrence is negligible.

The population of interference sources which would result in interference levels equal to the sensor threshold of –160 dBW, due to additive effects of side lobe coupling, can be calculated as follows:

Transmitted power	– 13 dBW
Transmitter antenna gain (side lobe)	– 10 dBi
Spreading loss (average) ($4\pi R^2$; R in m)	–130 dB/m^2
Atmospheric loss (average)	– 0.6 dB
Sensor antenna effective area (side lobe) S in m^2; 10 log S =	– 62.1
Interference threshold	–160 dBW
Margin below threshold	55.7 dB

A population of 380 000 transmitters would therefore, be required, for this threshold to be exceeded.

Sharing on a simultaneous basis between passive sensors and the fixed service thus appears feasible at and above 21 GHz based on examination of the impact of a population of low-powered radio-relay systems. Based on the substantial interference margins estimated, no special constraints need be imposed on the fixed service.

ANNEX II

ANALYSIS OF SHARING FEASIBILITY BETWEEN PASSIVE SENSORS AND THE MOBILE SERVICES

1. Introduction

This Annex examines the feasibility of sharing between passive microwave sensors and mobile systems at 1.4 and 21 GHz (assumed satellite altitude is 500 km). The 1.4 GHz analysis is representative of sharing below 10 GHz while the 21 GHz analysis is representative of sharing above 10 GHz.

2. Sharing feasibility near 1.4 GHz

At a frequency near 1.4 GHz the sensor interference threshold is –165 dBW in a bandwidth of 100 MHz. The maximum interference level occurs when the sensor is located in the main beam of the interference source.

The maximum allowable e.i.r.p. of the terrestrial station, in order for the interference threshold not to be exceeded, is computed as follows:

Interference threshold	–165 dBW
Sensor antenna effective area (side lobe), S in m^2; 10 log S =	– 38
Spreading loss ($4\pi R^2$; R in m)	–130 dB/m^2
Atmospheric loss	0 dB
Maximum allowable e.i.r.p.	3 dBW

Since mobile systems generally are omnidirectional, a single transmitter in view of the satellite could have 3 dBW of power. However, mobile systems are developed in networks and thus many hundreds or thousands could be expected. For example, 10 000 transmitters simultaneously in view would have to have individual powers less than –37 dBW; for 1000 transmitters only –27 dBW.

Thus, it is expected that realistic mobile systems, if they were in use in the preferred passive sensor bands, would produce unacceptable levels of interference whenever the sensors were near or over land. Thus, sharing with mobile systems below 10 GHz is not considered generally feasible.

3. Sharing feasibility near 21 GHz and above

At a frequency near 21 GHz the sensor interference threshold is -160 dBW.

The maximum allowable e.i.r.p. of a terrestrial station in order for the interference threshold not to be exceeded is computed as follows:

Interference threshold	-160 dBW
Sensor antenna effective area (side lobe) S in m^2; 10 log S =	$-$ 62.1 dB
Spreading loss (average) ($4\pi R^2$; R in m)	-130 dB/m^2
Atmospheric loss	$-$ 0.6 dB
Allowable e.i.r.p.	32.7 dBW

With an omnidirectional antenna, one transmitter could have 32.7 dBW of power. For 10 000 transmitters, each transmitter must have less than -7.3 dBW of power; for 1000 transmitters, the power must be less than 2.7 dBW per transmitter.

ANNEX III

ANALYSIS OF SHARING FEASIBILITY BETWEEN PASSIVE SENSORS AND THE FIXED-SATELLITE AND MOBILE-SATELLITE SERVICES NEAR 37 GHz

1. Introduction

This Annex illustrates the techniques used to determine the feasibility of frequency sharing between passive microwave sensors and the fixed and mobile-satellite services. (Assumed satellite altitude is 500 km.)

2. Sharing feasibility with the fixed and mobile-satellite service near 37 GHz

Rain rate, snow, ocean ice, oil spills, and clouds are the measurements which require a frequency near 37 GHz. Sensor interference threshold is -146 dBW for these measurements.

The analysis contained herein is based upon the assumed use of a broadband spread-spectrum system for the fixed and mobile-satellite space-to-Earth link.

The Earth-to-space links are assumed to have characteristics similar to those presently operating at lower frequencies. The transponders may be equipped with both spot beam as well as full coverage antennas. Up-link transmitter powers must be adequate to drive the transponder when a full coverage antenna is used. It is estimated that the fixed and mobile-satellite up-link parameters will be as follows:

	Fixed	*Mobile*
Transmitter power	29 dBW	41 dBW
Antenna gain	57 dBi	45 dBi
Transmit e.i.r.p.	86 dBW	86 dBW

Data are not available relating to the technical operational characteristics of fixed and mobile-satellite system down-links. However, some base-line characteristics can lead, with proper assumptions, to an estimate of the required satellite e.i.r.p. (assuming spread-spectrum techniques) in order to meet the link budget as follows:

$$\text{Required e.i.r.p.} = C_0/N_0 + L_S - A_r + k + T_R \qquad (\text{dB(W/Hz)}) \tag{6}$$

where:

C_0/N_0:	earth station required carrier-to-noise density ratio (+10 dB)	
L_S:	spreading loss ($4\pi R^2$; R in m)	162 dB/m^2
A_r:	earth station receiver effective area S in m^2; 10 log S =	$-$ 3
T_R:	earth station receiver noise temperature	33 dBK
k:	Boltzmann's constant	-228.6 dB

Therefore, the required mobile-satellite e.i.r.p. is:

Required e.i.r.p. = +10 + 162 + 3 − 228.6 + 33 = −21 dB(W/Hz).

The maximum interference level at the radiometer due to Earth-to-space transmission from a single interference source will occur when the radiometer is in the main beam of a fixed or mobile earth station. Assuming a 30° elevation angle of the earth station, this interference level would be:

Transmitter power of a typical mobile earth station	41 dBW
Antenna gain	45 dBi
Spreading loss (30° elevation angle)	−130 dB/m^2
Atmospheric absorption	− 0.5 dB
Radiometer antenna effective area (side lobe) S in m^2; 10 log S =	− 67
Power into radiometer	−111.5 dBW

or 34.5 dB above the radiometer interference threshold of −146 dBW.

Figure 3 illustrates the loss of coverage area resulting from operation of a single fixed or mobile-satellite earth station. The analysis is based on the gain range factor programme analysis procedure. The area lost corresponds to approximately 2% of the total visibility sphere around the earth station. The analysis assumes a 30° elevation of the earth station antenna directed to the geostationary satellite orbit.

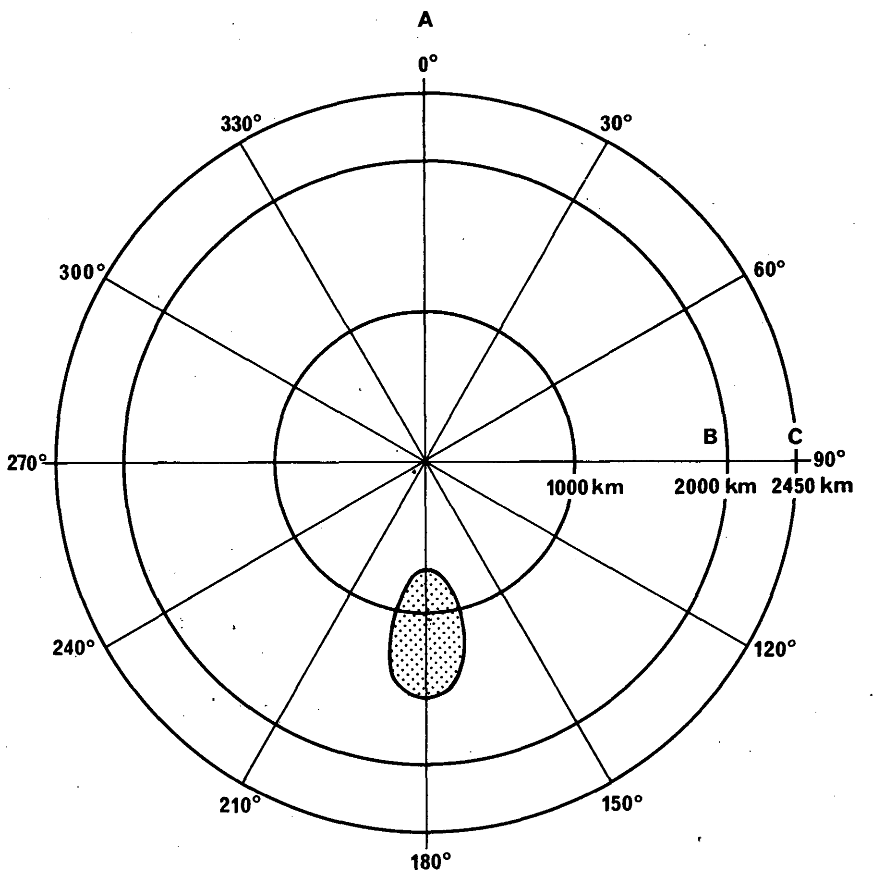

FIGURE 3 – *Map showing loss of coverage area (fixed and mobile-satellite services)*

A : pointing azimuth

B : great circle distance

C : horizon

Note. – Dotted area indicates the region where interference, and therefore loss of coverage, occurs. Earth station is located at the centre.

Figure 4 presents the results of the random interference analysis programme relating the amount of data loss to the number of fixed and mobile earth stations visible to the radiometer. As can be seen, large loss of data would occur if 15 dispersed earth stations are simultaneously in view. However, it is estimated that spatial density of earth terminals would not be so great. Additionally, many of the earth stations may be shipborne, and therefore would not be fixed interference sources.

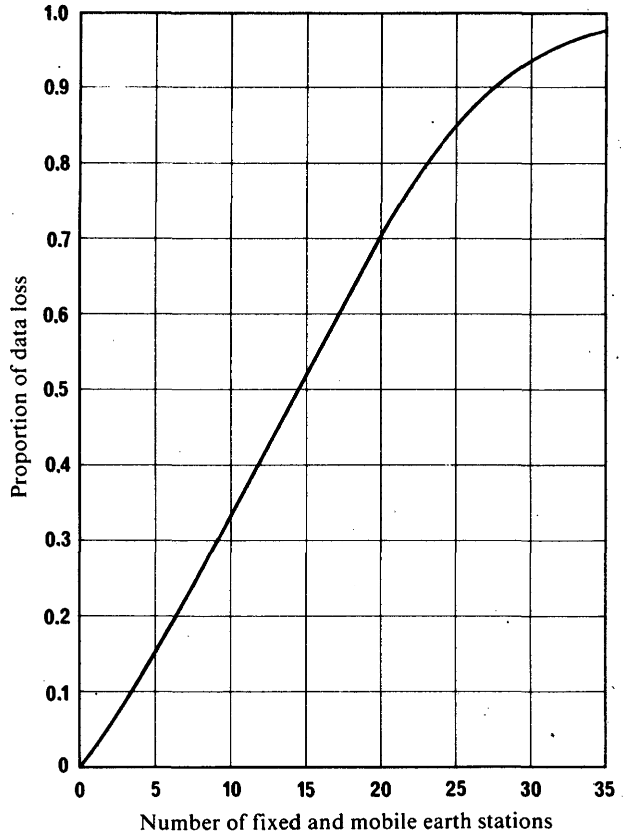

FIGURE 4 – *Data loss versus number of fixed and mobile earth stations*

The interference level produced by fixed and mobile-satellite down-link operations may occur from a reflected path in the main beam of the radiometer, or from a direct link through the back lobe of the radiometer antenna.

The level of interference produced from reflected energy is calculated below:

Fixed or mobile-satellite e.i.r.p.	– 21 dB(W/Hz)
Atmospheric attenuation	– 0.3 dB
Spreading loss to Earth ($4\pi R^2$; R in m)	–162 dB/m^2
Reflection coefficient	– 3 dB
Atmospheric attenuation	– 0.3 dB
Spreading loss to 500 km orbit	–125 dB/m^2
Area in view to radiometer main beam, A in m^2; 10 log A =	+ 57.7
Effective area of radiometer antenna (main beam), S in m^2; 10 log S =	+ 12
Interference level	–241.9 dB(W/Hz)

or –151.9 dBW in the 1000 MHz bandwidth of the radiometer, or 5.9 dB below the radiometer interference threshold of –146 dBW.

Interference entering the radiometer via the back lobe constitutes a lower level as seen by the following:

Mobile-satellite e.i.r.p.	− 21 dB(W/Hz)
Spreading loss	−162 dB/m^2
Radiometer antenna effective area (back lobe) S in m^2; 10 log S =	− 70
Interference level	−252 dB(W/Hz)

or −162 dBW in the 1000 MHz radiometer bandwidth, or 16 dB below the radiometer interference threshold.

The dominant mode of down-link interference is by reflection from the Earth. This interference will not affect sensor operation unless the radiometer is simultaneously in the main beam of more than four spacecraft. The probability of this occurrence is very small. Therefore, simultaneous sharing with the down link is feasible.

Simultaneous operation between spaceborne passive microwave sensors and the Fixed and Mobile-Satellite Service at 37 GHz is feasible. This conclusion is predicted on the assumption that the number of fixed and mobile earth stations will be small (< 30). Additionally, the number of stations which would be in view simultaneously is assumed to be small.

ANNEX IV

ANALYSIS OF SHARING FEASIBILITY BETWEEN PASSIVE SENSORS AND THE INTER-SATELLITE SERVICE IN THE 50-70 GHz REGION

1. Introduction

Measurements of thermal microwave radiation near the oxygen spectral lines in the 50 to 70 GHz region of the spectrum can be used to determine temperature profiles in the Earth's atmosphere.

This Annex presents the techniques and models needed to determine the feasibility of sharing frequency bands with the inter-satellite service. The example analysis which follows is performed for a frequency of 55 GHz.

2. Sensor technical parameters

Technical parameters for low orbit nadir-looking and limb-looking sensors in the 50 to 70 GHz range are:

	Nadir-looking	*Limb-looking*
Range	−70 to +30 °C	−70 to +30 °C
Accuracy	3 °C	3 °C
Sensitivity	1 K	0.3 K
Resolution	10 km	1 km (vertical)
Update rate	2 per day	2 per day
Integration time	1 s	1 s
Bandwidth	235 MHz	235 MHz
Sensor interference threshold	−157 dBW	−157 dBW
Orbital altitude	500 km, circular	500 km, circular
Inclination	70 to 110°	70 to 110°
Antenna	0.3 m	3 × 12 m

3. Inter-Satellite Service technical parameters

There are three possible inter-satellite service transmission links that must be analysed for interference with sensor operations:

- geostationary-to-geostationary satellite links,
- geostationary-to-low orbit satellite links, and
- low orbit-to-geostationary links.

3.1 *Geostationary-to-geostationary satellite models*

Separate models have been developed for geostationary communication satellites using non-tracking and tracking satellite antenna systems. The principal difference between these two models is that the antenna beamwidth of the non-tracking system must be large enough to accommodate the relative angular motions of both the transmitting and receiving spacecraft.

One of the models used to describe the non-tracking geostationary-to-geostationary inter-satellite systems is based on information contained in Report 451.

Figure 5 shows relative angular error due to station keeping uncertainties as given in Report 451.

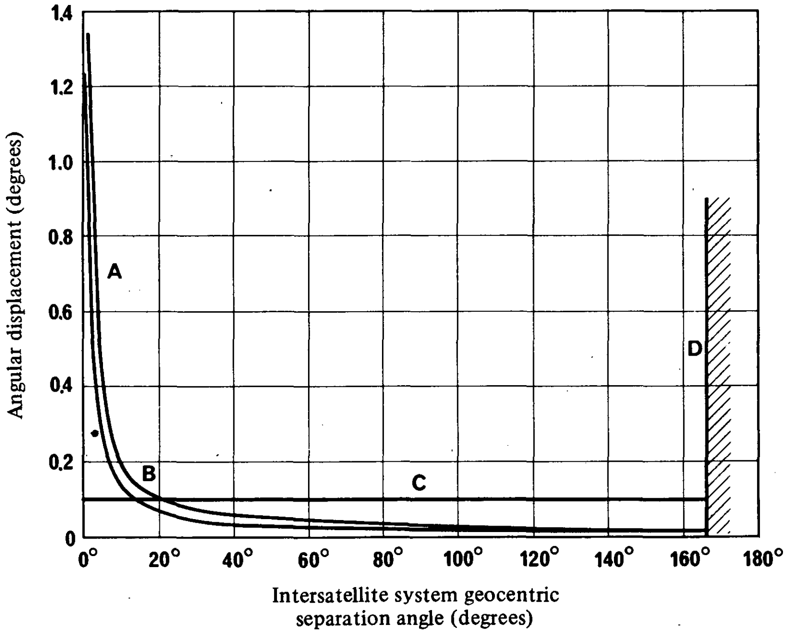

FIGURE 5 – *Relative angular error due to station keeping uncertainties*

A: North-South component

B: Altitude component

C: East-West component

D: Earth blockage

Equation (7) gives the power required by the transmitting satellite as a function of satellite separation, antenna diameters, frequency and other link and physical parameters of the inter-satellite system.

$$p = \frac{(C/N)\, kT(f)\, b}{g_r\, g_t} \left(\frac{\lambda}{4\pi R} \right)^{-2} \tag{7}$$

where:

g : main beam gain $= (\pi D/\lambda)^2 \eta$

η : aperture efficiency

f : frequency (GHz)

λ : wave length (m)

$T(f)$: receiver temperature at frequency $f = 9000\ \sqrt{f/55}$

p : power (W)

D : antenna diameter (m)

R : range (m) $= R_g \sqrt{2(1 - \cos\theta)}$

R_g : distance from geostationary satellite to centre of Earth

θ : geocentric separation angle (degrees)

k : 1.38×10^{-23} W/(K · Hz) = Boltzmann's constant

b : bandwidth (Hz)

C/N : carrier-to-noise ratio

Three of the terms shown in equation (7) require explanation. The receiver noise temperature variation with frequency, $T(f)$, is based on a noise figure of 15 dB at 55 GHz. The bandwidth and carrier-to-noise ratio chosen for the non-tracking model are 100 MHz and 30 dB respectively. These values are typical of communication links that may be used by INTELSAT type traffic (i.e., generally multiplexed voice traffic). Since the service requirements for commercial traffic are generally quite high, these requirements represent a practical worst case for development of the transmit power for non-tracking systems.

One of the principal reasons for utilizing inter-satellite links is the reduction of the time delay which would occur over a fixed satellite two-hop link. Since two inter-satellite spacecraft having an orbital separation of 30°, would have 66% of the time delay of full two-hop system, it would be expected that commercial voice traffic would be restricted to inter-satellite communciations between relatively closely spaced spacecraft.

The remaining models are based on inter-satellite systems which do not utilize INTELSAT type traffic. For example, Earth resource images, or other types of wide band digital data, may be relayed between geostationary spacecraft.

Figure 6 presents the inter-satellite transmit power requirement for the tracking antenna system model and for two different non-tracking system models as a function of spacecraft orbital separation. The results are plotted for non-tracking systems with antenna diameters of 1.2 and 2 m. The tracking system is assumed to utilize a 0.1° beamwidth antenna.

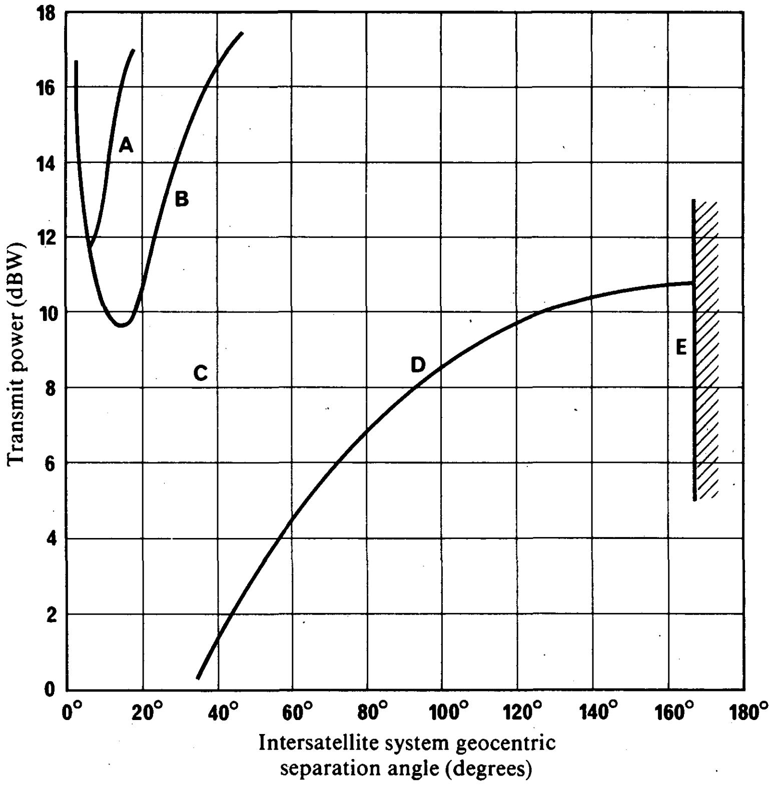

FIGURE 6 – *Inter-satellite system required transmit power at 55 GHz*

A : 1.2 m antenna diameter limitation
B : 2 m antenna diameter limitation
C : non-tracking system
D : tracking system
E : Earth blockage

These models lead to parameters which may be reasonable for inter-satellite systems in the 50 to 70 GHz portion of the spectrum, that is, maximum antenna sizes of either 2 m for the non-tracking system (i.e., compatible with large launch vehicles) or 4 m for the tracking systems (compatible with shuttle type payloads).

3.2 *Geostationary-to-low orbit satellite model*

The technical characteristics of geostationary/low orbit links in the Inter-Satellite Service have been estimated using an assumed design employing spread-spectrum techniques. The design parameters are as follows:

- Required predetection carrier-to-noise ratio: 10 dB
- Receiver noise: 15 dB
- Transmission bandwidth: 2 GHz
- Geostationary satellite antenna gain: 60 dBi
- Low orbit satellite antenna gain: 50 dBi

The satellite transmitter power required to permit communications over the link can be computed by:

$$P_t = N + 10 \text{ dB} - G_t - A_r + L \tag{8}$$

where:

N: receiver noise power,

G_t: transmitting antenna gain,

A_r: receiving antenna effective area,

L: spreading loss.

At 55 GHz the required transmitter power is 23.1 dBW.

4. Sharing feasibility

4.1 *Geostationary-to-geostationary satellite case*

Figure 7 illustrates the worst case interference level received by a radiometer when two geostationary satellites are communicating with one another. Additionally, the interference threshold for the radiometer is shown by the dashed line. As illustrated in Fig. 7, no interference will occur. Interference threshold is approached only when the main beam of the transmitting inter-satellite spacecraft approaches the Earth – even as in this case, the interference is 10.7 dB below the threshold of the radiometer.

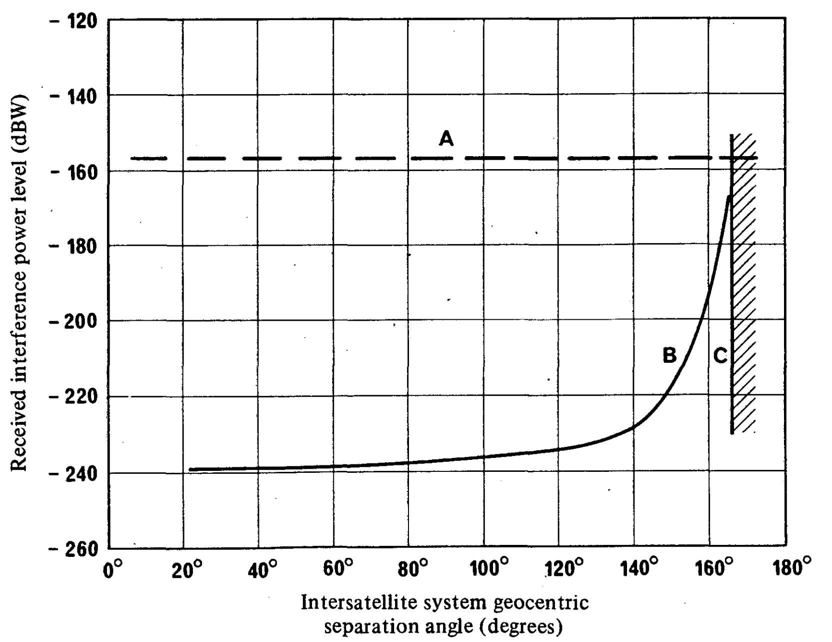

FIGURE 7 – *Worst case interference power received by nadir-looking radiometer at 55 GHz*

A: Interference threshold

B: Tracking system

C: Earth blockage

4.2 *Geostationary-to-low-orbit satellite*

The worst case interference geometry would occur if the radiometer, while scanning the Earth's limb, received a main beam signal from a geostationary satellite within the radiometer main beam. The interference level in this instance is computed as follows:

Transmitted e.i.r.p.	83.1 dBW
Bandwidth conversion factor (235 MHz/2 GHz)	– 9.3 dB
Spreading loss ($4\pi R^2$; R in m)	–163.0 dB/m^2
Radiometer antenna effective area (main beam), S in m^2; 10 log S =	+ 8.7
Received interference power	– 80.5 dBW

or 76.5 dB above the interference threshold of –157 dBW. For nadir-looking radiometers, the interference level would be 2.5 dB below the radiometer interference threshold. This interference would occur only when the geostationary satellite points at the Earth's limb.

The probability of occurrence and the duration of this interference situation is very small. For instance, a typical polar orbit adjusted for global repetitive coverage would cause the limb sounder to point to a geostationary satellite only twice per month. The maximum duration of interference in this case would be approximately three minutes and would constitute less than 0.02 per cent of the time. The interference situation therefore, would be an infrequent occurrence and the loss of data would be negligible.

Another potential interference situation occurs when the radiometer passes through the main beam of a geostationary satellite. In this case, coupling of the signal would be via the side lobe of the radiometer antenna (for both nadir and limb sounding) and the resulting interference level is computed as follows:

Transmitted e.i.r.p.	83.1 dBW
Bandwidth conversion factor (235 MHz/2 GHz)	– 9.3 dB
Spreading loss	–163.0 dB/m^2
Radiometer antenna effective area (side lobe) S in m^2; 10 log S =	– 70.3
Received interference power	–159.5 dBW

or 2.5 dB below the radiometer interference threshold of –157 dBW.

Consequently, for the two interference geometries presented above, no significant interference will be experienced by the radiometer due to the geostationary-to-low orbit link.

4.3 *Low orbit satellite-to-geostationary satellite*

The amount of interference received by the radiometer from a transmitter located on a low orbit spacecraft is highly dependent upon the distance between the two spacecraft, which can vary from tens to thousands of kilometres. The line of sight spreading loss therefore will vary as much as 60 to 70 dB.

Since the probability of main beam to main beam coupling is extremely remote, the only significant potential for interference, results from side lobe to side lobe coupling.

The following calculation determines the distance required between the two spacecraft in order that side lobe coupling does not cause interference.

Transmitter e.i.r.p. (0 dB gain)	23.1 dBW
Bandwidth conversion factor (235 MHz/2 GHz)	– 10.0 dB
Radiometer antenna effective area (side lobe) S in m^2; 10 log S =	– 56.3
Interference threshold	–(–157) dBW
Required spreading loss ($4\pi R^2$; R in m)	113.8 dB/m^2

or a distance of 155 km.

The probability of two spacecraft being closer than 155 km is small. Furthermore, the time duration of interference would be small.

5. Conclusion

Frequency sharing between passive sensors and systems operating in the inter-satellite service is feasible. No interference would occur from the geostationary-to-geostationary inter-satellite link. There is a possibility of infrequent, short duration interference due to transmission between geostationary and low orbit satellites in the inter-satellite service. Loss of data resulting from such interference would be negligible.

ANNEX V

ANALYSIS OF SHARING FEASIBILITY BETWEEN PASSIVE SENSORS AND THE RADIOLOCATION AND AERONAUTICAL RADIONAVIGATION SERVICES

1. Introduction

Frequency bands near 1.4 GHz, 4 GHz, and 15 GHz have been analysed to determine whether sharing between passive sensors and the radiolocation and aeronautical radionavigation services would be feasible.

2. Sharing feasibility near 1.4 GHz

At a frequency near 1.4 GHz, sensor interference thresholds range between -158 and -165 dBW.

Transmitters operating near 1.4 GHz in the aeronautical radionavigation and radiolocation services are typically pulsed radars. Essential characteristics representative of registered systems are as follows:

Transmitter power (peak)	67 dBW
Antenna gain	34.5 dBi
Pulse repetition rate	310 to 364 p/s
Pulse duration	2 μs
Transmitter bandwidth	14.4 MHz

The effect of a pulsed signal on the apparent radiometer measurement is a function of its average power rather than peak power.

Using a pulse repetition rate of 333 p/s, which is typical of long range radars, the average power output of the radar transmitter is found to be 35.2 dBW.

The radar characteristics used in the sharing analysis are as follows:

Transmitter power (average)	35.2 dBW
Transmitter antenna gain	34.5 dBW
Transmitter power (average)	69.2 dBW e.i.r.p.

The maximum interference level occurs when the radiometer is located in the main beam of the interference source. This occurs at low elevation angles as seen from the radar station.

The level of the interference would be:

Transmitter power	35.2 dBW
Transmitter antenna gain	34.5 dBi
Spreading loss ($4\pi R^2$; R in m)	-139 dB/m^2
Radiometer antenna effective area (side lobe) S in m^2; $10 \log S =$	-38
Received interference power	-107.3 dBW

or 57.7 dB above the sensor interference threshold.

The gain range factor analysis programme was utilized to simulate the couplings between the radiometer and transmitter antennas as the spacecraft orbits the Earth. The loss of coverage area was found to be 100% of the visibility sphere as seen from the terrestrial station.

The population of terrestrial radars operating near 1.4 GHz is such that passive sensor operation would be interfered with over large areas of the Earth's surface.

Sharing with the radiolocation and aeronautical radionavigation services at frequencies near 1.4 GHz is therefore not feasible.

3. Sharing feasibility near 4 GHz

Near 4 GHz, the passive sensor interference threshold is -158 dBW.

The use of the 4.2 to 4.4 GHz band by the radionavigation service is primarily for world-wide radar altimetry measurements. Large numbers of equipments are in operation today, with anticipated usage of the band expected to grow substantially.

Technical characteristics of the altimeters fall into two classes:

CW Systems

Transmitter power	– 6 dBW
Antenna gain	11 dBi
e.i.r.p.	5 dBW

Pulsed Systems

Transmitter peak power	23 dBW
Antenna gain	11 dBi
Pulse duration	0.05 to 0.1 μs
Pulse repetition rate	10 kp/s
Average power	– 7 dBW
e.i.r.p. (average)	4 dBW

Since the pulse duration of the pulsed systems is much less than the radiometer integration times the average power, (not peak power), would affect the radiometer performance. Hence, the two types of altimeters have similar values of e.i.r.p.

It is estimated that some 10 000 - 20 000 altimeters are operational today. Estimates of future use of the band indicate that about 50 000 units may be in operation by the year 2000.

Interference would occur when the passive sensor is in view of any number of emitters whose output powers total 800 Watts or, equivalently, 29 dBW. This is seen from the following calculation:

Output power	29 dBW
Antenna gain (back lobe)	– 5 dBi
Spreading loss ($4\pi R^2$; R in m)	-134 dB/m^2
Effective area of radiometer antenna (side lobe), S in m^2; 10 log S =	– 48
Received interference power	-158 dBW

Since typical radar altimeters employ average powers of -6 dBW, the radiometer would have to be in view of approximately 3000 aircraft simultaneously, for the interference threshold to be exceeded. Interference would occur to the radiometer from a direct overhead pass of the interference source. However, the duration of interference is of negligible impact to data measurements in an operational system. Also, the mobile nature of the interference source virtually guarantees that the interference would not be repeated on the next overpass of the same area.

Estimates of the maximum number of aircraft simultaneously in view of the sensor are of the order of 750 for coastal and ocean areas.

Consequently, even considering substantial growth, simultaneous operation with this service is considered feasible.

The criterion for sharing is that transmitters in the aeronautical radionavigation service should employ average powers of the order of -6 dBW.

The Radio Regulations (see No. 789) permit use of ground-based transponders in the 4.2-4.4 GHz band when associated with radio altimeters installed on board aircraft. One possible system which would use ground-based transponders for precision range determination has been analysed to determine the feasibility of sharing between it and passive sensors. The range determination system that was analysed consists of a modified radio altimeter and a forward-looking antenna on the aircraft and a transponder located on the ground. The equipment on board the aircraft occasionally diverts a pulse from the altimeter (1 in 20) and transmits it through the forward-looking antenna. The transponder, upon detecting this pulse, would shift the frequency slightly, amplify and shape the pulse, and re-transmit it towards the aircraft. The airborne receiver would measure the time difference between pulse transmission and pulse reception and compute the slant range to the surface transponder. Typical system characteristics are summarized in Table II.

TABLE II – *Pulsed transponder systems*

Transmit peak power (dBW)	
Altimeter	7
Range interrogator	7
Beacon	7
Antenna gain (dBi)	
Altimeter	12
Range interrogator	10
Beacon	15
Pulse duration (ns)	
Altimeter	20-200
Range interrogator	50
Beacon	50
Pulse repetition rate (pps)	
Altimeter	19 000
Range interrogator	1 000
Beacon	1 000
Average power (dBW)	
Altimeter	−5.2
Range interrogator	≤ −32
Beacon	−29

If 750 aircraft using conventional radio altimeters were simultaneously in view of the passive sensor, a total interference power of −164 dBW would be received by the sensor. Additional interference power of −159 dBW from altimetry/range finding systems could be accommodated before the interference threshold of −158 dBW for the passive sensor is exceeded. Analysis [Hines and Nicholas, 1981] shows that 2000-4500 systems, depending on geometry, each servicing 15 operating aircraft, would result in an interference level of −159 dBW. Since far less than 2000 systems would be expected, sharing is technically feasible.

4. Sharing feasibility near 15 GHz

At 15 GHz, the sensor interference threshold ranges from −156 dBW to −160 dBW.

Microwave landing systems are being planned which will operate in the vicinity of 15 GHz. The technical characteristics of planned systems are:

Transmitter power	7 dBW
Antenna gain	20 dBi

The random interference analysis programme was utilized to simulate the interference environment. Figure 8 presents the results of the analysis. The figure relates the probability of data loss versus the number of terrestrial transmitters simultaneously operating and visible to the radiometer. Although a large number of transmitters can be simultaneously operating within view of the radiometer without exceeding the interference threshold of −160 dBW, it is expected that even larger numbers will be in view of a spacecraft at 500 km orbital altitude.

Sharing frequency bands with the planned microwave landing system is therefore not considered feasible.

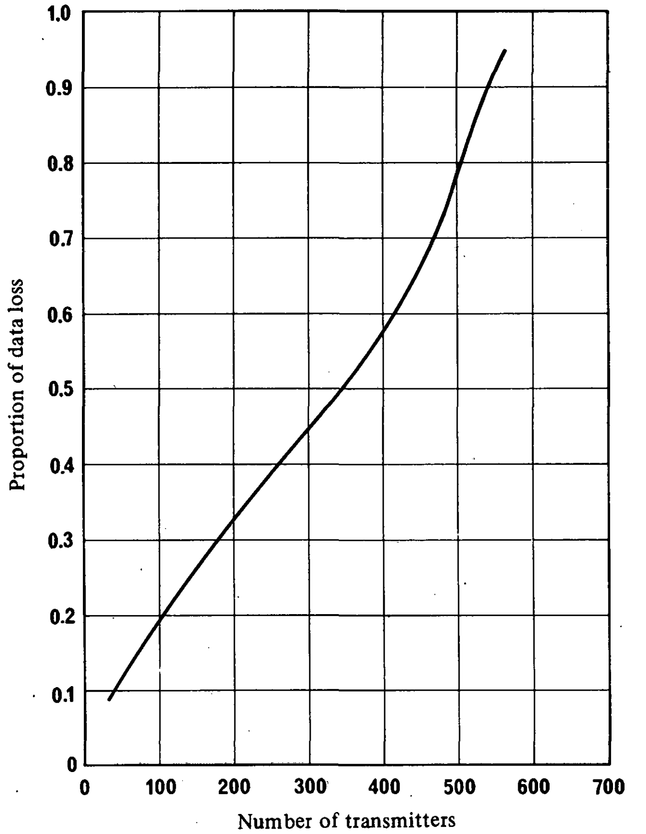

FIGURE 8 – *Data loss versus number of terrestrial transmitters of the aeronautical radionavigation service*

5. Conclusions

Sharing frequency bands between passive sensors and the radiolocation and aeronautical radionavigation services is generally not feasible. An exception to the above conclusion occurs in bands used exclusively for radar altimeters. Sharing, in that case, is feasible.

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REPORT 850-1 *

FREQUENCY SHARING BY PASSIVE SENSORS WITH THE FIXED, MOBILE EXCEPT AERONAUTICAL MOBILE, AND FIXED-SATELLITE SERVICES IN THE BAND 18.6-18.8 GHz

Minimum restrictions to other services in order to ensure satisfactory operations of passive sensors

(Study Programme 12B/2)

(1982–1986)

1. Introduction

Recommendation No. 706 of the WARC-79 requests that the CCIR study sharing between services allocated in the 18.6-18.8 GHz band in order to develop sharing criteria which would ensure satisfactory operations of passive sensors without jeopardizing the other services likely to use this frequency band.

This Report is a partial answer to Recommendation No. 706. In particular, it examines the question of the minimum restrictions which might be applied to the fixed, mobile, except aeronautical mobile, and fixed-satellite (space-to-Earth) services in order to ensure the satisfactory operation of passive sensors.

2. Interference criteria

The interference threshold for a passive sensor having a sensitivity of 1 K and a radio-frequency bandwidth of 200 MHz (Report 694) is:

$$P_H = 0.2\, k\, \Delta T_e\, B = -152 \text{ dBW}$$

where:

ΔT_e: radiometer sensitivity, 1 K,

k: Boltzmann's constant, 1.38×10^{-23} J/K,

B: radio-frequency bandwidth, 200 MHz.

A second criterion is that, for viable passive sensor operations, the data loss caused by interference levels above the interference threshold must be less than 5%. This amount of data loss could be composed of data loss when the passive sensor antenna points directly at an interference source, or conversely, when the sensor is within the main beam of an interfering source.

3. Passive sensor characteristics

The passive sensor satellite orbit, utilized for the analyses that follow, is a 500 km circular, polar orbit.

The sensor's antenna pattern is substantially better than usual CCIR patterns, since one purpose of the sensor antenna is to suppress as much energy outside of its main beam as possible. Approximately 90% of the energy received by the sensor comes through the main beam. Figure 1 represents the sensor antenna pattern. The gain of the antenna was selected to be 57 dBi, resulting in a spatial resolution of 2 km and a half-power beamwidth of 0.16°. A sensor can utilize a number of different types of scanning modes. These modes are:

a) nadir looking only;

b) conical scanning;

c) cross-track scanning; and

d) "push-broom" scanning.

When scanning, the angle off nadir is generally no greater than 45°. For modes a), b) and c), only one antenna/receiver combination is employed. The "push-broom" mode processes in parallel each resolution element in its swath, and thus requires many receivers to cover a given swath.

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* This Report should be brought to the attention of Study Groups 4, 8 and 9.

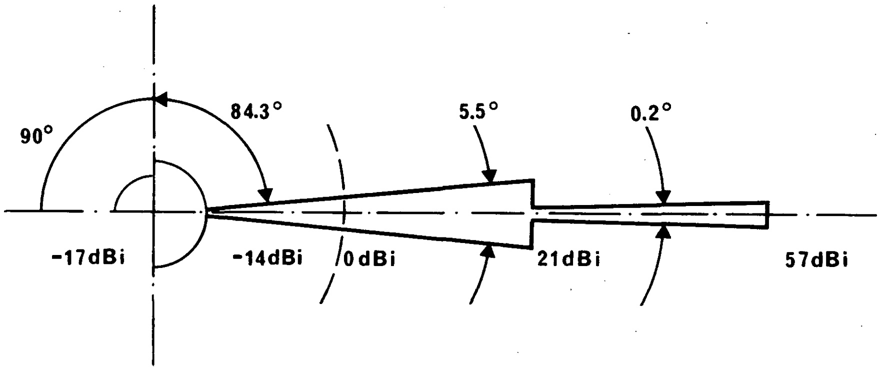

FIGURE 1 – *Under-illuminated radiation pattern for passive sensors*

The harmful interference threshold as previously calculated is −152 dBW. Half of the allowable interference power (−155 dBW) was allocated to the fixed and mobile services and half was allocated to the fixed-satellite service. The sensor characteristics are summarized in Table I.

TABLE I – *Passive sensor characteristics*

Satellite altitude	500 km
Antenna gain	57 dBi
Resolution	2 km
Half-power beamwidth	0.16°
Interference threshold	−152 dBW
Receiver RF bandwidth	200 MHz

4. Analysis of the feasibility of sharing with the fixed and mobile services

A parametric study has been performed to determine the effects on sharing potential of varying the population, antenna gain and transmitter power of the terrestrial transmitters. Instead of using a randomly distributed transmitter population, a more representative distribution of transmitters clustered around the 30 largest population centres in the United States and Canada was utilized in this study. Interference levels were determined for transmitter populations of 1000, 5000 and 10 000, transmitter antenna gains of 0, 10, 20, 30 and 40 dBi and transmitter powers of −10, −5, 0, +5 and +10 dBW.

A computer model was developed to determine interference levels at orbital altitude for all combinations of the above variables. The computer model used random azimuths for transmitter antenna pointing angles, assuming a uniform distribution of headings between 0 and 360°. The total number of emitters, the transmitter antenna gain, and the transmitter output power were treated as parameters, with assigned values. The interference which would have occurred to a sensor at the centre of each 2° × 2° latitude/longitude cell was computed for each transmitter in view, using the angular difference between the antenna centre line and the direction of the cell from the transmitter to determine transmitter antenna gain. Transmitter antenna gains were estimated using a standard CCIR side-lobe envelope approximation ($52 - 10 \log D/\lambda - 25 \log \varphi$ for $D/\lambda < 100$, see Report 391).

The combined effects of multiple interference input paths were then summed and compared with the sensor interference threshold. There are three types of interference paths, namely: terrestrial antennas main beams to sensor antenna side lobes, terrestrial antennas side lobes to sensor antenna main beams, and terrestrial antennas side lobes to sensor antenna side lobes (see Report 694). Those cells which had a cumulative interference level above the interference threshold were lost data areas. The total area of data loss was accumulated for each combination of input parameters and the results are plotted in Fig. 2.

It should be noted that the 2° × 2° cells over-estimate the data loss when that loss is small (< 3%), but not when considering losses comparable to 5% or greater. The over-estimation is significantly reduced for the < 3% loss region when scattering is considered.

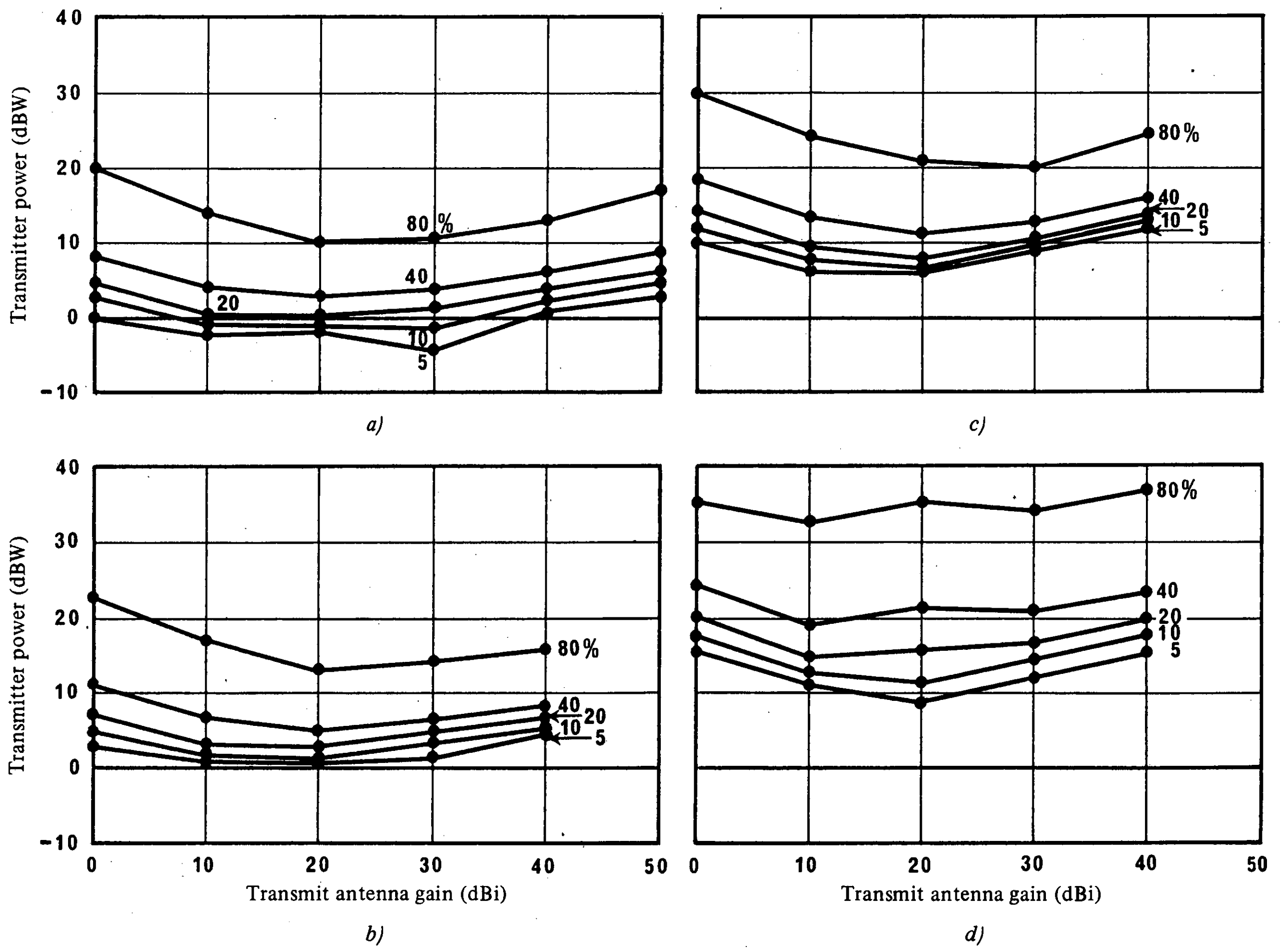

FIGURE 2 – *Loss of coverage area versus FS transmitter population, FS transmitter power, and FS transmitter antenna gain*

a) 10 000 transmitters
b) 5 000 transmitters
c) 1 000 transmitters
d) 250 transmitters

Frequency = 18.6 GHz

4.1 *Analysis of results*

Figure 2 confirms that higher transmitter power and larger numbers of transmitters cause increased loss of sensor coverage area.

Passive sensor interference criteria can be satisfied, resulting in satisfactory passive sensor operations, if the fixed and mobile services use combinations of transmitter power and antenna gains which maintain the loss of coverage area below the 5% data-loss level. For example, as shown in Fig. 2, the sensor's criteria would be met, when 10 000 transmitters are within line of sight to the passive sensor satellite, if each transmitter were to use a transmitter power of 0 dBW and an antenna gain of 40 dBi.

Permissible values of transmitter power and antenna gain depend on the total population of transmitters that are visible to the sensor satellite. In the United States, the 18.6-18.8 GHz band is used by the private operational-fixed microwave service. Based on the number of transmitters presently in operation in the 18.6-18.8 GHz band, and on market projections of growth in demand for this service, 10 000 appears to be a reasonable estimate of the total number of transmitters that might operate in this band. Current systems in the United States utilize transmitter powers of −12 dBW and antenna gains of 43 dBi. Sharing between passive sensors and the current systems in the United States is feasible, as can be seen from Fig. 2.

Further analyses of fixed systems have been undertaken covering high-capacity North-South systems, low-capacity distribution systems and scattering effects. Annex I presents an analysis of a high-capacity North-South system, designed and being implemented in Japan. Annex II analysed a low-capacity digital distribution system called a digital termination system (DTS), while Annex III analyses the effects of surface scattering on sensor data loss.

The feasibility of frequency sharing between passive sensors and fixed-service systems was found to be independent of the length and orientation of the fixed-service system (see Annex I).

Low-capacity distribution systems having transmission parameters as shown in Annex II were found to have no adverse effect on the feasibility of sharing.

Surface scattering is shown in Annex III to increase the interference received by passive sensors. The additional interference due to the scattered component was found to be about 75% of the level due to the direct-path component.

The type of scan employed by the passive sensor was found not to affect the results of the interference analysis.

4.2 *Possible approach to sharing**

Figure 2 would indicate that fixed systems with transmitter power as high as 0 dBW, and station population as great as 10 000 within line of sight to the sensor satellite, would permit sharing with passive sensors so long as the fixed systems used minimum antenna gains of 40 dBi. When scattering is taken into account, the compatible station population would be reduced by approximately 45%.

Based on the assumptions used in this Report, the results of the analysis would indicate that an approach to permit sharing between passive sensors and the fixed service in the 18.6-18.8 GHz band, would be to limit fixed service transmitter power to a maximum of 0 dBW and to limit antenna gain to a *minimum* of 40 dBi.

The mobile service typically employs low gain, hemispherical antennas (3 dBi). Sharing criteria which would permit sharing between passive sensors and the mobile service in the 18.6-18.8 GHz band could be established by limiting the maximum transmitter power of mobile systems to −5 dBW. No limits on antenna gain or e.i.r.p. would be required.

5. Analysis of the feasibility of sharing with the fixed-satellite service (FSS)

The results of this analysis are independent of sensor antenna pointing and therefore of the sensor scan configuration, since for a given surface PFD, the power received at the sensor is independent of range. This fact is shown in the following derivation.

Two interference paths are possible between a passive sensor and an FSS space-to-Earth link:

- coupling of the down-link signal via the back lobe of the sensor antenna, and
- coupling of the down-link signal into the main lobe of the sensor antenna by scattering from the Earth's surface.

* In Japan, systems are planned which may not satisfy the criteria discussed in this section.

The FSS satellite e.i.r.p. which will produce interference at the sensor threshold level can be calculated as follows for the case of coupling via the back lobe of the sensor antenna:

Sensor interference level	–155 dBW
Effective area of sensor antenna (back lobe), S in m^2; 10 log S =	– 63
Therefore power flux at sensor	– 92 dB(W/m^2)
Spreading loss	–162 dB/m^2
Maximum FSS satellite e.i.r.p.	70 dBW

The maximum FSS satellite e.i.r.p. which avoids interference into the sensor's back lobes is thus 70 dBW and the corresponding power flux-density limit (PFD) at the Earth's surface –92 dB(W/m^2) in the 200 MHz sensor bandwidth. This PFD is 10 dB lower than the value derived from the limit of –105 dB(W/m^2) in any 1 MHz band for angles of arrival greater than 25° above the horizontal plane, the value permitted by the Radio Regulations. The above comparison presumes that the FSS satellite radiates uniformly over the entire 200 MHz sensor bandwidth.

Interference to the sensor from FSS satellites employing e.i.r.p. greater than 70 dBW would occur whenever the sensor satellite is in the main beam of the FSS satellite. Note also that the above calculation corresponds to the case where the sensor satellite is within the main beam of one FSS satellite having a total e.i.r.p. of 70 dBW in a 200 MHz bandwidth. If the sensor satellite were in the main beams of multiple FSS satellites, loss of coverage would result for FSS satellite e.i.r.p.s of 70 dBW. The percentage of area loss for both situations would depend on the FSS satellite antenna beamwidth and the population of FSS satellites.

A more severe interference problem results from the fixed-satellite signal scattered from the Earth's surface into the main lobe of the sensor antenna. The interference power received by the sensor is:

$$P_R = \left[\frac{P_T\,G_T}{4\pi R_{TE}^2}\right]\left[\frac{\sigma_0}{4\pi}\right]\left[\frac{A_S}{R_{ER}^2}\right]A_R$$

where:

$P_T G_T$: FSS satellite transmitter e.i.r.p.,

R_{TE}: range from the fixed-satellite transmitter to Earth,

σ_0: scattering coefficient,

A_S: footprint area of the sensor antenna on the Earth,

R_{ER}: range from the Earth to the sensor receiver,

A_R: effective area of the sensor antenna.

The above equation can be expressed as:

$$P_R = \left[\frac{P_T\,G_T}{4\pi R_{TE}^2}\right]\left[\frac{\lambda^2\pi}{64\cos\theta_i}\right]\sigma_0$$

where θ_i is the incidence angle of the sensor antenna and λ is the wavelength.

Since the first term on the right side of the above equations is the PFD produced by the FSS satellite, the maximum PFD which will not cause interference can be determined from:

$$PFD = \frac{P_R\,(64\cos\theta_i)}{\lambda^2\pi\sigma_0}$$

by substituting the sensor interference level for P_R.

The value of σ_0 is a function of the angle of incidence, soil humidity, soil roughness, vegetation cover, soil type and terrain slope.

The results in Annex III can be presented in terms of the maximum PFD which would permit sharing, as a function of σ_0. The PFD necessary to maintain interference below the sensor interference threshold, for a one beam (50 dBi) FSS satellite, is:

$$PFD = -106 \text{ dB(W/(m}^2 \cdot 200 \text{ MHz))} - \sigma_0$$

and when σ_0 is -5 dB (see Annex III), then the maximum PFD would be:

$$PFD = -101 \text{ dB(W/(m}^2 \cdot 200 \text{ MHz))}$$

For a 10 beam (50 dBi each) FSS satellite, the allowable PFD would have to be reduced by another 3 dB.

5.1 *Areas of passive sensor data loss for Earth coverage FSS systems*

An Earth-coverage FSS satellite operating at the PFD limit specified in the Radio Regulations (-105 dB(W/(m^2 · MHz))) would result in interference to a passive sensor anywhere within line of sight. A value of -22 dB for σ_0 would be required to limit interference to small areas, and as Fig. 3 shows, values of σ_0 as low as -22 dB are not expected.

A decrease in PFD of 22 dB would result in interference only for values of σ_0 greater than 0 dB. These values of σ_0 can occur only when geometrical relationships result in specular reflection. This requires that the sensor antenna must be aligned within 10° of the specular direction of the reflected fixed-satellite signal.

The alignment of the sensor's main beam along the specular direction to the FSS satellite will happen infrequently and these areas can still be sensed at other orbit passes where such alignment does not occur.

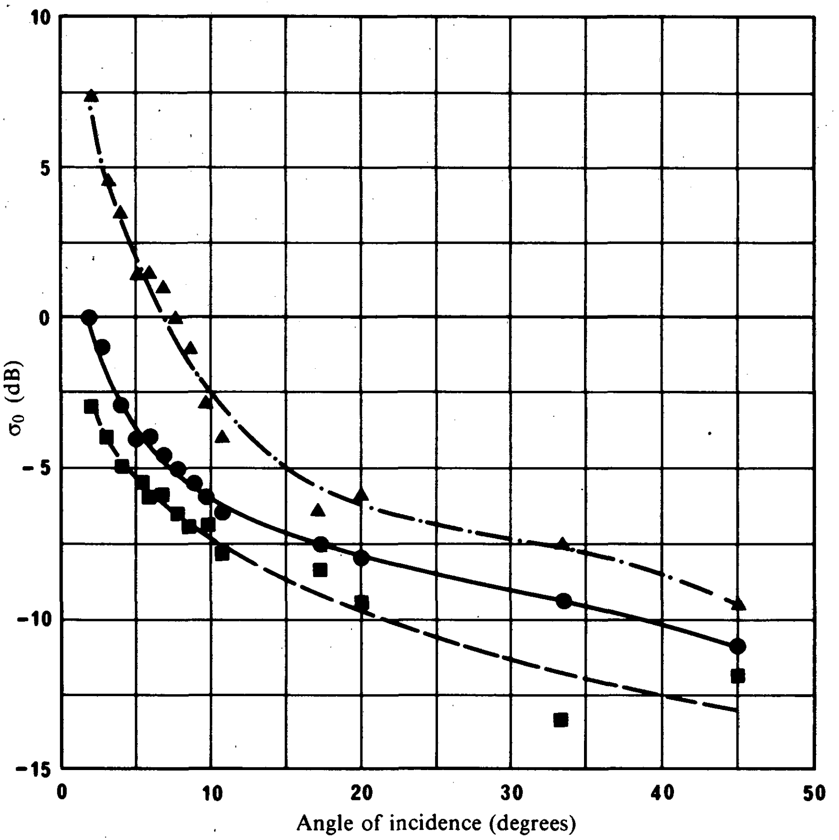

FIGURE 3 – *Differential scattering coefficient measured at various sites in the United States with Skylab S-193 scatterometer during summer of 1973. (Vertical polarization) [Purduski, 1978]*

90 % level

Mean

10 % level

5.2 *Areas of passive sensor data loss for spot beam fixed satellite*

At 18 GHz, fixed-satellite systems are likely to employ spot beams to keep transmitter power at achievable and reliable levels, and to meet fade margin requirements due to high rainfall attenuation.

A developmental fixed-satellite system being considered in the United States for operation in the 17.7-19.7 GHz band [NASA, 1981] would contain 10 spot beams to provide high capacity service between major population centres plus two scanning spot beams for lower rate service. Each beam would have a beamwidth of 0.3° and a peak gain of 55 dBi.

Area C in Fig. 4 is the area lost to passive sensing based on the current PFD limits. Clearly, the large area lost would seriously affect the full operation of the passive sensor at 18 GHz under the current allowable PFD. If the PFD were reduced by 16 dB, the area lost would be reduced from area C in Fig. 4 to area A where PFD levels as high as -102 dB(W/(m^2 · 1 MHz)). The loss would occur regardless of the orientation of the sensor antenna with respect to the direction of specular reflection from the FSS satellite. A further reduction of PFD by 6 dB to 22 dB below the current limit would result in the loss to the passive sensor occurring only when the sensor antenna is aligned within ± 10° of the specular direction. A still further reduction of PFD by an additional 8 dB would eliminate interference even when the sensor is aligned with the direction of specular reflection from the FSS satellite.

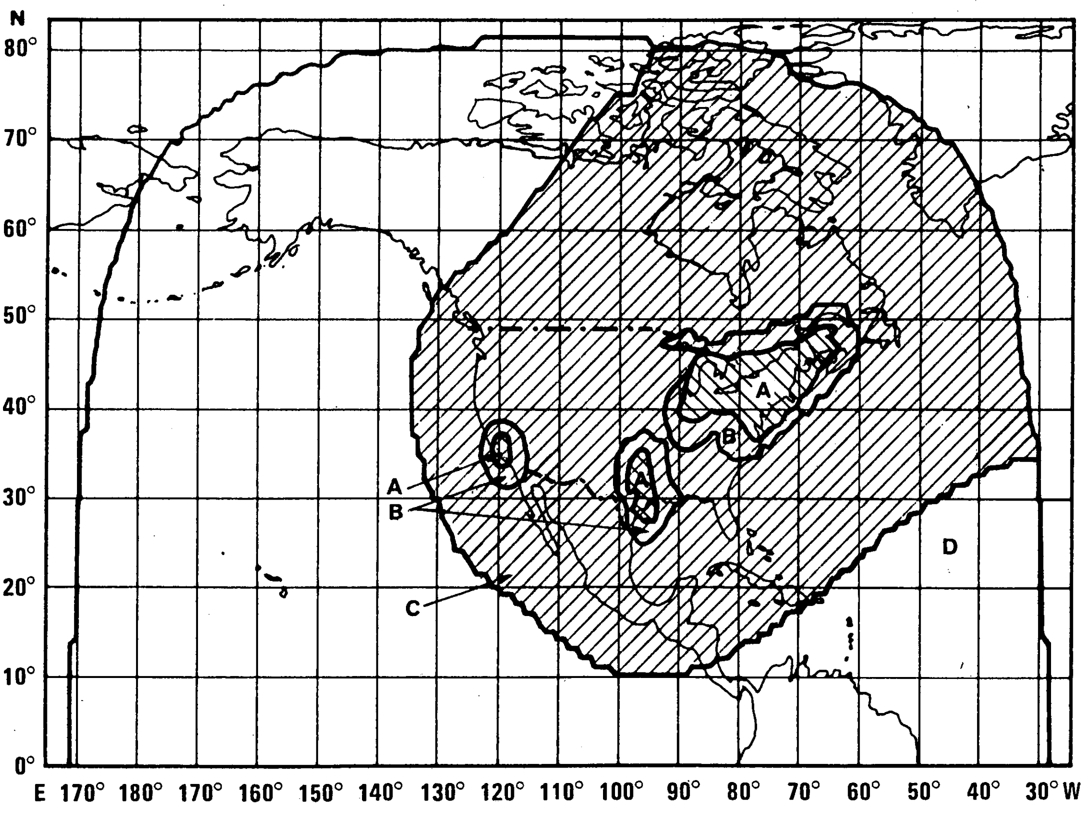

FIGURE 4 – *PFD contours and passive sensor data loss areas due to interference from a ten-beam fixed satellite system*

Areas A: PFD ⩾ -108 dB(W/(m^2 · 1 MHz))
B: PFD ⩾ -115 dB(W/(m^2 · 1 MHz))
C: PFD ⩾ -125 dB(W/(m^2 · 1 MHz))
D: PFD ⩾ -135 dB(W/(m^2 · 1 MHz))

Note. – Crossed hatched area (C) is the data loss area for the current PFD limit. Area (A) is the data loss area for a PFD 16 dB or 22 dB below the current limit.

5.3 *Selection of sensor scan angle to minimize interference*

Regardless of the scanning method, whether conical, cross-track, or "push-broom" scanning, wide area interference will not be affected as it is not a function of look angle (see derivation, § 5). There would be certain areas where data may be lost due to specular reflection even if the PFD were reduced by 22 dB (see Annex III). However, these areas would not be large and the data could be collected at other "look" angles away from the specular direction.

5.4 *Use of fixed-satellite guard channels for sensors*

A fixed-satellite channel plan which placed a guard channel at 18.7 GHz would reduce the power flux-density in the 18.6-18.8 GHz band without other impact to fixed-satellite systems. Figure 5 shows the amount of PFD reduction which would result between channels with the filter response being studied for the United States developmental satellite system although these particular filters would have little effect at 18.6-18.8 GHz.

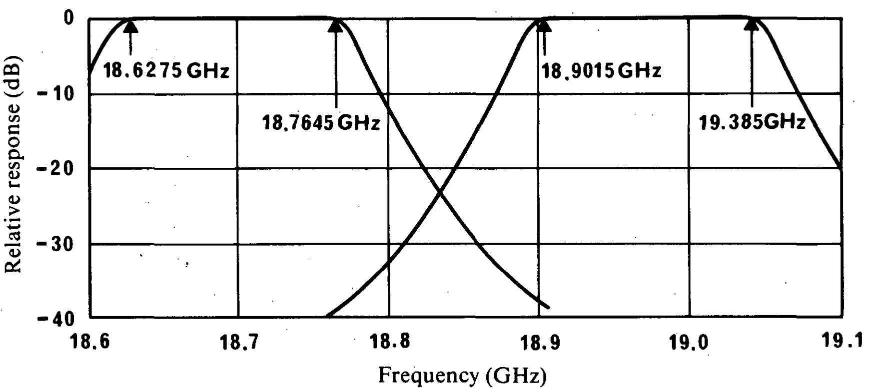

FIGURE 5 – *Input multiplexer filter response*

5.5 *Possible approaches to sharing**

Operation of passive sensors in the 18.6-18.8 GHz frequency band would be severely compromised by unconstrained emissions from space stations in the fixed-satellite service at or near the maximum permissible power flux-density.

In order to ensure satisfactory operations of passive sensors it would be necessary to employ lower power flux-densities, minimize the areas on Earth subjected to high power flux-densities, or to use a combination of both steps.

Power flux-density could be reduced either by reduced fixed-satellite e.i.r.p. or by adoption of a channel plan having a guard channel at 18.7 GHz.

6. Conclusions

Recommendation No. 706 of the WARC-79 requests the CCIR to study sharing criteria which would ensure satisfactory operations of passive sensors without jeopardizing the other services likely to use the 18.6-18.8 GHz band.

The question of minimum restrictions which might be applied to the fixed, mobile except aeronautical mobile, and fixed-satellite (space-to-Earth) services consistent with satisfactory sensor operations has been examined in this Report.

* The developmental fixed-satellite system being considered in the United States for operation in the 17.7-19.7 GHz band would produce power flux-densities more than 22 dB below maximum levels permitted by the Radio Regulations and would employ a peak antenna gain greater than 52 dBi. However, existing Japanese communication satellites are using about 40 dBi peak antenna gain to cover all of Japan. Although existing Japanese satellites also produce power flux-densities more than 22 dB below the maximum permitted levels, this value cannot be confirmed for future satellites.

Based on the assumptions used in this Report, the results of the analysis would indicate that an approach to permit sharing between passive sensors and the fixed service would be to limit fixed service transmitter power to a maximum of 0 dBW and to require the antenna gain to be 40 dBi or greater.

Restrictions which would permit sharing between passive sensors and the mobile services in the 18.6-18.8 GHz band could be established by limiting the maximum transmitter power of mobile systems to −5 dBW. No other restrictions would be required.

Based on the assumptions used in this Report, the results of the analysis indicate that an approach to permit sharing between passive sensors and the fixed-satellite service would be to reduce the allowable PFD in the 18.6-18.8 GHz band by at least 22 dB, or to adopt a channel plan providing at least 22 dB of isolation.

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ANNEX I

SHARING BETWEEN PASSIVE SENSORS AND LONG-HAUL, NORTH-SOUTH MICROWAVE RELAY SYSTEMS

1. Introduction

In the analyses of interference from fixed systems in this Report, the interference to passive spaceborne sensors from a short-haul microwave relay system was modelled. Since a long-haul, high-capacity digital, North-South* fixed system covering the 18.6-18.8 GHz band has been designed and partially implemented for Japan [Nakamura *et al.*, 1977] a model of this system was developed and an analysis to determine the compatibility of such a system with passive sensors was performed [Nicholas *et al.*, 1983]. This Annex contains the results of the analysis.

2. Description of a Japanese long-haul fixed system

The Japanese fixed system is designed to operate as a long-haul system over a 2500 km distance in the 17.7-21.2 GHz band. Repeater stations are to be separated by distances varying from about 2 km to 6 km over the length of Japan. System design elements include an interleaved frequency arrangement in which 320 MHz wide channels alternate between vertical and horizontal polarization. Transmitter power of the repeater stations that have been implemented is −8 dBW per channel. The antennas have approximately 48 dBi gain.

3. Description of the interference model

The model employed is similar to that described in § 4 of this Report. A region of the Earth encompassing Japan was divided into 2° × 2° latitude-longitude cells. The number of radio-relay transmitters placed at the centre of each cell was determined from information presented in [Nakamura *et al.*, 1977]. A population of 2000 radio relays operating with both polarizations in the 200 MHz passive sensor band was used as an upper bound for the fully implemented system. A standard CCIR fixed-service side lobe envelope pattern was assumed for system transmit antennas. The average trendline for the backbone system was chosen to be 40° clockwise from 0° N, and two spurs were positioned at 90° from that trendline. Fixed-system antennas were pointed within a 30° variance of the backbone trendline or spur trendline.

The interference that would arrive at a sensor in each orbital position in view of the modelled system was computed and compared to sensor interference threshold of −155 dBW. The 320 MHz channel widths and overlapping polarized channel structure were included in the calculation algorithm. Sensor coverage loss was determined in the same manner as described in § 4 of this Report.

* Actually, the Japanese system runs 40° off due North. The analysis presented in [Nicholas *et al.*, 1983] shows that the results presented in this Annex are independent of trendline direction.

4. Sensor coverage loss results

Study results indicate that:

- for the −8 dBW per channel transmit power used by the actual system, sensor coverage loss would be less than 2% for 2000 transmitters;
- for the 0 dBW per channel transmit power suggested as a possible limit in this Report, sensor coverage loss would still be less than 2% for 2000 transmitters.

These predicted coverage losses are below the 5% level given as acceptable in the main body of this Report.

As discussed in [Nicholas *et al.*, 1983] when transmit stations are confined to a trendline, the modelled loss of 2° cells exaggerates the actual sensor coverage loss. Even taking into account the interference contributions from scattering (see Annex III), study results indicate that coverage loss due to a long-haul, North-South radio-relay system with 2000 repeaters would be limited to 0.6% for transmit powers as high as 0 dBW and antenna gains of 48 dBi. Data loss would thus be substantially below the criterion given in § 2 of this Report.

5. Discussion of results

As in the case of the model developed for short-haul systems in this Report, a rapid increase in loss of sensor coverage area occurs above a threshold transmit power. For both short-haul and long-haul cases, the threshold occurs near 5 dBW for a population of 2000 transmitters.

The one main conclusion to be drawn from this study is that the feasibility of frequency sharing between passive sensors and fixed-service systems is unaffected by the length and orientation of the fixed-service system.

The total number of fixed transmitters, their transmitted power and antenna gain, are the critical parameters for determining sharing feasibility for both long-haul, North-South oriented fixed systems and short-haul systems with random orientation. The relationships between these parameters and sensor data loss are discussed in this Report.

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ANNEX II

FREQUENCY SHARING BETWEEN PASSIVE SPACEBORNE SENSORS AND DIGITAL TERMINATION SYSTEMS IN THE 18.6-18.8 GHz BAND

1. Introduction

The possibility exists that point-to-point, point-to-multipoint combination systems might be implemented in the 18 GHz region. Such a system has been referred to as a digital termination system (DTS) [Manichaikul *et al.*, 1983].

Since DTS systems are not currently implemented, and not all the parameters of interest are well specified, a parametric analysis based on existing fixed-service hardware and DTS systems being considered at 10 GHz, was developed for each of the various DTS links. Based on these transmission parameters, the model described in § 4 of this Report was utilized to determine the feasibility of sharing between DTS and passive sensors.

2. Description of the DTS

A DTS system would comprise multiple users (subscribers) clustered around a nodal station. Transmission to the nodal station would be as point-to-point, but the reverse transmission would be point-to-multipoint. The nodal stations could be interconnected by a typical fixed-service point-to-point link (possibly with multiple hops), or space relay or cable linkage could be used. The DTS concept is presented in Fig. 6.

Subscriber antennas are envisaged to be high gain, of the order of 40 dBi. Nodal antennas for transmission to subscribers are envisaged to be effectively omnidirectional in azimuth with 19 dBi gain, through the use of several 19 dBi "sector" antennas. Node-to-node transmission is expected to use antennas similar to other fixed systems at 18 GHz with gains of at least 40 dBi.

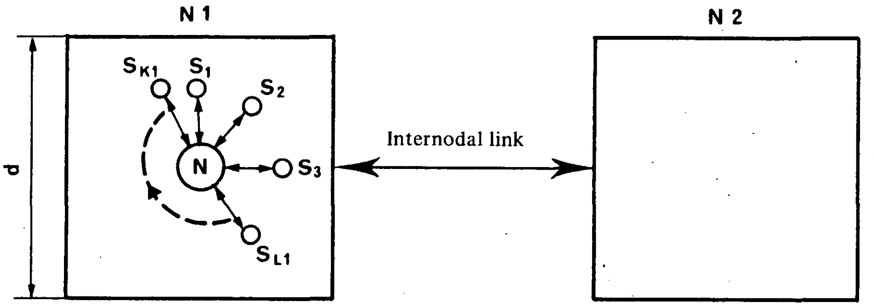

FIGURE 6 – *DTS system architecture*

S_1: subscriber number 1
N: nodal station
d: nodal span (twice the nodal radius)

A channel plan and transmit power requirements for an 18 GHz DTS system have not been established. Consequently, each DTS link has been analysed separately as if only that link occupied the 18.6-18.8 GHz band. The transmit power requirements are critical to the nodal span and outage times for a DTS system. Transmit power, distance and outage-time trade-off calculations were made using DTS link parameters based on existing United States and Japanese fixed systems. DTS link parameters are presented in Table II. The results along with the resultant total power in the sensor's 200 MHz bandwidth and the number of compatible nodal stations are presented in Table III.

TABLE II – *DTS system parameters* *

Subscriber-to-node:	
Gain (dBi)	40
Outage time	1% (0.1%)
Fade margin	10 dB (20 dB)
Transmit power	0.000025 W/250 kHz (0.00025 W/250 kHz)
Maximum link distance (km)	10
Node-to-subscriber:	
Gain (dBi)	19
Outage time	1% (0.1%)
Fade margin	10 dB (20 dB)
Transmit power	0.000025 W/250 kHz (0.00025 W/250 kHz)
Maximum link distance (km)	10
Node-to-node hop length:	
Gain (dBi)	43
Outage time	0.01%
Fade margin	40 dB
Transmit power	0.0015 W/250 kHz
Maximum link distance (km)	3

* For the node-to-subscriber and subscriber-to-node links, a two-phase coherent PSK with a $C/N = 14$ dB (probability of error (P_e) $< 10^{-9}$) was assumed. The fade margins 10 dB (20 dB) for these two links allows for at least 1% (0.1%) in rain regions A to M (see Reports 382 and 721).

TABLE III – *DTS system-sensor compatibility results*

DTS link node	Spectral transmitter power density/250 kHz	Total power per 200 MHz per node (W)	Link distance (outage time) (km)	Number of compatible nodes (1)
Subscriber-to-node	0.00025	0.2	10 (0.1%)	> 10 000
	0.000025	0.02	10 (1%)	> 10 000
Node-to-subscriber	0.00025	0.2	10 (0.1%)	> 10 000
	0.000025	0.02	10 (1%)	> 10 000
Node-to-node	0.0015	1.2	3 (per hop)	10 000

(1) Each node represents full utilization of the 200 MHz passive sensor band of interest. For example, if each subscriber had 250 kHz of bandwidth, then there could be 800 subscribers per node. If subscribers were to time-share a channel, substantially more subscribers would be utilizing the DTS system.

3. Conclusion

Based on the envisaged link parameters for a DTS system, sharing with passive sensors would be feasible with any link. Sharing with any combination of links within the passive sensor's 200 MHz bandwidth would, by implication, also be feasible.

DTS systems now under consideration in Canada would use outage times of 0.01% and fade margins of 25 to 30 dB. The compatibility of such a fixed system with passive sensors has still to be determined.

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ANNEX III

EFFECTS OF TERRAIN SCATTERING ON SHARING WITH FIXED AND FIXED-SATELLITE SYSTEMS

1. Introduction

In the analyses contained in this Report, including Annexes I and II, no consideration has been given to scattered energy from fixed transmitters, and only a very general consideration to scattered energy from FSS satellites. The analysis of this Annex is based on a recent model [Nicholas *et al.*, 1983] for analysing surface scattering. This model is an extension of work by [Beckmann, 1963].

2. Scattering analysis for the case of the fixed service

The type of terrain over which a fixed-service transmitter operates is crucial for determining the power scattered towards a passive sensor. Based on the model presented by [Nicholas *et al.*, 1983] and data presented in [Long, 1975] the average surface normalized scattering coefficient, σ_0, would be around -10 dB for urban and residential areas. For heavily forested regions, σ_0 falls in the range of -18 to -10 dB; however, to provide a reasonable conservative bound, a σ_0 of -10 dB is used in the following analysis.

The power received by a spaceborne sensor due to scattering will be:

$$P_R = \Sigma\ P_i = \Sigma\ P_T G_T \cdot \frac{1}{4\pi\left(r_{1_i}\right)^2} \cdot \sigma_0\ A_i \cdot \frac{1}{4\pi\left(r_{2_i}\right)^2} \cdot G_R\ \lambda^2/4\pi \tag{1}$$

where:

r_{1_i} :	distance from the transmitting antenna to the scattering surface (m),
r_{2_i} :	distance from the elementary scattering surface to the spacecraft (m),
P_R :	power received (W),
P_i :	power received due to scattering from an elemental area A_i (W),
A_i :	elemental area of the scattering surface (m^2),
$P_T G_T/4\pi(r_{1_i})^2$:	pfd arriving at the elemental scattering surface (W/m^2),
σ_0 :	scattering coefficient (dB),
$1/4\pi(r_{2_i})^2$:	spreading loss to the spacecraft (m^{-2}),
$G_R\lambda^2/4\pi$:	effective area of the sensor antenna in the direction of the scattering surface (m^2).

The summation is performed over the complete scattering surface A to determine the signal power entering the sensor side lobes, and over the sensor main-beam footprint on the Earth to determine the signal power entering the sensor main beam.

In order to obtain the scattered signal PFD at the Earth's surface, it is necessary to determine the gain contours of the fixed-service antenna on the surface of the Earth. This was done for a typical fixed-service antenna of 40 dBi gain, pointing horizontally and mounted 20 m above the Earth. The gain contours of 25 dBi, 10 dBi, 0 dBi and -5 dBi* are plotted in Fig. 7. The line-of-sight distance for a 20 m antenna height is 16 km.

2.1 *Side-lobe case*

The line-of-sight region, a circle of 16 km radius, was divided into areas with sizes of 0.5×0.5 km, 1×1 km and 2×2 km in order to accurately perform the summation over the gain contours. The total power summation was then calculated over the complete area A. For a fixed-service transmitter power of 1 W, the area within the $G_T = 25$ dBi contours was found to contribute the equivalent of a 0.15 W transmitter with an omnidirectional antenna located at the centre of A. The balance of the total scattering area contributes 0.10 W for a total of 0.25 W omnidirectionally distributed.

For the direct path from the fixed transmitter to the sensor, the power associated with the fixed transmitter -5 dBi side lobes is equivalent to a 0.32 W omnidirectionally distributed transmitter. Thus, scattering will cause the effective side lobe-to-side lobe interference to increase by 2.6 dB. Consequently, the number of 1 W transmitters which would just meet the criterion contained in this Report would be reduced from 10 000 to 5555.

Another way to envisage the results of this analysis is that a line-of-sight transmitter emits half of its power towards the Earth's surface where some is absorbed and some scattered. This analysis indicates that half of the power incident on the Earth's surface is absorbed and half scattered for surfaces with $\sigma_0 = -10$ dB.

2.2 *Sensor main beam-to-scatter surface case*

Without consideration of scattered energy, an area the size of the sensor's resolution, 2×2 km, is "lost" due to interference when the main beam of the passive sensor's antenna is pointed at a fixed service transmitter. Figure 7 shows the area "lost" to sensing due to scattering for the conditions given in § 2.1 and a σ_0 of -10 dB. As indicated by C, an area substantially larger than 2×2 km around the site is lost.

* The antenna pattern for fixed services is presented in Report 614. Note that the far back-lobe level is stated to be 0 dBi; however, a footnote to § 5 indicates that where multiple entries from fixed transmitters are to be considered, -5 dBi appears to be a more appropriate level.

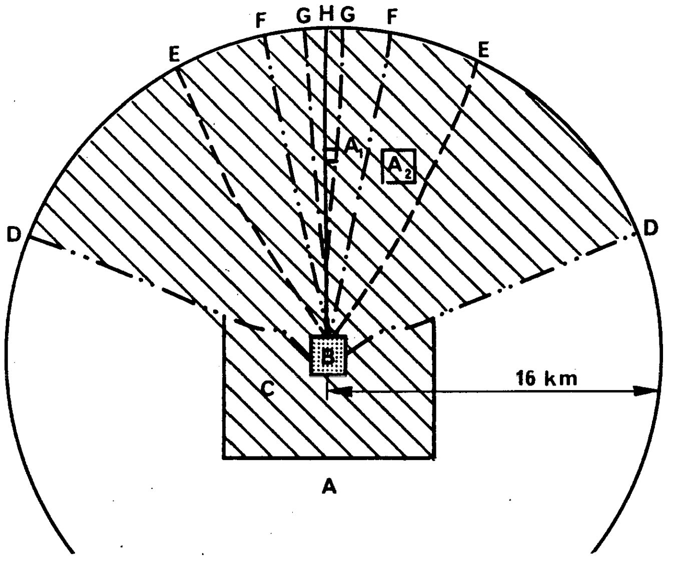

FIGURE 7 – *Fixed antenna ground gain intersections and sensor main-beam data loss area*

A: scattering area

A_1: 0.5 × 0.5 km typical area

A_2: 2 × 2 km typical area

B: 2 × 2 km resolution element lost due to sensor main-beam pointing at fixed station (no scattering)

C: area lost due to scattering when sensor main-beam points into this area (lined area)

D: —··— −5 dBi gain contour intersection with the Earth

E: — — — 0 dBi contour

F: —··— 10 dBi contour

G: —·— 25 dBi contour

H: ——— 40 dBi contour

The conclusions drawn in the Report are unaffected, however, since the modelled 2° by 2° cells (220 × 220 km at the equator) used in the model over-estimate the actual loss. The over-estimation is only significant when considering small percentage area loss (< 3%), but not for area loss comparable to 5%, or greater, data loss. The over-estimation is significantly reduced for the < 3% loss region when scattering is considered.

3. Fixed-satellite service spot beam scattering analysis

The scattering model presented [Nicholas *et al.*, 1983] was used to determine the power scattered from the Earth's surface by a fixed satellite at 18 GHz.

At 8/7 GHz (x band), the values of σ_0 presented in [Nicholas *et al.*, 1983] indicate that typical Earth land surfaces have β_0 values of 6° to 12° and H values of 1/5 to 1/13. The term β_0 is defined as arc tan $[2\sigma/T]$ where σ is the surface roughness and T is the surface horizontal correlation distance. The term, H, is defined as $4\pi\sigma/\lambda$. Projecting these β_0 and H values to 18 GHz yields β_0 = 12° to 24° and H = 2/5 to 2/13. Confirmation of these values can be seen in Skylab 15 GHz back-scatter data, which produce values of β_0 of 12° to 24° and H = 0.5 to 0.25 [Nicholas *et al.*, 1983]. The values of σ_0 for all three-dimensional directions was calculated utilizing these values for β_0 and H, and for incoming angles of arrival from a fixed satellite of from 10° to 90°. The model presented in [Nicholas *et al.*, 1983] yielded σ_0 values that ranged from −25 dB to +3 dB. In order to provide a conservative bound, the maximum σ_0 value in all directions was determined. It was found that σ_0 was less than −5 dB in all directions except for ± 10° about the specular direction, in which case $-5 < \sigma_0 < 3$ dB.

The reflected power that a sensor will receive (in dB) is:

$$P_R = PFD + BW_s + \sigma_0 + A_s + G_s + \lambda^2/4\pi + 1/4\pi R^2$$

where:

PFD:	fixed-satellite PFD (dB(W/(m^2 · MHz))),
BW_s:	sensor bandwidth relative to 1 MHz (23 dB),
σ_0:	average normalized radar scattering cross-section (dB),
A_s:	area within sensor 3 dB beamwidth and Earth intersection (66 dB(m^2)),
G_s:	sensor antenna gain (57 dBi),
λ^2:	wavelength (−36 dB(m^2)),
$1/4\pi R^2$:	spreading loss (−125 dB(m^{-2})).

The power received then can be simplified to:

$$P_R = PFD - 26 + \sigma_0 \qquad \text{dBW}$$

A sensor interference level of −155 dBW implies that σ_0 must be less than −24 dB for sharing to be feasible when the PFD is −105 dB(W/(m^2 · MHz)), the present limit. Based on the scattering model for 18 GHz and the Skylab data, such values would virtually never occur. In fact, −5 dB is a more typical value for the vast majority of surfaces at 18 GHz. Thus a reduction of 19 dB in PFD would be required to limit data loss to small angles around the specular direction. Figure 8 illustrates the area (A + B) lost due to one fixed satellite having a 50 dBi spot-beam antenna and operating at the current PFD.

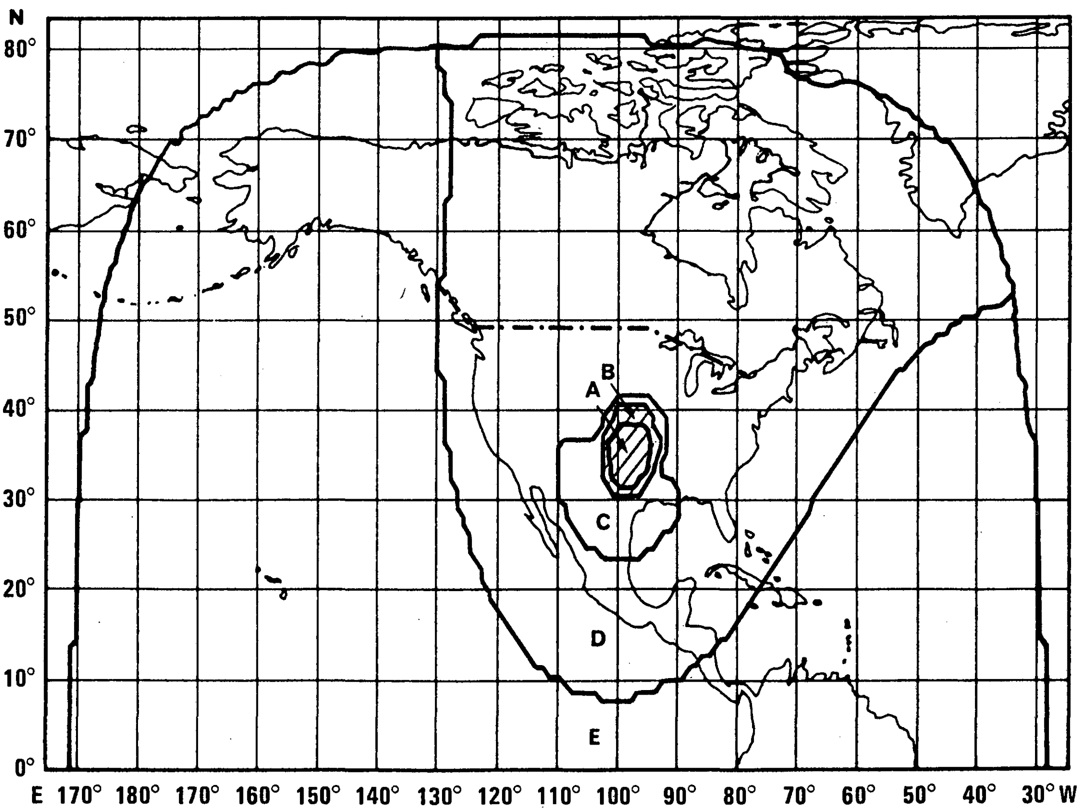

FIGURE 8 – *PFD contours and data loss areas due to a system operating at the current PFD limit utilizing one FSS satellite beam (G_T = 50 dBi)*

Areas A: PFD ⩾ −115 dB(W/(m² · 1 MHz))
B: PFD ⩾ −125 dB(W/(m² · 1 MHz))
C: PFD ⩾ −135 dB(W/(m² · 1 MHz))
D: PFD ⩾ −145 dB(W/(m² · 1 MHz))
E: PFD ⩾ −155 dB(W/(m² · 1 MHz))

Note. – Crossed hatched areas represent data loss regions.

Since a satellite at 18 GHz would likely have more than one spot beam, a 10-beam satellite system was analysed based on the proposed system for the United States of America discussed in the main text. Area C in Fig. 4 is the area lost to passive sensing based on the current PFD limits. Clearly, the large area lost would seriously affect the full operation of the passive sensor at 18 GHz under the current allowable PFD. If the PFD were reduced by 16 dB, the area lost would be reduced from area C in Fig. 4 to area A where PFD levels as high as -102 dB(W/(m^2 · MHz)) are found. The loss would occur regardless of the orientation of the sensor antenna with respect to the direction of specular reflection from the FSS satellite. A further reduction of PFD by 6 dB to 22 dB below the current limit would result in the loss to the passive sensor occurring only when the sensor antenna is aligned within ± 10° of the specular direction. A still further reduction of PFD by an additional 8 dB would eliminate interference even when the sensor is aligned with the direction of specular reflection from the FSS satellite.

4. Conclusions

In the case of the fixed service, scattering reduces, almost by half, the number of possible transmitters operating on a shared basis at the criteria proposed in this Report. However, this lower number is still expected to exceed the number of transmitters actually in service in the visibility area of the passive sensor. Hence, sharing at the proposed criteria would be feasible.

In the case of the fixed-satellite service, scattering considerations would require a 22 dB reduction in the PFD limit in order to permit satisfactory operation of passive sensors. A further 8 dB reduction would preclude interference occurring in the specular direction.

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REPORT 987

INTERFERENCE TO SPACEBORNE REMOTE PASSIVE MICROWAVE SENSORS FROM ACTIVE SERVICES IN ADJACENT AND SUB-HARMONIC BANDS

(Question 12/2 and Study Programme 12B/2)

(1986)

1. Introduction

The purpose of this Report is to present the results of analyses to determine the compatibility between remote passive microwave sensors on satellites and active services in adjacent and sub-harmonic bands.

These analyses have required the determination of typical sensor and interferer filter characteristics, and the development of a model suitable for the quantization and assessment of the cumulative interference to the sensors.

2. Sensor characteristics

Sensor characteristics and interference thresholds are presented in Reports 693 and 694. The interference threshold is defined in Report 694 as 20% of the minimum discernible power change.

The sensor antenna is assumed to be an under-illuminated, high-efficiency antenna having a beamwidth commensurate with the resolution requirements given in Report 693. It is modelled as in Report 850 with 90% of the received power coming from the main beam of the antenna. Seven per cent of the received power is attributed to the region which includes the near side-lobes, 2% to the far side-lobes and 1% from the back-lobe region.

Input or RF filters are not typically used on sensors because of the extremely low power levels being detected. Input passband characteristics are therefore determined by the IF bandwidth, antenna, antenna switch, and waveguide characteristics. It is estimated that the input passband of a typical sensor can be modelled by use of the passband characteristics of a 4-pole Butterworth filter. For a description of Butterworth filters, see [ITT, 1972].

3. Terrestrial interferer characteristics

Data required to characterize typical terrestrial transmitting stations include bandwidth, transmit power, main beam gain, number of units, and allocated band within which all units of the particular station class can be found. Values of these parameters were chosen to best represent all assignments. Knowing the main-lobe gain of a particular station, side-lobe gains can be predicted with the patterns given in Report 391.

An upper bound for harmonic output power from interfering stations can be predicted from the table of maximum permitted spurious emission power levels in Appendix 8 to the Radio Regulations. Because of the uncertainty in predicting interferer characteristics at high harmonics, especially those of antennas, this study was limited to the first two sub-harmonics of the sensing bands. The gain of antennas up to the third harmonic was assumed to be constant because of the offsetting effect of the increased antenna effective area as opposed to the increased antenna surface tolerance losses, and the decreased antenna feed efficiencies with increasing frequency.

After reviewing the ITU and domestic United States of America regulations it was determined that a 3-pole Butterworth filter characteristic would best represent the interferer spectrum for out-of-band emissions. The number and characteristics of interferers used in the analysis were determined from statistics compiled from the frequency assignments in the United States of America.

4. Spaceborne interferer characteristics

It was determined that a 3-pole Butterworth filter characteristic is suitable for modelling spaceborne transmitters.

For spurious emission power levels, it was assumed that the levels contained in Appendix 8 to the Radio Regulations could be extended to apply to space services.

5. Out-of-band rejection factor (OBRF)

An out-of-band rejection factor, OBRF, can be defined as the fraction of interference power that is accepted by the sensor. It is of the form:

$$OBRF = \frac{\int_0^\infty B(f)\,\mathrm{d}f}{\int_0^\infty A^2(f)\,B(f)\,\mathrm{d}f} \tag{1}$$

where:

f: frequency (Hz),

$A(f)$: normalized sensor receiver amplitude response,

$B(f)$: normalized interference spectrum.

If both the sensor receiver passband and the interferer spectrum can be modelled by a Butterworth filter characteristic, then:

$$A^2(f) = \frac{1}{\left(\frac{2(f-f_r)}{B_r}\right)^{2N_r} + 1} \tag{2}$$

$$B(f) = \frac{1}{\left(\frac{2(f-f_i)}{B_i}\right)^{2N_i} + 1} \tag{3}$$

where:

B_r : -3 dB receiver bandwidth (Hz),

N_r : number of receiver filter poles,

f_r : receiver centre frequency (Hz),

B_i : -3 dB interferer bandwidth (Hz),

N_i : number of interferer filter poles,

f_i : interferer centre frequency (Hz).

In order to evaluate these integrals using numerical techniques, it was assumed that the receiver filter has a maximum rejection of 70 dB. Similarly, it was assumed that the interferer power is contained within ± 10 times its -3 dB bandwidth.

Figure 1 shows the relationship between OBRF, the number of poles in the receiver filter, and the guard band (i.e. the separation between the -3 dB frequencies of the sensor and the interferer) for an interferer having the indicated characteristics. A new set of curves is required for each different combination of receiver and interferer bandwidths.

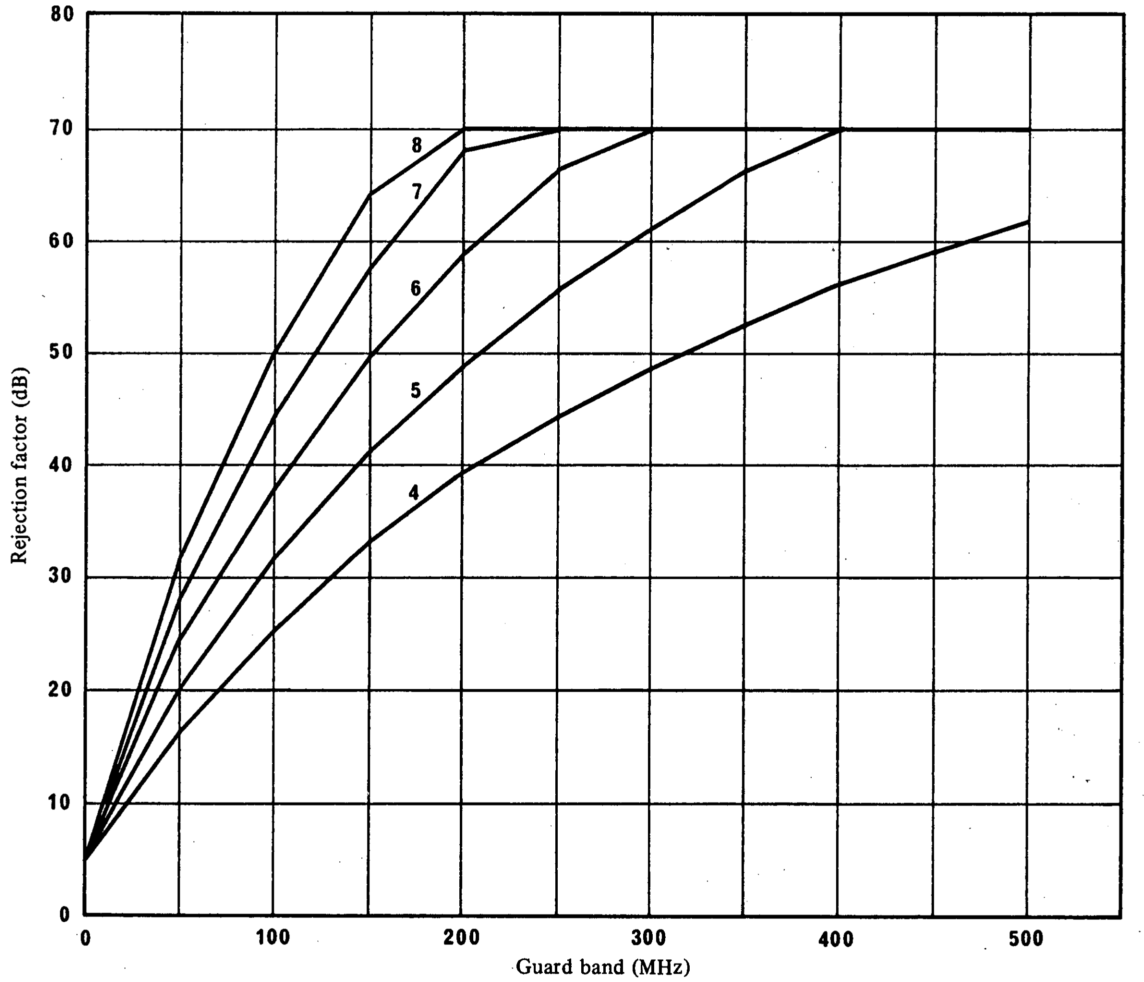

FIGURE 1 – *Out-of-band rejection factor for a 20 MHz bandwidth interferer (200 MHz bandwidth receiver with 4 to 8-pole Butterworth filter characteristics. Interferer spectrum modelled by 3-pole Butterworth filter characteristics)*

6. Interference modes

This Report analyses interference levels into passive sensors from both terrestrial stations and space stations using techniques similar to those in Report 694. Interference from terrestrial stations is computed using a uniform distribution model.

6.1 *Interference modes in the case of transmitting terrestrial stations*

There are three separate modes of interference that must be evaluated. Interference can occur when a terrestrial transmitter is within the main beam and near side-lobes of the sensor antenna. Interference can also occur when the main beam of a terrestrial transmitter illuminates the sensor. In both these cases, a single transmitter can cause the loss of data over a small area of the Earth corresponding to the area within the beam of the sensor during the time that interference occurs. To determine if interference occurs, the spreading loss and the OBRF are applied to the transmitted power of the interferer to determine the interference power received by the sensor. This power is compared to the interference threshold to determine if harmful interference exists. To determine the percentage of area lost to remote sensing, all individual lost areas are summed and the sum is compared to the total area.

The third mode of interference involves small interference contributions from all transmitters within line-of-sight of the sensor. Similar calculations to those above permit determination of the interference power from each transmitter and contributions from all interferers are summed to determine if the harmful interference threshold is exceeded. If the threshold is exceeded in this mode, all the visible area is lost.

6.2 *Interference modes in the case of transmitting space stations*

Two interference modes are considered in the assessment of interference from space stations: interference into sensor back-lobe from the interferer main-lobe and interference into the sensor main-lobe and near side-lobes from energy reflected from the Earth. Sample calculations of the interfering power levels into a sensor from fixed-satellite space stations in the adjacent band and shown in Table I.

TABLE I – *Adjacent band interference from the fixed-satellite service into the 18 GHz sensor band*

Contribution from back-lobe				
Interferer e.i.r.p. (including OBRF) (dBW)		26.4		
Allowance for spreading loss (dB(m^2))		–162.0		
Back-lobe effective area (dB(m^2))		–63.5		
Receiver power (dBW)		–199.1		
Contribution from main-lobe and near side-lobes				
Interferer e.i.r.p. (including OBRF) (dBW)		26.4		26.4
Allowance for spreading loss to Earth (dB(m^2))		–162.0		–162.0
Allowance for reflection loss (dB)		–8.0		–8.0
Allowance for spreading loss ($4\pi R^2$, R in m) from Earth to low orbit (dB(m^2))		–125.0		–125.0
Sensor footprint (dB(m^2))	Main-lobe gain	65.0	near side-lobes	79.0
Effective area (dB(m^2))	Main-lobe gain	13.1	near side-lobes	–11.9
Received power (dBW)	Main-lobe gain	–190.5	near side-lobes	–201.5
Total received power (dBW)		–190.2		

7. Results

7.1 *Interference from terrestrial stations*

Using the previously described models, an assessment of the interference from adjacent and sub-harmonic bands to remote passive microwave sensors was made for conditions representative of those over the United States of America. For the case of sensor receivers which have 4-pole Butterworth filter characteristics, the total interference levels from terrestrial stations in adjacent and sub-harmonic bands are tabulated in Table II. Each row in Table II lists the sensor frequency band, the interference threshold (from Report 694), the calculated level of total interference power into the sensor far side-lobes (mode 3) and the percentage of area loss. In those cases where the interference received in the far side-lobes exceeds the interference threshold, 100% of the visible area is lost to passive sensor operations. If this condition does not pertain, the percentage of area loss is that resulting from modes 1 and 2.

TABLE II – *Interference levels from terrestrial stations – 4-pole receiver filter characteristics*

Sensor frequency		Interference threshold (dBW)	Interference received into far side-lobes (dBW)	Percentage of area lost (%)
1400-1427	MHz	–171.0	–139.0	100.0
1406-1421	MHz	–174.0	–162.1	100.0
4200-4400	MHz	–158.0	–148.5	100.0
4225-4390	MHz	–159.0	–159.0	3.4
6425-7075	MHz			
6425-6625	MHz	–158.0	–150.7	100.0
6445-6645	MHz	–158.0	–158.9	11.8
6650-6850	MHz	–158.0	–181.0	0.4
6845-7045	MHz	–158.0	–158.0	3.8
6875-7075	MHz	–158.0	–146.3	100.0
10.600-10.700	GHz	–156.0	–170.5	0.6
15.200-15.400	GHz	–160.0	–164.8	0.6
18.600-18.800	GHz	–152.0	–166.9	0.2
21.200-21.400	GHz	–160.0	–186.3	0.0
22.210-22.500	GHz	–155.0	–189.1	0.0
23.600-24.000	GHz	–157.0	–175.0	0.5
31.300-31.800	GHz	–156.0	–192.4	0.1
36.000-37.000	GHz	–146.0	–189.8	0.0
50.200-50.400	GHz	–157.0	–264.9	0.0
51.400-59.000	GHz			
51.400-51.600	GHz	–157.0	–336.8	0.0
55.100-55.300	GHz	–157.0	–336.8	0.0
58.800-59.000	GHz	–157.0	–336.8	0.0
64.000-65.000	GHz			
64.000-64.200	GHz	–157.0	–300.5	0.0
64.400-64.600	GHz	–157.0	–300.5	0.0
64.800-65.000	GHz	–157.0	–300.6	0.0
86.000-92.000	GHz	–138.0	–187.0	0.0
100.000-102.000	GHz	–150.0	–204.0	0.0
105.000-126.000	GHz			
105.000-107.000	GHz	–150.0	–229.7	0.0
114.500-116.500	GHz	–150.0	–230.5	0.0
124.000-126.000	GHz	–150.0	–231.2	0.0
150.000-151.000	GHz	–150.0	–270.1	0.0
164.000-168.000	GHz	–150.0	–261.6	0.0
182.000-185.000	GHz	–150.0	–342.2	0.0
217.000-231.000	GHz	–150.0	–227.9	0.0
275.000-277.000	GHz	–150.0	–334.3	0.0

In those cases where allocated bands are wider than the sensor bandwidth, for example the 51.4-59.0 GHz band, the 64-65 GHz band and the 105-126 GHz band, the analysis was carried out at the lower edge of the band, at the centre of the band, and at the upper edge of the band.

For all bands above 10 GHz the received interference in the far side-lobes (mode 3) is below corresponding interference thresholds and the percentage of area lost by modes 1 and 2 is below 5%.

At the lower end of the 6425-7075 MHz band, i.e., 6425-6625 MHz, and at the high end, i.e., 6875-7075 MHz, the interference level in the far side-lobes is above threshold. Interference is below threshold within the range of 6445-7045 MHz. Note, however, that harmful interference may result from fixed-service transmitters operating throughout the 6425-7075 MHz band (see Report 694) and the question of interference from transmitters in adjacent bands may be of secondary importance.

For the 4200-4400 MHz band, the received interference power in the far side-lobes (mode 3) exceeds the threshold by 9.5 dB and the percentage of area lost is therefore 100%. However, for a sensor bandwidth reduced from 200-165 MHz, and centred on 4308 MHz, the interference level due to mode 3 is below threshold and the area lost by modes 1 and 2 is 3.4%.

For the 1400-1427 MHz band, the interference in the far side-lobes exceeds the threshold by 31.7 dB. For a reduced sensor bandwidth of 15 MHz, centred at 1414 MHz, the interference level still exceeds the threshold, in this case by 11.9 dB. Note that the calculated percentage of area lost is valid only near land areas with a density of interferers such as that which exists in the United States of America (see Report 694, Annex I).

The analysis of sensor operation was further refined for the 1400, 4200 and 6400 MHz bands by considering the effect of a 10-pole receiver filter. These results are shown in Table III.

TABLE III – *Interference levels from terrestrial stations – 10-pole receiver filter characteristics*

Sensor frequency (MHz)	Interference threshold (dBW)	Interference received into far side-lobes (dBW)	Percentage of area lost (%)
1406-1421	–174.0	–163.1	100.0
4200-4400	–158.0	–152.4	100.0
4210-4400	–158.0	–160.4	1.2
6425-7075			
6425-6625	–158.0	–154.9	100.0
6430-6630	–158.0	–160.4	3.7
6650-6850	–158.0	–181.1	0.3
6865-7065	–158.0	–158.4	1.3
6875-7075	–158.0	–149.7	100.0

In the 1400 MHz band, the reduced sensor bandwidth of 15 MHz centred on 1414 MHz combined with the use of a 10-pole filter results in interference, primarily due to interferers in sub-harmonic bands, which exceed the threshold by 10.9 dB.

In the 4200 MHz band, use of a 10-pole filter permits operation with a sensor bandwidth of 190 MHz centred on 4305 MHz with an interference level due to mode 3 which is below threshold and with an area loss due to modes 1 and 2 of 1.2%.

Finally, the range where interference from adjacent bands is not a factor in the 6400 MHz band expands up to 6430-7065 MHz when a 10-pole receiver filter is used.

7.2 *Interference from space stations*

Calculations of interference levels into sensors due to space stations in adjacent and sub-harmonic bands were performed for each of the allocated sensor bands using interferer characteristics representative of all classes of space stations in the respective adjacent and sub-harmonic bands. The results show that interference from space stations in adjacent and sub-harmonic bands is below the harmful threshold in all cases. Note, however, that there is a potential in-band interference problem in the band 18.6-18.8 GHz which is considered in Report 850.

8. Conclusions

8.1 For sensor operation in allocated bands above 10 GHz, the calculated interference levels due to terrestrial transmitters in adjacent and sub-harmonic bands are below threshold and the percentage of area lost is less than 5% using only a 4-pole receiver filter. For these frequency bands, harmful interference from transmitters in adjacent and sub-harmonic bands does not constitute a problem.

In the 6425-7075 MHz band, transmitters in adjacent bands would cause harmful interference to sensors operating near the lower and higher edges of the band.

In the 4200-4400 MHz band, sensor operation with a full 200 MHz bandwidth results in interference levels above threshold. Provision of guard bands can improve this result. Interference levels due to mode 3 are below threshold. Area loss due to modes 1 and 2 of less than 5% result from sensor bandwidth and filter types, for example, of:

– sensor bandwidth of 165 MHz centred at 4308 MHz using a 4-pole filter, and
– sensor bandwidth of 190 MHz centred at 4305 MHz using a 10-pole filter.

In the 1400 MHz band, calculated interference levels exceed the threshold for both of the receiver filter types examined in this study:

– a 27 MHz sensor bandwidth or a 15 MHz bandwidth centred at 1414 MHz using a 4-pole receiver filter, and
– a 15 MHz bandwidth centred at 1414 MHz using a 10-pole receiver filter.

The predominant form of interference in the 1400 MHz band is due to interferers in sub-harmonic bands.

8.2 Interference to passive sensors in allocated bands from space stations transmitting in adjacent and sub-harmonic bands was determined to be below the harmful interference threshold in all cases.

8.3 Note that the analyses described above are considered to be for the worst geographic case situation. For much of the world's land and ocean surface areas, not within or near the United States of America, the observed levels of interference are likely to be less than those calculated in this Report. However, the use of passive sensors at 1400 MHz near land areas having a large number of transmitters in sub-harmonic bands should be aproached with caution because of the possibility of harmful interference.

The analyses given in this Report are based on the extrapolation, above 17.7 GHz for terrestrial services and above 960 MHz for space services, of the maximum permitted spurious emission power levels contained in Appendix 8 to the Radio Regulations.

REFERENCES

ITT [1972] *Reference Data for Radio Engineers.* Fifth Edition. Howard Sams and Co. Inc., New York, NY, USA.

RECOMMENDATION 516*

FREQUENCY BANDS FOR ACTIVE SENSORS USED ON EARTH EXPLORATION AND METEOROLOGICAL SATELLITES

(Question 12/2 and Study Programme 12B/2)

(1978)

The CCIR,

CONSIDERING

(a) that, in certain frequency bands, space-borne active microwave sensors can provide unique information on physical properties of the Earth, as explained in Report 693;

(b) that space-borne active microwave sensors currently used are radars, radiating in general very short bursts of microwave energy;

(c) that existing and planned space-borne active microwave sensors have operating characteristics similar to those of terrestrial and air-borne radars;

(d) that terrestrial and air-borne radars share common frequency bands;

(e) that Report 695 examines a probable worst case example of mutual interference between some space-borne active microwave sensors and terrestrial radars;

(f) that Report 695 shows sharing to be feasible between some space-borne active microwave sensors and terrestrial radars in some bands of the Radiolocation Service,

UNANIMOUSLY RECOMMENDS

1. that it would be technically feasible for some bands of the Radiolocation Service to share with space-borne active microwave sensors.

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* This Recommendation should be brought to the attention of Study Group 8.

REPORT 695-2*

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACEBORNE RADARS AND TERRESTRIAL RADARS IN THE RADIOLOCATION SERVICE

(Question 12/2 and Study Programme 12B/2)

(1978-1982-1986)

1. Introduction

This Report documents the feasibility of radio frequency sharing between spaceborne active sensors on Earth exploration satellites and terrestrial radars in the radiolocation service.

It has been assumed that spaceborne active sensors may operate in bands allocated to the radiolocation service. The WARC-79 allocated several frequency bands to that effect between 1 and 80 GHz either in the Table of Frequency Allocations, or in Footnotes Nos. 713, 828, 897 and 912. However, no formal studies of sharing feasibility are known to have been documented. The purpose of this Report is to fill this gap.

2. Background

Although many of the active microwave sensor efforts to date have been concentrated in laboratory and aircraft experimentation, several active microwave systems have been flown on spacecraft. The Skylab Earth Resources Experiment Packages (EREP) flown in 1973, contained a microwave radiometer/scatterometer and altimeter. The GEOS-3 launched in 1975 also carried an altimeter. Seasat, launched in 1978, carried an altimeter, scatterometer and synthetic aperture radar (SAR) (see Report 535). Additional active microwave sensors are being considered by the United States of America for flight missions in the 1980's. For example, active microwave sensor experiments are planned for the Severe Storm Observation Satellite. It can also be expected that future Shuttle/Spacelab missions will have payloads containing active microwave sensors for Earth exploration.

3. Study approach

The approach adopted for this study was to determine the amount of harmful interference that can occur between very susceptible terrestrial and spaceborne radars. The reasoning used for this approach was that sharing will be generally feasible between spaceborne and terrestrial radars if the most susceptible radars can operate on a shared basis.

The spaceborne radar selected for the analysis was the SAR, since this type of radar is likely to be the most abundant and susceptible spaceborne radar. More specifically, the Seasat (SAR) was chosen since its technical operating parameters are typical of spaceborne SAR radars.

The terrestrial radar mode utilized in the analysis was based on two air route surveillance radars, the ARSR-1 and ARSR-2. Although this analysis pertains to radiolocation devices and the ARSR-1 and ARSR-2 operate in a different service (the radionavigation service), where a minute amount of interference may be harmful, the ARSR-1 and ARSR-2 were used for the terrestrial radar model for the following reasons:

- current use: these ARSR radars employ normal and Moving-Target-Indicator (MTI) radars which are commonly employed by both the aeronautical radionavigation and radiolocation services, and hence a generic radar model can be constructed which is representative of a large variety of radars;
- interference susceptibility: normal and MTI radars could be highly susceptible to interference from a spaceborne radar;
- interference potential: these ARSR radars have peak powers up to 5 MW, which is as high as, or higher than, other radars in the vicinity of SAR operations.

Report 827 discusses some of the parameters utilized in various radars. Based on this information and a US survey of the preferred frequency bands for active sensors (Report 693), the following can be concluded:

- a worst-case terrestrial radar output power is about 5 MW;
- typical main beam antenna gains are around 35 dBi;

* This Report should be brought to the attention of Study Groups 1 and 8.

- the vast majority of bandwidths are between 1 to 10 MHz, tending toward the lower end;
- the pulse duration (PD) varies mostly between 0.2 and 2 μs;
- the emission is typically P0N or PXN.

Radar processing is of particular concern in a radar sharing analysis. In order to make the model as general as possible, four types of radar processing modes were considered: normal, MTI, integrated and digital modes.

4. System characteristics

4.1 *Spaceborne radar*

The spaceborne radar, the Seasat SAR, had the following emission and orbit characteristics [NASA, 1976]:

4.1.1 *Emission characteristics*

– frequency:	1.285 GHz centre frequency
– power:	800 W peak (nominal)
– gain:	35 dB
– beam shape:	6.3° cross track, 0.9° wide; pointed 20° off nadir and perpendicular to the spacecraft's velocity vector
– swath width:	100 km (−3 dB points of antenna)
– pulse repetition rate:	1464, 1540 or 1647 pps
– pulse duration:	33.8 μs
– modulation:	chirp 0.562 MHz/μs
– polarization:	horizontal
– bandwidth of emission:	19 MHz
– spectrum density over bandwidth:	approximately uniform

4.1.2 *Orbit characteristics*

– altitude:	800 km
– period:	100.75 min
– inclination:	108°

4.2 *Radiolocation radar*

The relevant technical characteristics of a generic radiolocation radar were based on the ARSR-1 and ARSR-2 [FAA, 1964 and 1973].

The ARSR is a pulsed radar having three analogue processing modes and one digital processing mode. These modes are:

- normal video
- integrated normal video
- MTI video
- digital processed video

In order to overcome clutter in normal video, techniques such as integration, MTI, or digital processing are employed.

Other characteristics of the ARSR-1 and ARSR-2 are:

4.2.1 *Transmitter*

– frequency:	co-channel
– power:	4 MW and 5 MW peak (minimum)
– pulse repetition rate:	360 pps or 3 pulse staggered (13:14:15) mode, averaging 360 pps
– pulse width:	2 μs

4.2.2 *Receiver*

– bandwidth:	normal (1 MHz) and MTI (3 MHz)
– sensitivity:	normal (–113 dBm), MTI (–111 dBm) and integrated (–116 dBm)
– minimum detectable signal:	ARSR-1 [normal (–109 dBm), MTI (–107 dBm) and integrated (–112 dBm)]; ARSR-2 (–111, –109, –114 dBm respectively)
– system noise figure:	less than 4 dB
– subclutter visibility (MTI):	27 dB
– cancellation ratio (MTI):	33 dB

4.2.3 *Digital processor*

– special digital processing of normal or MTI video

4.2.4 *Antenna*

– gain:	34 dB along axis of maximum radiation
– beamwidth:	horizontal 1.35° and vertical 6.2° for ARSR-1 and 1.2 by 4° for ARSR-2. Beam in elevation is a modified cosecant squared pattern
– polarization:	horizontal or circular
– scan rate:	6 r.p.m.

5. Sharing analysis

5.1 *Down-link analysis*

There are four primary considerations regarding interference experienced by the terrestrial radar and, consequently, the ability to share with a spaceborne SAR. These considerations are:

– processing effects on interference,
– amount of time, expressed as a percentage, that the spaceborne SAR produces power in the terrestrial radar receiver bandwidth exceeding the minimal detectable signal (MDS). This amount of time is based on long-term antenna "couplings" between these radars,
– amount of time that the SAR emissions exceed the MDS on individual passes,
– form of the interference, as presented on an operator's planned position indicator (PPI).

5.1.1 *Normal and MTI modes*

In the normal mode, the processing is such that any interference pulse, on the same centre frequency, will be detected when above the receiver MDS. In the MTI mode, the MTI canceller, whose delay time is not equal to the interferer interpulse period, can in general produce several interference pulses for each interference pulse above MDS.

The power received by a pulsed terrestrial radar from a pulse compression spaceborne transmitter is given by:

$$p_r = \left(\frac{p_t\, g_t\, g_r}{4\pi R^2}\right)\left(\frac{\lambda^2}{4\pi}\right)\left[\left(\frac{BW_r}{BW_t}\right)\left(\frac{T_2}{T_1}\right) \times (0.42)\right], \qquad \text{for } BW_r < BW_t \qquad (1)$$

where:

p_t: power of transmitter source (W),

g_t: gain of transmitting SAR antenna,

g_r: gain of terrestrial radar receiving antenna,

R: range (m),

λ: wavelength (m),

BW_r: bandwidth of the terrestrial radar receiver (Hz),

BW_t: bandwidth of the SAR transmitter (Hz),

T_1: pulse duration of the terrestrial radar,

T_2: pulse duration of the SAR.

Rearranging (1):

$$\frac{p_r\,(4\pi)^2}{p_t\,\lambda^2} \times \left[2.38\left(\frac{BW_t}{BW_r}\right)\left(\frac{T_1}{T_2}\right)\right] = \frac{g_t\,g_r}{R^2} \qquad (2)$$

If the value of received power used, is the minimum detectable signal, the parameters on the left-hand side are then all system constants, while those on the right-hand side are a function of geometrical relationships. A computer program was developed to calculate $g_t g_r / R^2$ curves as a function of time. The resultant curves for the terrestrial radar and SAR antennas, and Seasat orbital parameters, are presented in Fig. 1.

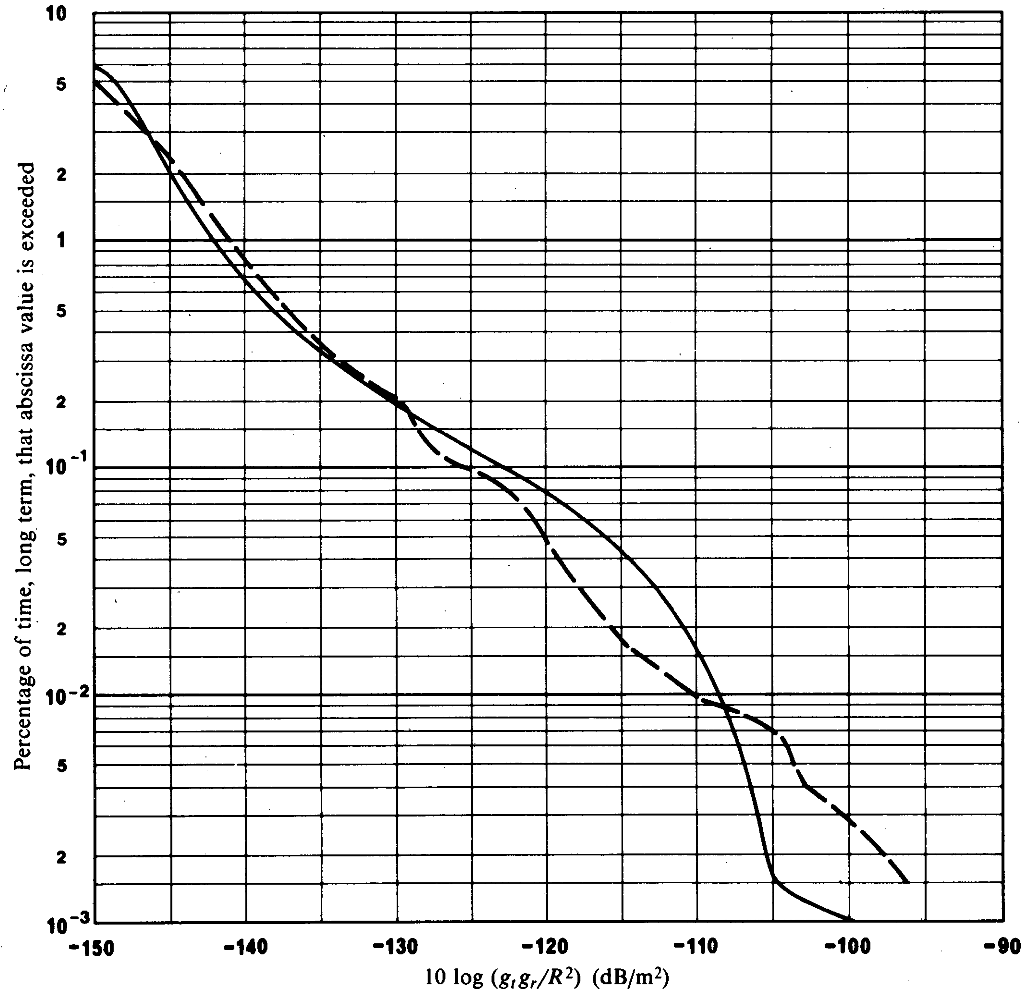

FIGURE 1 – *$g_t g_r/R^2$, long term couplings between spaceborne side-looking fan beam antenna and terrestrial radars for the Seasat orbital parameters*

——— typical 360° scan terrestrial radar

— — typical tracking terrestrial radar

The harmful values of $g_t g_r / R^2$, utilizing SAR and terrestrial radar system parameters, equal −122.6 dB in the normal mode and −120.6 dB in the MTI mode. From the curves of Fig. 1, it can be seen that these values are exceeded for 0.094% and 0.075% of the time respectively.

Figure 2 characterizes the display of detected interference pulses on an operator's PPI. The interference pattern generated is called a "running rabbit" pattern and is common among pulsed radars. For a given SAR orbit, the duration of the pattern depends basically on the elevation of the satellite SAR from the terrestrial radar and the mutual antenna couplings as the terrestrial radar antenna rotates.

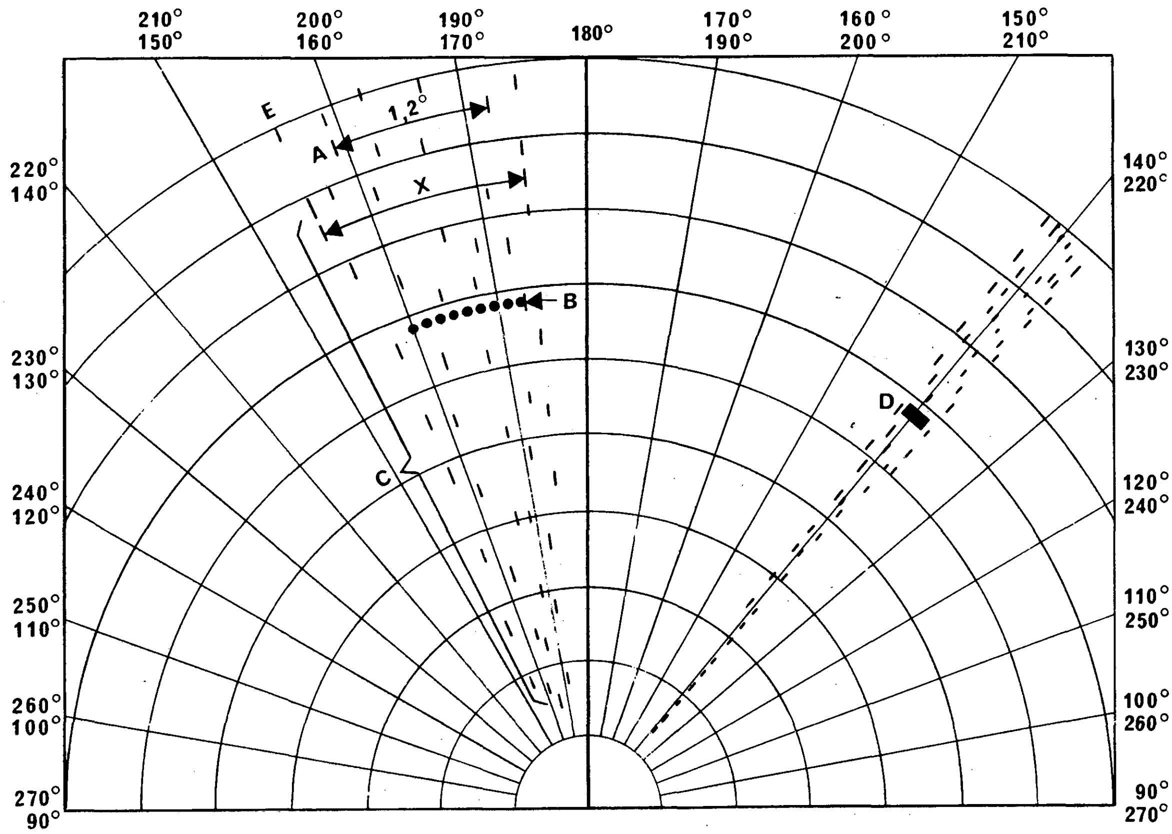

FIGURE 2 – *Normal video echo return with pulsed radar interference*

A: Individual range scans, expanded scale over one beamwidth of the terrestrial radar

B · Target

C : Interference

D: Actual appearance on PPI display

E : Range maximum, approximately 400 km

X: Width of interference sector, which is a function of antenna couplings

A near-overhead satellite pass produces the worst-case short-term PPI interference situation. In the normal mode, interference patterns could last for as much as 30 s for the worst-case pass; however, this pass occurs only once every 18 days for each typical Earth exploration satellite.

The more common type of interference mode will occur at low elevation angles from the terrestrial radar. Near the horizon, the terrestrial radar would experience approximately 1 s of interference per sweep (i.e. 10% of PPI display), for as long as the spaceborne radar is in line-of-sight – which is about 1 min for a near horizon pass. For a pass occurring near 50° elevation from the terrestrial radar, the interference time reduces to 0.1 s per sweep (i.e. 1% of PPI display) for as long as the spaceborne radar is in line-of-sight, which is approximately 12 min. On a daily average basis, two passes will occur during the day-time and two during the night-time period. However, as previously calculated, the overall long-term interference occurs for less than 0.094% of the time for either the normal or MTI modes [NASA, 1977].

5.1.2 *Integrated normal video and digital processing mode*

Integration is a method of summing a number of consecutive radar returns for the purpose of improving detection. Interference pulses, whether random or in a pulse train, will not add in a reinforcing manner in the integrator, unless their pulse period equals or is a multiple of the transmitting radar. Also, no single pulse could be large enough to trigger the threshold detector due to input limiting. However, pulse interference does slightly raise the probability of a false alarm from noise.

The digital processor, as commonly employed, performs a function similar to the analogue integrator, except that the digital processing is better able to reject clutter and interference through digital decision processes.

Thus, when in the digital processing or integrated modes, potential interfering pulses should be neither processed nor should appear on an operator's PPI display.

5.1.3 *Parametric analysis of interference for normal and MTI modes*

Figure 3 presents the results of a parametric computer simulation of normal and MTI mode interference times, the parametric variables being satellite power, receiver sensitivity (or MDS) and the number of satellites in orbit. The curves are all derivations of the $g_t g_r / R^2$ curve (Fig. 1). The satellites are assumed to be co-channel with the terrestrial radar for a worst-case interference situation. Also, atmospheric attenuation was not included so that one curve, for all frequencies, could be presented. Thus, the curves present an upperbound worst-case situation.

The following examples illustrate the use of Fig. 3:

Example 1: If the maximum acceptable percentage of the time for terrestrial radar interference were 0.1% and two satellites were operating co-channel, the upper limit of the maximum satellite transmitter power-to-receiver sensitivity (or MDS) ratio, to avoid harmful interference, would be 158 dB. If the receiver sensitivity (or MDS) were approximately −130 dBW, then the maximum allowable satellite transmitter power would be 29 dBW, or 800 W.

Example 2: If the maximum acceptable percentage of the time for interference were 1%, and all other factors were the same as in Example 1, then the maximum allowable satellite transmitter power would be 49 dBW or 100 kW.

Example 3: If there were 10 satellites and all other factors were the same as in Example 2, then the maximum allowable satellite transmitter power would be 35 dBW or 3 kW.

5.1.4 *Tracking and sector scan radars*

In addition to the terrestrial radars which scan the horizon in a 360° search pattern, there are pulsed radars which utilize narrow circular beams to track airborne targets. Characteristics of these radars can be considered identical to the search radar described previously with the exception of the following antenna parameters:

- gain 45 dBi
- beamwidth 0.9° circular
- back-lobe gain −10 dBi

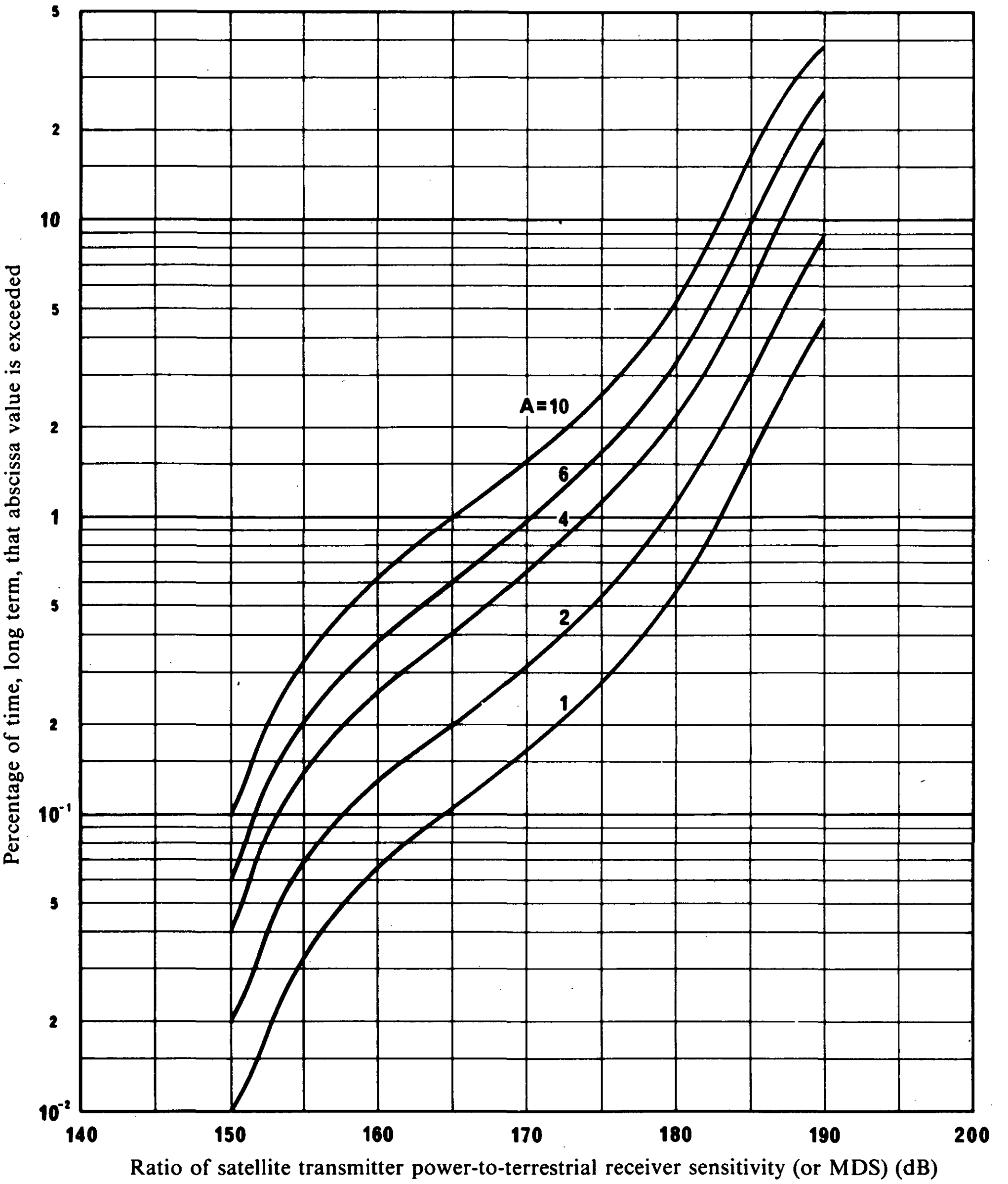

FIGURE 3 – *Parametric interference curves*

A: number of satellites carrying a spaceborne radar

The tracking radar was assumed to be pointed with equal probability within 0 to 30° of elevation and in any azimuth direction. Following the same procedure as described in § 5.1.1, a graph of $g_t g_r / R^2$ versus the long term percentage of time was obtained by computer simulation. The results for tracking radars are shown in Fig. 1. The higher gain and higher elevation angles of the tracking radar results in a value of $g_t g_r / R^2$ that exceeds, for small percentages of time, the value of $g_t g_r / R^2$ for a 360° scanning radar. This means that interference levels at the tracking radar receiver will be higher for small percentages of time, than in the case of the 360° scanning radar. However, Fig. 1 shows that the harmful level of $g_t g_r / R^2$ (-122.6 dB/m^2 for the model parameters) is exceeded for a somewhat lower percentage of time. It can be concluded that the long term percentage of time that the tracking radar would experience interference signals above the receiver threshold is of the same magnitude as for the 360° scanning radar case. Radar processing techniques for tracking radars, which are not accounted for in this analysis, could further reduce the effect of the interfering signal as they do in the case of the scanning radar digital and integrator modes.

Sector scan radars are similar to 360° scan radars in that they have a fan-shaped, low elevation beam that scans in a search pattern, except that the radar scan is restricted to a certain azimuthal sector around the antenna. The $g_t g_r / R^2$ curve and long term interference percentage of time are identical to the 360° scan radar case, with the exception of a radar scanning only the sector directly north (south in the southern hemisphere) of the antenna. In that case, the satellite orbit statistics result in higher long term interference percentage of time than would result in the case of a 360° scanning radar. The percentage of time that the receiver threshold would be exceeded is approximately twice that for the 360° scanning radar.

5.2 *Up-link analysis*

The same considerations regarding interference, as presented in the down-link analysis, apply to this analysis with the exception that interference effects on an image, rather than PPI, must be considered.

The SAR processes reflected signals in range and azimuth. High resolution in range is achieved by pulse compression techniques while azimuth resolution is achieved through "synthesizing" a long antenna by utilizing coherent processing.

Consequently, the analysis requires consideration of the SAR system range and azimuth processing outputs which include the wanted signal, an interfering signal from a terrestrial radar and system noise.

5.2.1 *Range processing*

Range processing is accomplished through the use of a matched filter. The output of the filter is the convolution of the input and filter transfer function. However, an "ambiguity function" can be substituted and is more useful since the derived output will be a function of not only input delay, but Doppler effect also.

The complex ambiguity function, in its most general form, is defined as:

$$\chi_{12}(\tau, \nu) = \frac{1}{2} \int_{-\infty}^{\infty} \mu_1(t)\, \mu_2^*(t - \tau)\, e^{j2\pi\nu t}\, dt \qquad (3)$$

where:

τ : delay

ν : Doppler frequency

$*$: complex conjugate

and,

$\mu_1(t)$: input signal

$\mu_2(t)$: signal for which the filter is matched.

When the input signal is matched to the filter, the ambiguity function is called the auto-ambiguity function. When the input is mismatched, the function is called the cross-ambiguity function. In both cases, the function represents the output, $Y(t)$, of the filter for a given Doppler shift of the input.

$$Y(t) = C_0 \,|\, \chi(t, \nu = \text{constant}) \,| \qquad (4)$$

For the desired signal, the auto-ambiguity function for a chirp signal is well known [Berkowitz, 1965; Cook and Bernfeld, 1967; Rihaczek, 1969] and is:

$$|\chi(\tau, \nu)| = \sqrt{BT} \left(1 - \frac{|\tau|}{T}\right) \frac{\sin\left[\pi T (k\tau + \nu)\,(1 - |\tau|/T)\right]}{\pi T (k\tau + \nu)\,(1 - |\tau|/T)} \qquad (5)$$

where:

B : bandwidth

T : period

k : chirp rate

If the input signal to the matched filter had an amplitude A, then the maximum output of the matched filter would be $\sqrt{BT} \times A$. Thus, the peak power gain for a matched filter is BT. For the Seasat SAR, the desired output pulse from the matched filter has a power gain (BT) of 28 dB and a duration, defined as the 3 dB points ($1/B$), of 53 nanoseconds.

For an interfering, non-chirp pulsed signal, the cross-ambiguity function is:

$$| \chi_{12} (\tau,\nu) | = 1/2 \left[(C(Z_1) + C(Z_2))^2 + (S(Z_1) + S(Z_2))^2\right]^{1/2} \tag{6}$$

where C and S are the Fresnel integrals. The resulting matched filter output for a terrestrial interference pulse, based on numerical evaluation, has a 2.28 dB gain, and a time extent at the 3 dB points, of the order of 2 µs.

For noise, since the matched filter is designed so that its frequency transfer function is $| H(f) | = 1$ over its bandwidth, the filter gain is 0 dB.

5.2.2 *Azimuth processing*

Azimuth processing is accomplished through the summation of returns received from different positions of the real antenna.

For the wanted signals, an N-summation yields an output that is N times the originally received signal – an output power gain of 20 log N.

For noise, an N-summation yields an output of only 10 log N, since samples from the same random process add incoherently.

For the interfering signal, the analysis of the azimuth processing is analytically difficult. However, it is possible to simulate and approximate the effect of the interfering signal. A computer programme was written to simulate successive range scans and the cumulative azimuth integration process.

The simulated time relationships, for interference pulses falling within the same pulse with a tolerance of ± 2 µs of successive range scans, are shown in Fig. 4. The bottom curve in Fig. 4 is the cumulative effect of azimuth processing summation of the various interference pulses over the chosen range. The oscillatory nature of this curve will be repetitious over the complete processed azimuth range scan due to the periodic nature of the radar signal. Also, the "phase" of each succeeding completely processed range scan will differ due to the time differences between the terrestrial radar and SAR PRF's and the SAR azimuth integration time. Such out-of-phase oscillations in line-video systems produces an interference effect that looks like a "wood grain" pattern.

The voltage oscillations in the azimuth processed range scan vary between one and approximately three times the peak voltage of one interference pulse out of the matched filter, as shown in Fig. 4. Consequently, instantaneous peak powers for azimuth processed interference pulses vary between 0 and 9.5 dB above the matched filter output for one interfering pulse.

5.2.3 *Input/output system comparisons and summary*

Table I summarizes the input/output power relationships as determined by system processing gains.

The maximum interference input signal is limited to the value presented in Table I due to the saturation of the spaceborne receiver. In the Seasat SAR, the received signal was amplified and frequency converted for transmission to an earth station – the range and azimuth processing took place on the ground. The functional requirements for the Seasat SAR receiver called for the receiver to have a variable gain of 77 to 99 dB and to hard-limit at +13 dBm. Since the minimum receiver gain was specified to be 77 dB, an interfering signal with −64 dBm of peak power would have saturated the Seasat receiver. Of course, if the Seasat receiver were in its highest gain mode (98 dB), a signal of −85 dBm could saturate the receiver. In either situation, interfering pulse powers into the range and azimuth processors would be peak-limited, and the resulting interference would vary in an oscillatory pattern from 1 to 10 dB above noise, as shown in Table I.

Table II presents the saturation interference times expected to be experienced by the SAR as the terrestrial radar swept past the SAR. Locations of interference refer to the terrestrial radar site.

Interference time per terrestrial radar sweep decreases as the spacecraft moves higher in elevation in relation to the terrestrial radar – the exception being when the SAR main beam traverses the terrestrial radar site (near-overhead pass).

For saturation times less than the SAR integration time (2.49 s), the processed interference video waveform will have oscillations of less than 1 to 10 dB above the system noise. For example, for 0.86 s of saturation the oscillations would vary between 1 to 3 dB above system noise, since only two interference pulses (out of six in Fig. 4) could add during the azimuth processing of any 4 μs range group.

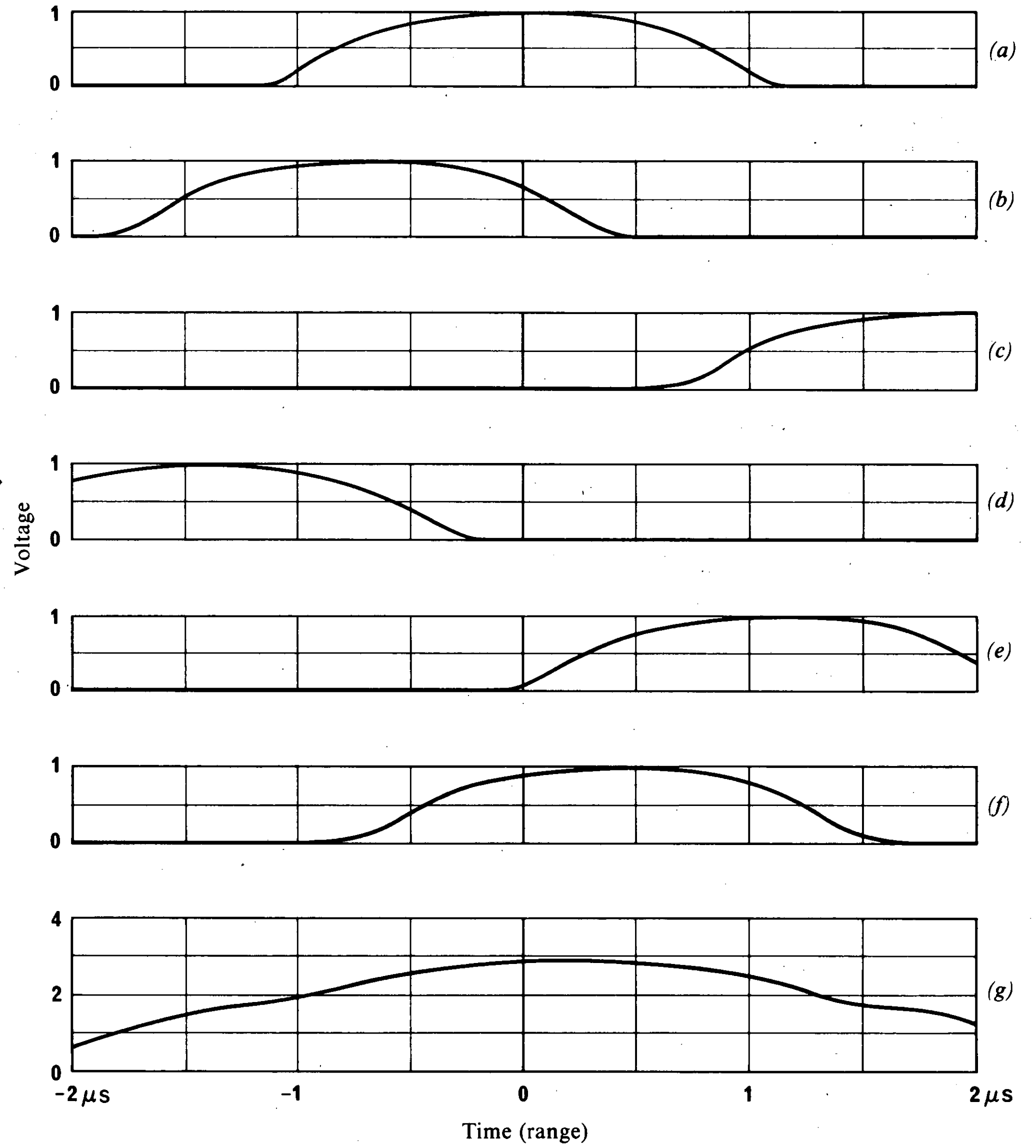

FIGURE 4 – *Interference output from SAR azimuth processor*

(a) to *(f)*: successive scans

(g): cumulative

TABLE I – *Input/output system comparisons*

Signal type	Input power (dBm)	Range processing (filter gain) (dB)	Azimuth processing (processing gain) (dB)	Output[1] power (dBm)
Noise	−98.5[2]	0	35.6	−62.9
Minimum desired signal	−162.1	28	71.2	−62.9
Maximum desired signal	−134.6	28	71.2	−35.4
Maximum interfering signal[3]	−64	2.3	0 to 9.5[4]	−61.7 to −52.2

(1) Gains and losses not dependent on signal waveform, such as the receiver gain setting or space-to-Earth transmission losses, for ease of presentation, have not been included in this Table.

(2) Antenna temperature 290 K, receiver noise temperature 550 K and bandwidth of 19 MHz.

(3) At lowest receiver gain setting.

(4) Based on *equal* pulse powers being processed.

TABLE II – *Interference times per terrestrial radar sweep*

	Input interference level	
	Low gain mode −64 dBm	High gain mode −85 dBm
Interference times (s)		
At the horizon	0.86	All the time
At 50° elevation	0.11	0.77
Near-overhead	1.27	All the time

Previous experience has indicated that actual scenes tend to "break-up" small magnitude interference patterns. Thus, when the SAR is in the low gain mode (maximum interference varying between 1 and 3 dB above noise for very short times) no harmful interference is expected. Also, from the operational viewpoint, the terrestrial radar will not be likely to sweep past the satellite SAR at the same azimuth heading on every pass. Consequently, "wood grain" interference would not occur in the same image-frame and, hence, multiple passes will obtain uncontaminated images.

The high gain mode, though, may provide somewhat more of a problem, since interference varies between 1 to 10 dB for long durations at the horizon and around the terrestrial radar site. However, regardless of gain mode, the spaceborne SAR could be designed to eliminate terrestrial radar interference by further receiver limiting to a level of +3 dBm. Such limiting will reduce SAR dynamic range by at least 3 dB and possibly more, depending upon linearity design constraints on the SAR receiver [NASA, 1977].

6. Summary and conclusions

The analysis of potential up-link interference to a spaceborne SAR, from a terrestrial radar, can be summarized as follows:

- The SAR is a state-of-the-art radar and is representative of a broad range of radars expected to be utilized in space.
- In the SAR low-gain mode, no harmful interference is expected.
- In the SAR high-gain mode, perceptible interference may occur; however, the nature of such interference would be similar to that encountered by airborne mapping radars currently operating in the radiolocation service.
- Interference-free SAR operation could be achieved through use of lower power saturation levels in the SAR receiver although at the cost of reduced dynamic range.

The analysis of potential down-link interference to a terrestrial radar from a spaceborne SAR, can be summarized as follows:

- The ARSR, on which the generic terrestrial radar model is based, is representative of a broad class of modern, high utilization radars.
- In the digital processing mode, the most common mode of terrestrial radar operation, and the integrated mode, the SAR emissions should not cause discernible interference due to processor discrimination, provided that the SAR pulse repetition rate is not at a harmonically related multiple of the terrestrial radar pulse repetition rate.
- In the normal and MTI modes, interference could be perceptible, and be of a nature such as that caused by other airborne and terrestrial radars. Perceptible interference will occur only for a very small percentage of the time – less than 0.094% from the Seasat type of SAR. The short term interference is a complicated function of elevation angle between the spaceborne radar and terrestrial radar. For a worst-case geometry, interference could occur over a 12 min period. In this case, interference time is 0.1 s per sweep for a total of 7.2 s over the 12 min period. The nature of the interference would be the appearance of "running rabbits" over 1% of the area of a PPI display.
- The analysis utilized a 800 km orbit for the spaceborne SAR, which is typical of the type foreseeable for Earth exploration satellites. Also, the gain patterns of typical Earth exploration satellite active microwave sensor antennas are likely to be of the form, $(\sin^2 X)/X^2 (\sin^2 Y)/Y^2$ which was used in the analysis. Consequently, the $g_t g_r / R^2$ curve derived in the analysis is representative for this type of service. The analysis showed that even utilizing powers as great as 2.4 kW, (three times greater than the power used in the analyses and the most powerful active sensor launched by NASA to date) the interference time would be less than 0.15% of the time. Or conversely, the terrestrial service would be interference free 99.85% of the time.
- The percentages of time given for perceptible interference apply specifically for 360° scanning terrestrial radars; however, they are approximately the same for the case of tracking and sector scan radars.

The $g_t g_r / R^2$ curve is strictly dependent on gain and range coupling geometries. Figure 1 is based on the particular terrestrial and spaceborne radars analyzed. Location of a point on the $g_t g_r / R^2$ curve (long term percentage of interference) is determined by the interferer transmitter power, receiver minimum detectable signal, frequency of operation and the modulation transfer function.

The conclusion to be drawn from these analyses is that sharing between spaceborne radars and systems in the radiolocation service is technically feasible. Although an aeronautical radionavigation radar was used to derive the generic terrestrial radar model, sharing between spaceborne radars and systems in the aeronautical radionavigation service, where safety of life is of paramount concern, was not considered as perceptible interference may occur in certain operating modes.

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RECOMMENDATION 362-2

FREQUENCIES TECHNICALLY SUITABLE FOR METEOROLOGICAL SATELLITES

(Question 12/2 and Study Programme 12C/2)

(1963-1970-1982)

The CCIR,

CONSIDERING

(a) that the value of meteorological-satellite systems is well proven;

(b) that some meteorological satellites are operating in a routine manner as indicated in Report 395;

(c) that certain bands are now allocated internationally to the meteorological aids service;

(d) that certain of the frequency needs of meteorological satellites may be satisfied through the use of the meteorological aids allocations established at present,

UNANIMOUSLY RECOMMENDS

1. that bands 8, 9 and 10 are technically suitable for narrow-band and wideband meteorological data transmission;

2. that frequencies allocated to the radiolocation services in bands 10 and 11 are technically suitable for use by the precipitation detection radar and cloud detection radar on board meteorological satellites.

REPORT 395-4

RADIOCOMMUNICATIONS FOR METEOROLOGICAL SATELLITE SYSTEMS

(Question 12/2 and Study Programme 12C/2)

(1963-1966-1970-1974-1978-1986)

1. Introduction

The Radio Regulations define the meteorological satellite service as an Earth exploration-satellite service for meteorological purposes. Many techniques of observation and data transmission are common to both meteorology and the study of Earth resources. The objectives of meteorological satellites differ from other Earth exploration satellites and apart from some sensing functions, which are conducted within the EES service allocations, operate in bands specifically allocated for the service.

This Report concerns the radio-frequency requirements of the present operational system of low orbit and geostationary spacecraft utilizing passive sensors in the infra-red and microwave (millimetre wavelength) portions of the electromagnetic spectrum. Sensing bands in use are those selected for optimum measurement of surface and cloud-top temperatures, for calculation of the vertical temperature and moisture profiles (soundings) of the atmosphere, and for estimation of winds at several altitudes. Reference is made also to frequencies needed for the use of active sensors for the parameters already noted, and for sea state, winds at multiple heights, and above all, for more detailed and accurate world-wide profiles of temperature and moisture throughout the atmosphere, and over shorter time intervals.

2. Meteorological satellite systems

Operational meteorological satellites constitute an integral part of the World Meteorological Organization (WMO) observational programme called the world weather watch (WWW) [WMO, 1983]. Operation of the WWW spacecraft is described in [WMO, 1975]. Through the aegis of the WMO, coordination and planning for future satellites, including both sensor standardization and frequency utilization, is carried out, both for geostationary and low-orbit spacecraft. An Ad Hoc Group of all satellite operators has met annually since 1972 as a body called Coordination of Geostationary Meteorological Satellites (CGMS) [CGMS, 1984].

Meteorological satellites carry sensors to provide images at visible, infra-red and radio wavelengths and data transmitters and transponders to return the image information to Earth. They also carry data collection systems to receive information of meteorological interest from platforms on the Earth's surface. Low-orbit satellites of the United States of America carry search and rescue transponders as a part of the International SARSAT Programme [Miller and Sparkman, 1984].

2.1 *Low-orbit spacecraft*

Low-orbit meteorological spacecraft, usually placed in Sun-synchronous orbits, are operated by the United States of America and the USSR [USSR, 1981]. Sensors include 1 km instantaneous field-of-view (IFOV), multi-spectral imagers, and an atmospheric temperature and moisture profiler using up to 23 infra-red channels, and five microwave channels, for tropospheric and stratospheric structure determination.

Table I lists characteristics of the present low-orbit meteorological satellites.

TABLE I – *Low-orbit meteorological satellites*

Name	Orbit height (km)	Orbit period (min)	Name	Sensors band	IFOV at sub-point (km)
METEOR (USSR)	900	102	Scanning telephotometer	0.5-0.7 μm	1
			Scanning telephotometer	0.5-0.7 μm	2
			Scanning infra-red radiometer	8-12 μm	8
			Spectrometer (8 channels)	11.10-18.70 μm	30
NOAA (United States of America)	850	101	Imager, advanced very high resolution radiometer (AVHRR) (5 channels)	0.58-12.5 μm	1
			Sounder, high infra-red resolution sounder (HIRS) (20 channels)	0.69-14.96 μm	17.5
			Stratosphere sounder, stratosphere sounding unit (SSU) (3 channels)	15 μm	147.3
			Microwave sounder, microwave sounding unit (MSU) (4 channels)	5.5 mm	105

2.2 *Geostationary spacecraft*

Because geostationary satellites view their earth sectors continuously, they have grown in importance as sensor and data relay platforms for many suddenly-occurring life-threatening natural hazards: hurricanes, tornadoes, severe thunderstorms and frontal disturbances, flash floods, earthquakes, and tsunamis.

Operational geostationary satellites have multi-channel imagers, and in the case of the United States of America spacecraft, additional channels for experimental soundings. Tests indicate that soundings from geostationary satellites can have a quality equal to those from low-orbit spacecraft. However, sensors to provide soundings from geostationary satellites as rapidly as images are scanned, have not yet been developed [Johnson, 1984].

Table II lists present and planned geostationary spacecraft.

TABLE II – *Geostationary meteorological satellites*

Operator	Name	Location
ESA	METEOSAT	0° E
India	INSAT	74° E
Japan	GMS	140° E
United States of America	GOES-West	135° W
United States of America	GOES-East	75° W
United States of America	GOES-Central (WEFAX only)	107° W
USSR (planned)	GOMS	76° E
USSR (planned)	GOMS-1	14° W
USSR (planned)	GOMS-2	166° E

3. Telecommunications requirements for meteorological satellites

Space telecommunications for meteorological satellites are required for several distinct functions, namely:

– for direct transmission of sensor data from spacecraft to earth stations;
– for active and passive sensing of the atmosphere, in the infra-red and several microwave bands from 1-200 GHz;
– for data relay from remote earth-located sensors (i.e. data collection platforms) to central data processing facilities (see Report 538) and for distribution of both data and data products from central processing facilities to distant users on land, at sea, or airborne; and
– for satellite control, sensor switching, and for multiple housekeeping functions.

3.1 *Measurement frequencies and bandwidths*

3.1.1 *Passive measurements*

The selection of spectral bands for passive sensing of the atmosphere is determined by the character of atmospheric transmission of electromagnetic radiation. These bands total in bandwidth from a few micrometres in the infra-red to a few megahertz in the microwave region (see Report 693 and Recommendation 515).

In both the infra-red and microwave regions of the spectrum, the frequency bands of value for atmospheric sounding and surface sensing are those at which either marked interaction, or a minimum interaction, occurs between atmospheric constituents and the passage of radiant energy. Frequencies are selected for the reactions that occur:

– with ozone (O_3) for determinations of temperatures and winds in the stratosphere;
– between radiation and water vapour and carbon dioxide for tropospheric sensing; and
– within atmospheric "window" channels for sensing surface temperatures and characteristics.

Microwave bands already used in experimental and operational satellites include: 1.27, 1.4, 3.5, 6.6, 8.8, 10.7, 13.5, 13.9, 14.6, 19.35, 22, 31, 33, 37 and 50-60 GHz, for atmospheric temperature and moisture profiles, and for sea surface temperature, surface roughness, and sea ice. Bands at 104, 118 and 140 are regions with windows and absorption bands suitable for atmospheric temperature profiles occur at 118 and 183 GHz (see Fig. 1, Report 852). Bands now planned for use in the advance microwave sounding unit (AMSU), for launch aboard NOAA-series spacecraft beginning in 1989, are listed in Table III (see also Report 693).

TABLE III – *AMSU channels*

Frequency (GHz)	Bandwidth (MHz)	Comment
23.8	270	Total precipitable water over oceans
31.4	200	Window, for clouds and precipitation
50.3	200	Temperature profiles (O_2)
52.8	400	
53.3	400	
54.4	400	
54.9	400	
55.5	400	
57.3 (6 channels)	330	
89	6000	High-resolution detection of precipitation, sea ice, snow, land features
166	4000	Water vapour profiles (H_2O)
183.3 (3 channels)	4000	

3.1.2 *Active measurements*

Report 693 describes the bandwidths and preferred frequency bands for active microwave sensors. The use of spaceborne active sensors in meteorology continues to be developed. The observations of surface winds over the oceans by scatterometers planned for future Earth exploration satellites (see Report 535) may also be undertaken by future meteorological satellites. Bandwidths of 1 MHz near 15 GHz are required for these sensors. Pulsed lasers (LIDARs) are planned to operate in the infra-red wavelengths in order to measure the motions of aerosols and clouds. These LIDAR measurements are for deriving profiles of atmospheric winds [Johnson, 1982; Miller and Sparkman, 1984].

3.2 *Data communications frequencies and bandwidths*

Both low-orbit and geostationary meteorological satellites require appropriate wide bandwidths for data up and down links, for read-out of raw image and sounding data, and for direct dissemination of derived meteorological information. Additional transponder bandwidth is required for data relay from remotely located data collection platforms (including ships, aircraft and buoys) to central processing facilities.

3.2.1 *Low-orbit spacecraft*

Multi-spectral imaging in the visible and infra-red from low orbit requires a bandwidth of about 2.8 MHz for down-link data from sensors with instantaneous fields-of-view (IFOV) of 1 km (visible and infra-red). Future addition of spectral channels and reduction of IFOVs to 500 m will probably double this mission data rate by the end of this century. Bandwidths of up to 100 MHz may be required for transmission of LIDAR or other active sensor data.

It appears unlikely that an enhanced capacity for on-board data processing in space will reduce the requirements for image data flow. At present, there is little justification for on-board data processing as the current requirement for ground station processing of image data results in an increase of the data flow, because the raw data channels can be combined in various ways to provide different outputs, e.g. sea surface temperature, vegetation index, etc. [Dismachek *et al.*, 1980].

Low orbit sounding data, although involving many channels (approximately 30, since TIROS-N, 1978), have large IFOVs and a correspondingly low data rate, i.e. 3680 bit/s. This is not likely to increase by more than a factor of 2-4 in the foreseeable future.

Bandwidths for increased imaging data rates are not available in the currently assigned frequency bands. It appears likely that a shift to higher frequencies will be required for mission data down links.

Table IV lists the frequencies now used by the low-orbit meteorological satellites. Figure 1 illustrates a typical low-orbit satellite telecommunications system.

TABLE IV – *Low-orbit meteorological satellite frequencies*

a) *United States NOAA series*

Link	Carrier frequency (MHz)	Direction
1. Beacon	137.77 136.77 (1)	S-E
2. Real time APT	137.50 137.62	S-E
3. Real time HRPT	1698.0 1707.0	S-E
4. Mission data to CDAs	1698.0 1702.5 1707.0	S-E
5. Data collection system	401.65	E-S
6. Command	148.56	E-S
7. Search and rescue	121.5 243.0 406.05	E-S
8. Search and rescue	1544.0	S-E

b) *USSR METEOR series*

Link	Carrier frequency (MHz)	Direction
1. Real time APT	137.15 137.30 137.40 137.50	S-E
2. Mission data read-out	466.50	S-E
3. Search and rescue	121.5 243.0 406.05	E-S
4. Search and rescue	1544.0	S-E

(1) Allocation status of this frequency becomes secondary in 1990 (WARC-79).

APT: automatic picture transmission
HRPT: high resolution picture transmission
CDA: command and data acquisition
S: space
E: Earth

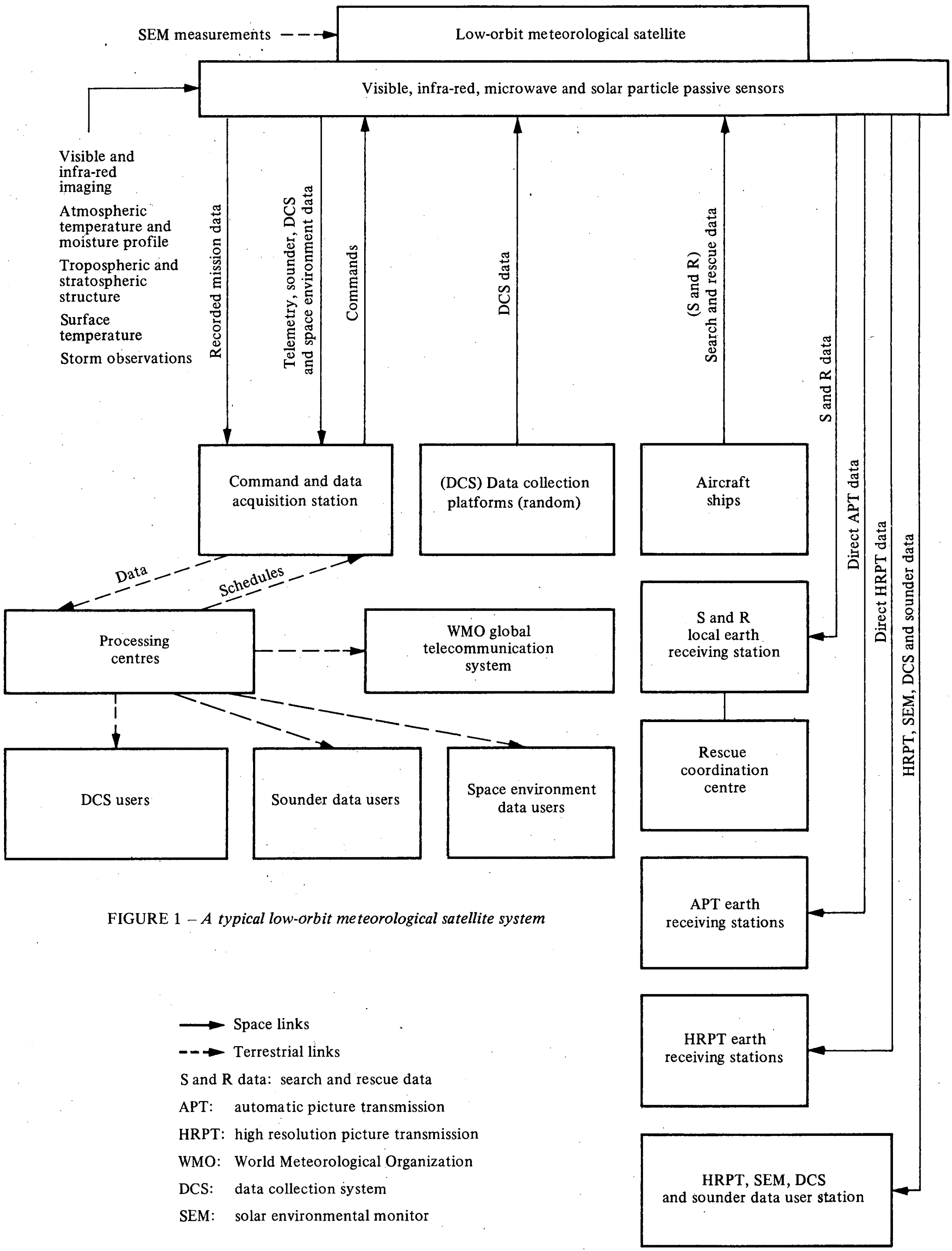

FIGURE 1 – *A typical low-orbit meteorological satellite system*

Space links
Terrestrial links
S and R data: search and rescue data
APT: automatic picture transmission
HRPT: high resolution picture transmission
WMO: World Meteorological Organization
DCS: data collection system
SEM: solar environmental monitor

3.2.2 *Geostationary spacecraft*

Use of a spinning platform for Earth observation from geostationary satellites levies a heavy penalty on sensor design and data flow rates. Sensors on spinning platforms for imaging and sounding view the Earth for only 1/18th of each platform revolution. Data rates during this brief Earth observation period reach 28 Mbit/s. When "stretched" by a ground station to fill in the remaining 17/18ths of each turn, the re-broadcast data transmission reduces to 1.75 Mbit/s.

Progress in spacecraft stabilizing techniques may permit the use of a non-spinning sensor platform, thus reducing the maximum data rates towards the 2 Mbit/s level. The success of INSAT as a three-axis-stabilized multi-purpose geostationary satellite with an imaging sensor has shown that a body-stabilized, imaging platform is feasible.

Table V lists the frequencies now used by the geostationary meteorological satellites. Figure 2 illustrates a typical geostationary meteorological satellite telecommunication system.

TABLE V – *Geostationary meteorological satellite frequencies*

(All frequencies are in MHz except INSAT and indicate the centre frequency of the respective channel)

	METEOSAT	GOES	GMS-2	GOMS	INSAT
Launch, TM	137.08	2214	2286.5		
Operating, TM	1675.929	1694	1694		
Launch, TC	149.34		2110.8		
Operating, TC	2098	2034.2	2034.2		
No. of DCP channels	66	66	33	66	33
DCP report E-S	402.1	401.9	402.1	401.9	402.75
DCP report S-E	1675.281	1694.5	1694.5	1696.9	4 GHz
DCP interrogation E-S	2098	2034.9	2034.9	2118.85	
DCP interrogation S-E	468.9	468.825	468.8	468.85	
Raw image bit rate	166 kbit/s (2.7 Mbit/s) ([1])	28 Mbit/s	several Mbit/s	1.5 Mbit/s	400 kbit/s
Raw image	1686.833	1681.6	1681.6	1685	4 GHz
Dissemination channel I (E-S)	2101.5	2032.1 (WEFAX only)	2033 (WEFAX only)	2116 (WEFAX only)	
Dissemination channel I (S-E)	1691	1691 (WEFAX only)	1691 (WEFAX only)	1691 (WEFAX only)	
Dissemination channel II (E-S)	2105	2029.1	2029.1	2117 (WEFAX only)	
Dissemination channel II (S-E)	1694.5	1687.1	1687.1	1692 (WEFAX only)	
High-accuracy ranging E-S	2101.5 2105	2026 2030.2 2032.2	2026 2030.2 2032.2		
High-accuracy ranging S-E	1691 1694.5	1684 1688.2 1690.2 2209.086	1684 1688.2 1690.2		

([1]) Back-up mode.

DCP: data collection platform
TC: telecommand
TM: telemetry
WEFAX: weather facsimile
E: Earth
S: space

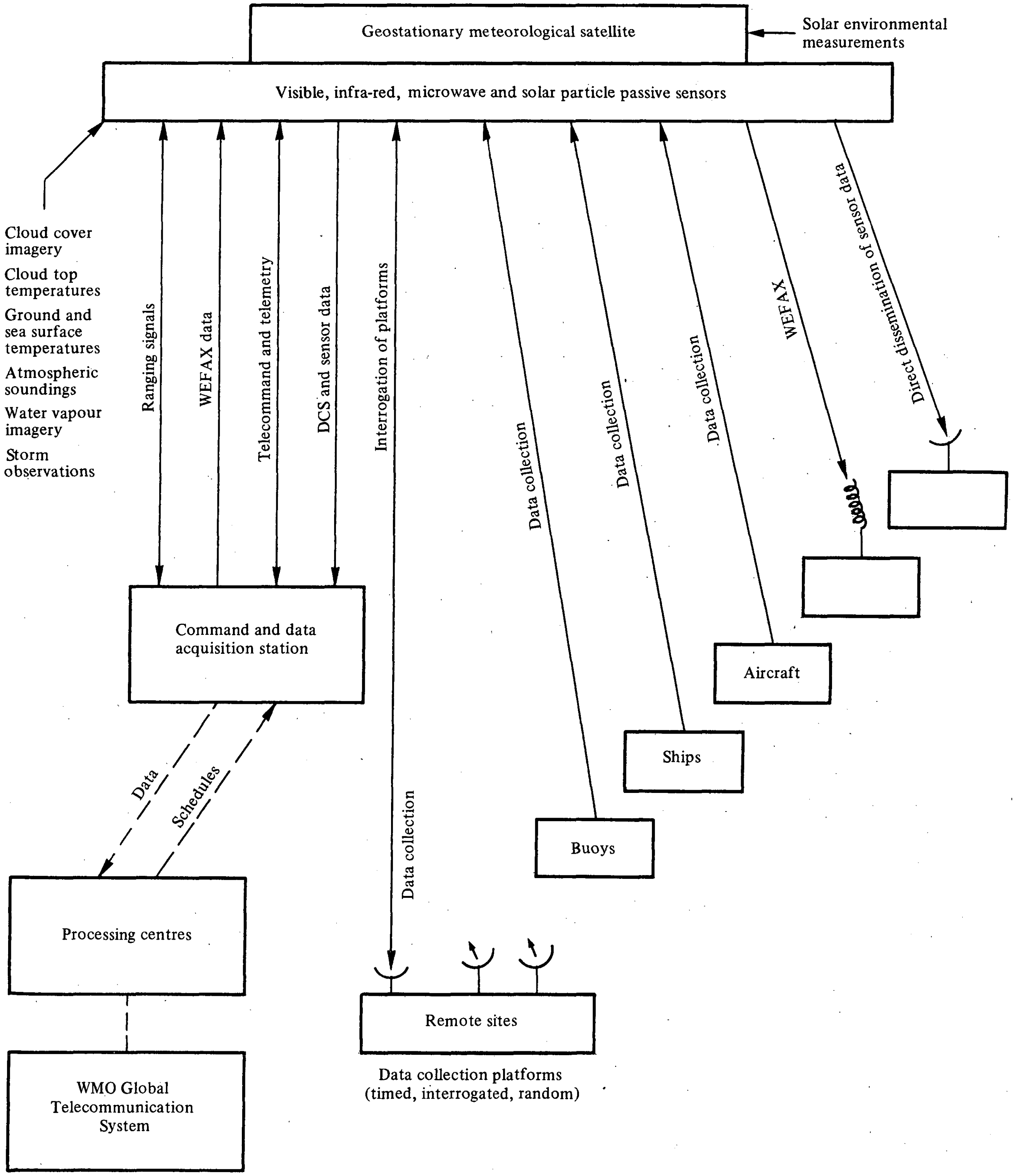

FIGURE 2 – *A typical geostationary meteorological satellite system*

Space links
Terrestrial links
WEFAX: Weather facsimile

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REPORT 851 *

POWER FLUX-DENSITY LIMITATION IN THE BAND 1670-1710 MHz FOR DISSEMINATION OF METEOROLOGICAL INFORMATION TO SMALL EARTH TERMINALS

(Study Programme 12C/2)

(1982)

1. Introduction

The problem of data dissemination is an increasingly important aspect of meteorological satellite systems. Various kinds of data generated by these systems are of very high and direct interest to a wide community of individual users.

These data can be disseminated by the meteorological satellites themselves which generated them, in the frequency band allocated to the meteorological-satellite service (1670-1710 MHz). This solution has been successfully illustrated for several years by the geostationary meteorological satellite systems in operation, which implement the meteorological data dissemination mission in a cost effective way, as an integral part of their data generation/processing and transmission facilities. Many users have now procured the appropriate terminals enabling them to acquire the data disseminated and there is an increasing demand from the user's community towards improvement and extension of this service. This demand originates particularly from developing countries for which the service proposed is an important means – if not the only one – to alleviate the deficiencies of the existing infrastructure and which can hardly afford the necessary costly receiving equipment, and from those potential users which usually experience severe operational conditions (e.g. ships, offshore installations) and which might use this facility as a warning tool.

2. Improvements of services

Two major areas of improvement can be considered for near future systems:

– reduction of cost of the user's terminals which acquire the disseminated data;
– reduction of their operational complexity, particularly in view of shipborne or offshore utilization.

In these respects, one parameter of primary importance is the factor of merit of the terminal (antenna dimension and gain, receiver noise figure). For the terminals presently in operation with the METEOSAT System, the minimum G/T figure compatible with acceptable performance is $+2.5$ dB(K^{-1}) (corresponding roughly to a 2.0 m dish associated with a transistorized preamplifier) due to:

– limitation of the e.i.r.p. of the satellite;
– pfd limits on the Earth's surface (see No. 2557 of the Radio Regulations).

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* This Report should be brought to the attention of Study Group 9.

Technological progress in the area will easily allow an increase in the e.i.r.p. of the future satellites, but this can only be done if the currently valid power flux-density (pfd) limitation is relaxed (see RR 2557); the subsequent paragraph proposes such a relaxation, which should be applicable to an appropriate portion of say 10 MHz of the band 1670 to 1710 MHz. With a view to protecting the radioastronomy service in the band 1660 to 1670 MHz, the 10 MHz band should preferably be selected in the upper part of the band, for instance between 1690 MHz and 1700 MHz.

2.1 *Relaxation of pfd limitation*

The objective is to decrease the G/T figure of the terminal to a value of -4 dB(K^{-1}), while keeping the bandwidth occupied by the meteorological data signal to its standard value. This would have the following main advantages:

- decrease the dimension of the antenna to a diameter of less than 1 m, with the corresponding significant reduction of procurement cost as well as a reduction in the complexity of installation, maintenance, etc.;
- render possible the compatibility of meteorological data dissemination with small ship terminals which are under development in the framework of INMARSAT; (these small terminals are working in the 1540 to 1660 MHz band and typically have a G/T figure of -4 dB(K^{-1}) at 1540 MHz).

The bandwidth of image data analogue signals which are currently being disseminated by the present systems can be assumed to be 30 kHz. A typical spectrum of this signal is given in Fig. 1, and shows that the maximum power density within a 4 kHz slot is 3.6 dB below the level of the unmodulated carrier.

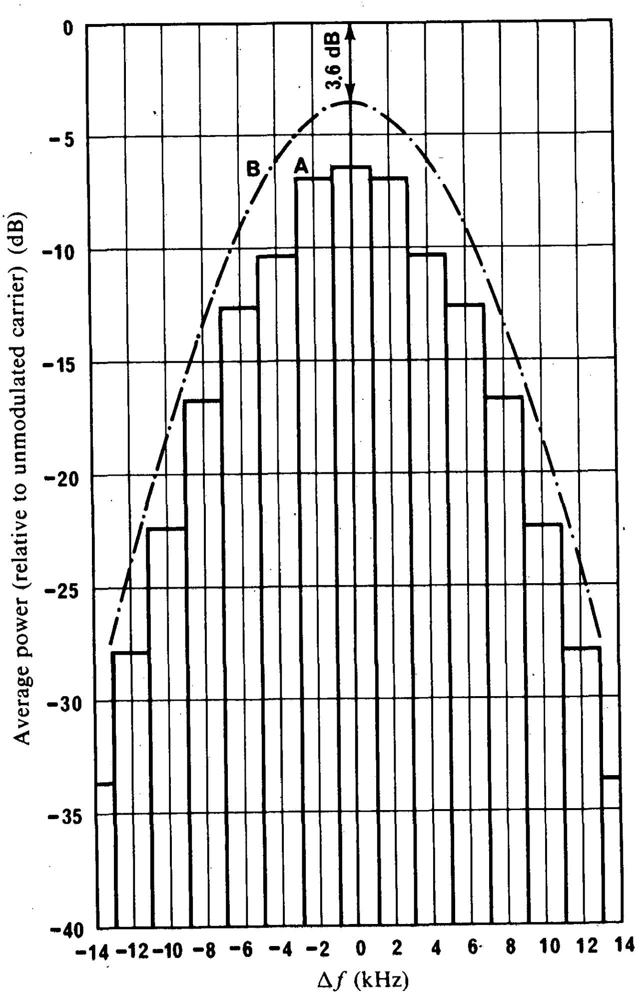

FIGURE 1 – *WEFAX spectrum*

(Integration time: 1 picture)

A: in 2 kHz slot

B: in 2 adjacent slots (≃ 4 kHz)

2.2 *Characteristics of terminal*

$G/T = -4$ dB(K^{-1}), which corresponds to a dish diameter of 0.9 m, with a system noise temperature of 400 K.

2.3 *Minimum performance*

$S/N \geqslant 12$ dB in 30 kHz

Received signal $S = pfd \times G \times \frac{\lambda^2}{4\pi}$

Noise signal $N = kTB$

$$\frac{S}{N} = pfd \times \frac{G}{T} \times \frac{\lambda^2}{4\pi} \times \frac{1}{kB} \geqslant 12 \text{ dB}$$

2.4 *Power flux-density*

Total minimum $pfd = -141.7$ dB(W/m^2)

$pfd/4$ kHz $= -141.7$ dB(W/m^2) -3.6 dB $= -145.3$ dB(W/($m^2 \cdot 4$ kHz)) (see Fig. 1)

This is applicable for all elevation angles.

3. Conclusion

The requirements of low performance reception stations in the 1670-1710 MHz band of the meteorological satellite service can be met with a pfd limitation at the Earth's surface, of -144 dB(W/m^2) in any 4 kHz band *for all angles of arrival* (this is the current pfd limit for angles of arrival greater than 25°). This pfd should be applicable to a 10 MHz portion (for instance, between 1690 MHz and 1700 MHz) of the 1670 to 1710 MHz band, whereas in the rest of the band, the current provision of RR 2557 is acceptable. The effect of such a change in pfd limits on terrestrial services has not been examined.

REPORT 541-2

FEASIBILITY OF FREQUENCY SHARING BETWEEN A GEOSTATIONARY METEOROLOGICAL SATELLITE SYSTEM AND THE METEOROLOGICAL AIDS SERVICE IN THE REGION OF 400 MHz AND IN THE UPPER PART OF BAND 9 (1 TO 3 GHz)

(Study Programme 12C/2)

(1974-1978-1982)

1. Introduction

This Report describes typical meteorological aids and satellite systems that may share frequency bands in the region of 400 MHz and in the upper part of band 9 (1 to 3 GHz), and presents sharing criteria that will ensure that neither system suffers nor causes harmful interference.

1.1 *Meteorological satellite system characteristics*

The meteorological satellite systems considered in this Report are at present in operation; these are the Geostationary Operational Environmental Satellite (GOES) system which has been developed by the United States, and the METEOSAT system, developed by the European Space Agency and the Geostationary Meteorological Satellite (GMS) system developed by Japan. These systems have communication links in the region of 400 MHz and in the upper part of band 9. Typical system transmitter, receiver and antenna characteristics that are relevant to an interference analysis for band 9 are shown in Tables I, II, III, IV, V and VI.

The systems use frequencies in the region of 400 MHz for reporting to the satellite from land-based data collection platforms (DCP's) and ocean buoys. Technical information on the DCP's is given in Table VIIa. Reports may be made by the platforms either in response to interrogations from the satellite or automatically on a regular basis controlled by an internal clock. Characteristics of the satellite receiver used in this link are given in Table VIIb.

TABLE I – *Characteristics of GOES satellite system which are pertinent to frequency sharing in the upper portion of band 9 – Transmitters*

Transmitters	e.i.r.p. (dBW)	G_t (dB)	Emission	Flux density at the surface of the earth for a bandwidth of 1·5 MHz (dB(W/m²))
Synchronous meteorological satellite				
to CDA (1) (meteorological data)	27·9	15·7	M25F9	−146·3
to CDA/TARS (2) (ranging data)	27·9	15·7	M1F9	−134·1
to DRGS (3) (stretched data)	27·9	15·7	M3·5F9	−137·7
to FC (4) (facsimile data)	27·9	15·7	26F4	−134·1
to CDA (DCP (5) data)	7·0	15·7	400F9	−155·0
to CDA (telemetry)	14·0	15·7	200F9	−167·5
Meteorological satellite earth stations				
CDA (stretched data)	73·4	46·4	M3·5F9	
CDA (facsimile data)	73·4	46·4	26F4	
CDA (command link)	56·4	46·4	30F9	
CDA (DCP interrogation)	56·4	46·4	0·1F9	
CDA (ranging data)	64·4	46·4	M1F9	
TARS (ranging data)	45·0	30·1	M1F9	

(1) CDA: Command and data acquisition station.

(2) TARS: Turn-around ranging station; this system transmits a CW unmodulated signal on 1684.0, 1688.2 and 1699.2 MHz during the 10 s acquisition mode.

(3) DRGS: Direct readout ground station.

(4) FC: Forecast centre station.

(5) DCP: Data collection platform.

TABLE II – *Characteristics of GOES satellite system which are pertinent to frequency sharing in the upper portion of band 9 – Receivers*

Receivers	G_r (dB)	T_s (K)	Noise bandwidth
Meteorological satellite			
(Data)	9·2	1630	8·2 MHz
(Command)			60 kHz
(DCP interrogation)			150 kHz
CDA (1)	47·6	100	25 MHz
			8·2 MHz
(Telemetry)			200 kHz
(DCP reports)			400 kHz
DRGS (1)	37·5	300	3·5 MHz
FC (1)	30·0	1500	50 kHz

(1) See Table I.

TABLE III – *Characteristics of METEOSAT satellite system which are pertinent to frequency sharing in the upper portion of band 9 – Transmitters*

Transmitter	Max. e.i.r.p. (dBW)	Max. G_t (dB)	Emission	Maximum power-flux density at the surface of the Earth (sub-satellite point) (dB(W/m²))	
				Averaged 1.5 MHz bandwidth	Averaged 4 kHz bandwidth
METEOSAT satellite					
to DATTS(1) (raw image data)	6.5	14	660F9	–155.6	–174.6
to DATTS/LBT(2) (ranging data)	21.3	14	660F9	–140.8	–159.8
to DATTS/PDUS(3) (high resolution pictures)	21.3	14	660F9	–140.8	–159.8
to DATTS/SDUS(4) (facsimile data)	21.3	14	26F4	–140.8	–144.4
to DATTS (DCP reports)					
normal	3.2	14	200F9	–158.9	–175.9
eclipse	–9.2	3	200F9	–171.3	–180
to DATTS (HK telemetry)					
normal	–5	14	30F9	–167.1	–175.9
eclipse	–16.2	3	30F9	–178.3	187
Meteorological satellite earth station					
from DATTS (high resolution pictures)	64	47	660F9		
from DATTS (facsimile data)	64	47	26F4		
from DATTS (DCP interrogation)	57	47	7F9		
from DATTS (HK telecommand)	57	47	30F9		
from DATTS (ranging data)	64	47	660F9		
from LBT (ranging data)	57	35	660F9		

(1) DATTS: Data acquisition telecommand and tracking station.

(2) LBT: Land-based transponder for ranging operations.

(3) PDUS: Primary data user station.

(4) SDUS: Secondary data user station.

TABLE IV – *Characteristics of METEOSAT satellite system which are pertinent to frequency sharing in the upper portion of band 9 – Receivers*

Receivers	G_r (dB)	T_s (K)	Noise bandwidth
Meteorological satellite			
(Disseminated and ranging data)			1000 kHz
(HK telecommand)	3	750	200 kHz
(DCP interrogation)			200 kHz
DATTS			
(Picture data)			
(DCP reports)	45	115	25 kHz
(HK telemetry)			
(Ranging data)			
PDUS	35	250	1000 kHz
SDUS	30	560	50 kHz
LBT	30	250	1000 kHz

TABLE V – *Characteristics of GMS system transmitters which are pertinent to frequency sharing in the upper portion of band 9*

Transmitter	Maximum *e.i.r.p.* (dBW)	Maximum G_t (dB)	Emission	Maximum power flux-density at the surface of the Earth for a bandwidth of 1.5 MHz (dB(W/m²))
GMS satellite				
to CDAS (1) (VISSR data)	29	18	20M0G1DDN	– 143
to CDAS/TARS (2) (ranging data)	29	18	2M00G3DXN	– 133
to CDAS/MDUS (3) (high resolution pictures)	29	18	1M00F3CLN	– 133
to CDAS/SDUS (4) (low resolution pictures)	29	18	260KF3CLN	– 133
to CDAS (DCP report)	9	18	400KG1DCN	– 169
to CDAS (HK telemetry)	13.5	18	200KG9DWF	– 138
Meteorological satellite earth station				
from CDAS (high resolution pictures)	77	49	1M00F3CLN	
from CDAS (low resolution pictures)	70	49	260KF3CLN	
from CDAS (DCP interrogation)	54	49	5K00G1DBN	
from CDAS (command)	54	49	35K0GXDXN	
from CDAS (ranging data)	77	49	2M00G3DXN	
from TARS (ranging data)	52	33	2M00G3DXN	

(1) Command and data acquisition station.

(2) Turn around ranging station.

(3) Medium scale data utilization station.

(4) Small scale data utilization station.

TABLE VI – *Characteristics of GMS system which are pertinent to frequency sharing in the upper portion of band 9 – Receivers*

Receivers	G_r (dB)	T_s (K)	Noise bandwidth
Meteorological satellite			
(Disseminated data and ranging data)	17	1200	8.2 MHz
(Command)			60 kHz
(DCP interrogation)			200 kHz
CDAS			
(VISSR data) (DCP reports) (HK telemetry) (Ranging data)	47.5	125	20 MHz
MDUS	35	700	1 MHz
SDUS	30	800	260 kHz
TARS	31.5	700	1 MHz

TABLE VII – *Characteristics of meteorological satellite systems in the region of 400 MHz*

TABLE VII a

Data collection platform (land-based) characteristics (for satellite elevation angles <45°)	GOES (Typical)	Meteosat (Typical)	GMS (Typical)
Transmitter power (dBW)	7	7	10
Feed loss (dB)	0.5	0.5	2
Antenna gain (dB)	10	10	11
Path loss (free space) (dB)	177	177	177
Polarization loss (dB)	0.2	1	7
Satellite antenna gain (dB)	7.3	0.5	
Feed loss (dB)	2.9	1.4	
Receiver power (dBW)	–156.3	–162.4	–151

TABLE VII b

Satellite receiver characteristics	GOES	Meteosat	GMS
Centre frequency (MHz)	401.9	402.1	402.2
Bandwidth (kHz)	400	200	400
Antenna gain (dB) (including feed losses)	4.4	0	7
Noise temperature (K)	385	600	300

1.2 *Meteorological aid system characteristics*

The meteorological aids system characteristics used in this analysis are those of a typical radiotheodolite/radiosonde system used for gathering weather information. Meteorological aids (radiosondes) are launched from weather service sites up to four times a day. These launches are coordinated and usually occur near 0000, 0600, 1200 and 1800 UTC. The balloon-borne radiosondes transmit temperature, pressure and humidity data to ground-based radiotheodolites as they rise to a maximum altitude of about 30 km. Typical lifetimes range from one to one and a half hours and are limited by the bursting of the balloon and the operating life of the water-activated battery.

In the 400.15 MHz to 406 MHz band, there are two types of radiosonde transmitters in use; one type provides a maximum of 1 W of transmitter power when launched and has an unstabilized oscillator. The other type uses a crystal controlled 0.5 W transmitter and, in addition to the atmospheric data, rebroadcasts either Omega or Loran C transmissions for aid in position determination. Experience has shown a degradation in transmitter output with altitude, probably caused by the weakening of the battery. The degradation in output power is about 3 dB when the radiosonde is at its maximum altitude.

The radiosonde antenna is a quarter-wave monopole, providing up to 2 dB of gain over an isotropic antenna and emitting a signal which is, nominally, vertically polarized. The maximum range of a radiosonde from its launch point and receiving station is usually taken to be 200 km. The radiosonde transmitter uses amplitude modulation but, due to its design, a large amount of frequency modulation also occurs.

Radiosonde receiving stations use a dipole array that provides a gain of approximately 9 dB. Receivers may be sensitive enough to receive signals as low as −145 dBW, but nevertheless some may require signal levels as high as −130 dBW. The minimum radiosonde signal at the receiver is usually at least −127 dBW (assuming free-space loss) which provides some margin. In this condition, the minimum carrier-to-interference ratio for successful operation could not be less than about 6 dB. Since the radiosondes transmit continuously throughout their lifetime, and since the parameters being measured change only slowly, short periods of interference are not particularly harmful. Missed data can often be estimated by interpolating between the values received. The reporting period for each meteorological parameter ranges from 10 s to 1 min. To date, the United States has had no known cases of interference to reception of radiosonde transmission. Table VIII summarizes the meteorological aids system characteristics in the region of 400 MHz.

Meteorological aids systems transmitting in the upper part of band 9 have characteristics (Table IX) somewhat different from those in Table VIII although the operation and purpose of these systems are similar.

2. Interference analysis

Six possible interference cases exist between meteorological aids and meteorological satellite systems:

- radiotheodolite transmissions interfering with reception by the meteorological satellite receiver in the region of 400 MHz;
- radiosonde transmissions interfering with reception by the meteorological satellite in the region of 400 MHz;
- radiosonde transmissions interfering with reception by the meteorological satellite earth station in the upper part of band 9;
- meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiotheodolite receivers in the region of 400 MHz;
- meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiosonde receivers in the region of 400 MHz;
- meteorological satellite transmissions interfering with radiotheodolite reception in the upper part of band 9.

These possible interference cases are considered separately in the sub-section which follows.

TABLE VIII – *Meteorological aids characteristics in the band 400.05 to 406 MHz*

1. *Radiosonde balloon transmissions* (down-link)	*Maximum*	*Minimum*
Transmitter power (dBW)	0	−6
Transmitter antenna gain (dB)	2	0
e.i.r.p. (dBW)	2	−6
Free-space path loss (at 200 km) (dB)	130	130
Receiver antenna gain (dB)	9	8
Minimum received signal (dBW)	−119	−128
2. *Radiotheodolite ground transmissions* (up-link)		
Transmitter power (dBW)	14·8	
Transmitter antenna gain (dB)	6	
e.i.r.p. (dBW)	20·8	
Free-space path loss (at 200 km) (dB)	130	
Radiosonde antenna gain (dB)	0	
Power level at radiosonde (dBW)	−109·2	
Receiver minimum sensitivity (dBW)	−125	

TABLE IX – *Characteristics of meteorological aids systems pertinent to frequency sharing in the upper part of band 9*

System	e.i.r.p. (dBW)	G_t (dB)	Emission	G_r (dB)	T_s (K)	Noise bandwidth
Radiosonde transmitter:						
— non-ranging	−6	0	15F2			
— ranging	−6	0	400F9			
Radiotheodolite receiver				28	2900	1·5 MHz

2.1 *Radiotheodolite transmission interfering with reception by the meteorological satellite in the region of 400 MHz*

The radiotheodolite transmitter has a higher e.i.r.p. than does the radiosonde transmitter (for this analysis, the worst case of intersection with the geostationary-satellite orbit is assumed). System parameters and hence the interfering power at the satellite are listed in Table X. The levels of interfering (theodolite) signal are significantly more than the typical signal levels from a DCP (see Table VIIa).

The theodolite transmissions are frequency modulated with a 75 kHz bandwidth and the DCP and the buoy, using PSK would be received at the meteorological satellite in a 400 kHz bandwidth. Thus, if the meteorological satellites and the theodolite operate on the same frequency, the entire interfering signal would be received by the satellites.

It is concluded that coordination of frequency assignments may be necessary in operational systems within a shared band.

TABLE X – *Interference at the satellite from a theodolite (400 MHz)*

System	GOES	METEOSAT
Theodolite e.i.r.p. (dBW)	+20·8	+20·8
Path loss (dB)	177·0	177·0
Polarization loss (dB)	3·0	3·0
Receiver antenna gain (dB)	7·3	0·5
Feed loss (dB)	2·5	0.5
Interfering power (dBW)	−154·4	−159.2

2.2 *Radiosonde transmissions interfering with reception at the meteorological satellite in the region of 400 MHz*

The radiosonde transmitters in this band radiate a maximum power of 0 dBW, which is approximately 16 dB less than the minimum power from the proposed data collection platforms. Taking into account polarization discrimination and the relative bandwidths of the wanted and interfering signals at the spacecraft receiver, the interfering effect of the radiosonde transmissions is insignificant.

2.3 *Radiosonde transmissions interfering with reception at the meteorological satellite earth station in the upper part of band 9*

Interference from the meteorological aids service to meteorological satellite earth station receivers is influenced by the fact that the meteorological aids transmitter (radiosonde) is not fixed and could be within line-of-sight of a meteorological satellite earth station to a distance of approximately 700 km. The meteorological aids service transmitters in band 9 (radiosondes) are typically launched from a given site at 6 h intervals. The radiosonde ascends at a rate of approximately 500 m/min to an altitude of 30 km before the balloon bursts.

Assuming an allowable carrier-to-interference ratio of 10 dB, the maximum values of the undesired signal, P_r, for the GOES meteorological satellite earth stations are:

GOES:	Command and data acquisition station (CDA) (25 MHz noise bandwidth):	–144.6 dBW
	Direct read-out ground station (DRGS) (3.5 MHz bandwidth):	–148.4 dBW
	Forecast centre station (FC) (50 kHz noise bandwidth):	–159.9 dBW

If a specific modulation technique and type of interfering signal are postulated, a different value of P_r might be obtained. For example, assuming the satellite-to-CDA link to be a quadriphase shift-keyed, coherently detected signal and the interference a narrow-band signal, the required protection ratio (carrier/interference) for a 10^{-6} symbol error probability would be 10 dB, if the link were designed for a carrier-to-noise ratio of 18 dB. However, if the link were designed for a carrier-to-noise ratio of 14 dB, then the required protection ratio for the same error probability would increase to 30 dB [Rosenbaum, 1969]. Using the various proposed satellite power levels and the above protection ratios, P_r could range from –125.5 dBW to –145.5 dBW. These values would only apply to the specific modulation technique and the interfering signal described above, but they demonstrate the sensitivity of the value of P_r to the assumptions made. A reasonable compromise in a situation where the system is not completely defined is to compute as above the thermal noise level of the receiver and limit the interference to some percentage of this level. This approach is especially applicable to power-limited down links.

The case of the METEOSAT system is treated in Annex I, and that of the GMS system in Annex II.

Assuming, as a worst case, free-space propagation, the power flux-density at the meteorological satellite earth station could be as high as –130 dB(W/m^2) from a radiosonde at a slant range of 700 km.

If the radiosonde were within the earth station antenna main beam with an emission bandwidth of 1 MHz, the interference signal levels within the receiver bandwidth of the earth stations would be as shown in Table XI. (Although it is a gross assumption, the power is assumed to be equally distributed across the 1 MHz band.) The negative margins shown are pessimistic in that they consider neither:

(a) radiation pattern discrimination of the meteorological satellite earth station antenna; nor

(b) the time duration of the interference; nor

(c) the time between periods of interference.

Regarding *(a)*, for earth station antennas such that the ratio of antenna diameter to the wavelength exceeds 100, the CCIR reference pattern (see Report 391) provides a measure of the out-of-beam discrimination available. For example, based upon the CCIR reference pattern, a 12 m parabolic antenna at 1680 MHz could provide sufficient discrimination against radiosondes more than about 7° off the main beam and approximately 700 km distant. For ranges less than 700 km, say 150 km, the antenna could provide the needed discrimination against radiosondes more than about 20° off the main beam.

Regarding *(b)* and *(c)*, the time duration and time interval between periods of interference are important considerations, since as has been previously pointed out, radiosondes have limited operating lifetimes. Although it is not possible to make a quantitative assessment of the time factor, this fact does seem to reduce the importance of radiosonde interference on the earth station, since it provides a possible sharing alternative.

TABLE XI – *Interference to GOES satellite earth stations in the upper portion of band 9*

Type of station	Bandwidth	Maximum permissible P_r (dBW)	Interference level from radiosonde in antenna main beam (dBW)	Margin of protection (dB)
Command and data acquisition .	25 MHz	−144·6	−108·4	−36·2
Direct readout	3·5 MHz	−148·4	−118·5	−29·9
Forecast centre	50 kHz	−159·9	−139·0	−20·9

2.4 *Meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiotheodolite receivers in the region of 400 MHz*

Remote platforms (DCP) operating on land would emit about 16.5 dBW e.i.r.p. and have a fairly directive antenna. To interfere with reception of radiosonde signals at a radiotheodolite receiving ground station, the e.i.r.p. of the DCP in the direction of the ground station would have to be such as to produce a signal of at least −6 dB with respect to the radiosonde signal. The interference would be a function of the distance between the DCP and the receiver, and the signal would depend on the distance between the radiosonde and the receiver.

Buoys would be placed on bodies of water, generally at sea. At such locations, they would usually be out of the line-of-sight of radiotheodolite receivers and would not cause interference to them.

Both DCP and buoy transmitters could produce interference to a radiotheodolite receiver within line-of-sight range. Interference may be avoided by constraining the DCP or buoy antenna gain in the pertinent direction. However, this would be required on an individual case-by-case basis and would include side-lobe gain determination. To avoid the possibility of interference, DCPs and buoys should not be located within the line-of-sight of the radiotheodolite receivers.

2.5 *Meteorological satellite terrestrial station (data collection platforms) transmissions interfering with radiosonde receivers in the region of 400 MHz*

Interference can occur only when the balloon drifts through the main beam of either the DCP or buoy transmitters, which emit 15 to 16 dBW e.i.r.p. in the main beam for approximately 10 s during any period of 6 h. If the balloon drifts through the DCP main beam during this single 10 s period, interference could occur as the balloon may be closer to the DCP than is the theodolite transmitter. However, it is concluded that the possibility of interference caused by DCPs and buoys to radiosonde operation will be operationally insignificant.

2.6 *Meteorological satellite transmissions interfering with radiotheodolite reception in the upper part of band 9*

The power flux-density limit adopted for sharing between meteorological satellites and terrestrial fixed services does not apply to meteorological satellites sharing the same frequency bands with the meteorological aids service. A power flux-density limitation is therefore developed here specifically for a geostationary meteorological satellite sharing a common band with a meteorological aids (radiotheodolite/radiosonde) system.

2.6.1 *Maximum allowable interference for the meteorological aids operations*

Table XII presents the computed maximum allowable interfering signal level for meteorological aids operation, using the minimum desired signal level approach. It is assumed that the interfering signal could be equal to the total noise at the input to a meteorological aids (radiotheodolite) receiver. The protection ratio is based upon empirical data obtained from a series of tests on a radiotheodolite system, and an analytical study of the interference susceptibility of conical scan tracking radar. The minimum level of the desired radiosonde signal applies only for the maximum range of 200 km. A radiotheodolite system tracks a radiosonde during a typical mission over a range from zero to 200 km, and for only a very small proportion of the mission would the desired signal level be as low as −133 dBW.

TABLE XII – *Maximum allowable interference in a radiotheodolite receiver (limited by minimum value of desired signal)*

Radiosonde e.i.r.p. (250 mW, 0 dB antenna gain) (dBW)	−6
Free-space loss (200 km at 1680 MHz) (dB)	143
Radiotheodolite antenna gain (normal) (dB)	28
Losses (dB)	−2·0
Minimum radiosonde signal level at receiver input (no fading) (dBW)	−123
Protection ratio required (dB)	10
Permissible interference level at receiver input in 1·5 MHz bandwidth (dBW)	−133

2.6.2 *Probability of interference between the two systems*

The probability that the flux-density from a geostationary meteorological satellite would exceed the interference threshold has been analyzed and summarized in Fig. 1. The analysis was based upon the assumption that the probability of the radiotheodolite antenna traversing the satellite would be proportional to the solid angle defined by the effective radiotheodolite antenna beamwidth. The amount of time the interference from the satellite would exceed the maximum allowable interference would then be a function of the flux-density from the satellite, the effective radiotheodolite antenna beamwidth and the scan rate of the radiotheodolite antenna.

The highest power flux-density at the surface of the Earth from the proposed geostationary meteorological satellite would be −134.1 dB(W/m^2) in a 1.5 MHz bandwidth. Figure 1 shows that, with a probability of 98%, the interference to the radiotheodolite would not exceed the allowable value of −133 dB(W/(m^2 · 1.5 MHz)) for longer than one minute; with a probability of 99.9%, the interference level would not be exceeded for longer than four minutes.

The basic unit of bandwidth used in quoting power flux-density values has been 1.5 MHz instead of the 4 kHz that is commonly used in flux-density limits for sharing with radio-relay systems. A radiotheodolite receiver operating in this band has a nominal 1.5 MHz bandwidth and, therefore, this is the proper basic unit of bandwidth for use in establishing limits of power flux-density from satellites sharing with the meteorological aids service. Limiting the interference to −133 dBW in a 1.5 MHz bandwidth would, in effect, allow the satellite to transmit a signal with a total power so that the power in a bandwidth wider than 1.5 MHz could be greater than −133 dBW, as long as the total power within any 1.5 MHz bandwidth would not exceed −133 dBW; and would also allow the interference power to be equal to −133 dBW in any bandwidth narrower than 1.5 MHz, as long as the total power within any 1.5 MHz bandwidth would not exceed −133 dBW.

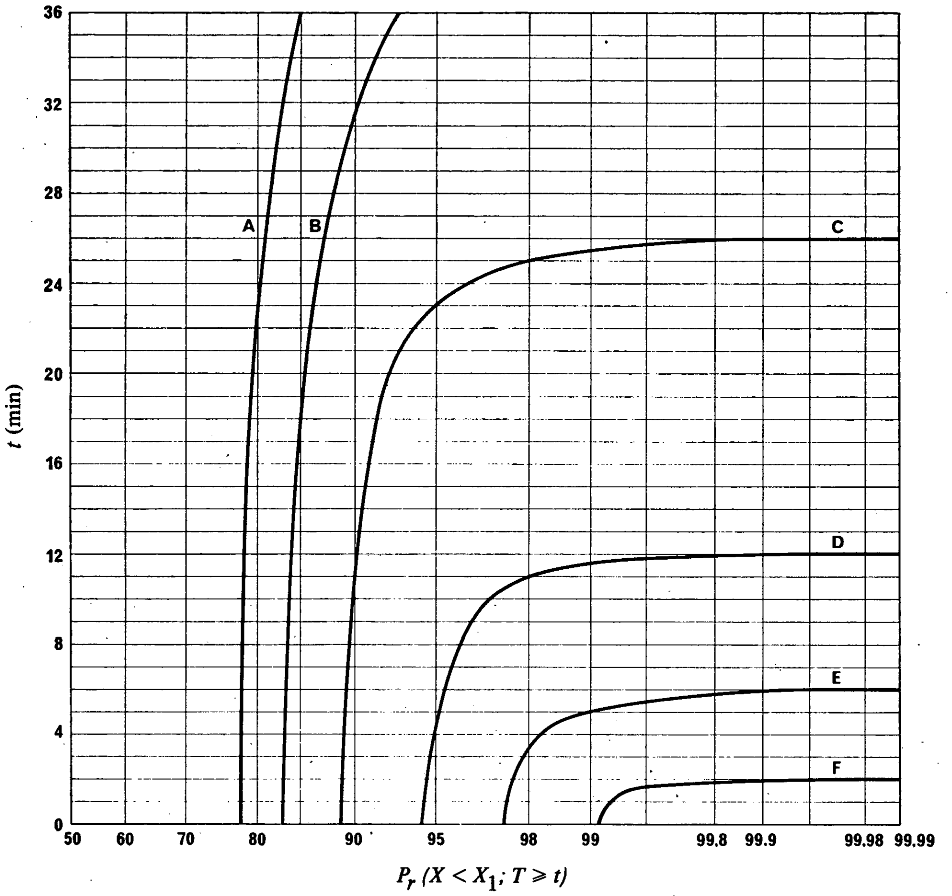

FIGURE 1 – *Probability that interference at the radiotheodolite receiver does not equal or exceed the maximum allowable interference for ⩾ t minutes*

Assumptions:
Maximum allowable interference: –133 dBW in a bandwidth of 1.5 MHz,
Radiotheodolite antenna: 3 m parabolic,
Gain: 32 dB,
Half-power beamwidth: 4°,
Radiation pattern of a 3 m plane polarized antenna,
Scanning rate: 1°/min

Values of P_0 *(dB (W/(m² in 1.5 MHz)):*

A: –108	D: –122
B: –112	E: –132
C: –118	F: –139

3. Summary

It is concluded that sharing in the region of 400 MHz between meteorological aids and meteorological satellite systems is technically and operationally feasible provided that the use of the following techniques is considered:

– coordination of frequency assignments;
– geographical separation.

It is noted that both systems would be operated by meteorological organizations and that operational time sharing may also be used to advantage.

It is also concluded that sharing in the upper part of band 9 is technically and operationally feasible.

Interference may occur from transmitters in the space-to-Earth links of geostationary meteorological satellites to receivers in the meteorological aids service. If the power flux-density at the surface of the Earth from the satellite transmission is limited to -133 dB(W/m²) in any 1.5 MHz bandwidth, the probability of interference will be low.

There is a potential problem as regards interference from radiosondes at the satellite earth station. The possible alternatives available for sharing, considering the different types of earth stations involved are:

- coordination of frequency assignments between radiosondes and specific satellite down links;
- time sharing of satellite transmissions with radiosonde operations within a given radius of an earth station. The radius of coordination with radiosonde operations will depend upon the type of earth station and antenna discrimination available;
- coordination on the distance between radiosonde operations and satellite earth stations (the actual coordination distance will depend upon the type of earth station and antenna discrimination available).

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ANNEX I

FREQUENCY SHARING OF THE UPPER PART OF BAND 9 BETWEEN RADIOSONDES AND THE METEOSAT DOWN-LINK TRANSMISSIONS

1. Introduction

After more detailed studies, and in the light of the advanced systems definition of the Meteosat meteorological satellite (the METEOSAT system is described in Report 395), it has been found that the conclusions of this Report concerning the METEOSAT system need to be reviewed.

The present Annex supplies guidance to meteorological authorities located in the European coverage zone of Meteosat, regarding the sharing problems between the operation of radiosondes and METEOSAT in the vicinity of the DATTS and/or PDUS and SDUS installations*. The situation in other parts of the coverage zone will be different depending upon the geographical location of the meteorological data user stations.

The indicative values furnished in this Annex apply to the METEOSAT system only and may well be different for other meteorological satellites.

2. Summary of relevant parameters of DATTS and radiosondes

2.1 *DATTS characteristics*

The DATTS (data acquisition telecommand and tracking station) is the earth station that ensures the Earth-to-space and space-to-Earth links with Meteosat, in the upper part of band 9. The DATTS is located in the Odenwald, Federal Republic of Germany (08° 50′ E, 49° 40′ N). Besides its Earth-to-space transmission functions, which are not considered in the present Annex, DATTS receives on a 24 hours per day basis, the following signals transmitted or relayed by Meteosat:

- raw-image telemetry;
- ranging data and/or disseminated meteorological data;
- housekeeping telemetry.

It is of paramount importance for the safety of operations, and thus the success of the METEOSAT mission, that these links operate continuously and free from harmful interference.

DATTS receiving equipment performance

Antenna gain: 45 dBi

System noise temperature: 115 K

Saturation level: −80 dBW (at preamplifier input, within the band 1655 to 1715 MHz)

Antenna beamwidth: 0.8° at −3 dB

Discrimination due to antenna pattern (referred to gain of main beam):

−50 dB for directions within the sector 15° to 30° off the main beam axis;

−55 dB for directions within the sector 30° to 90° off the main beam axis;

−70 dB for directions >90° off the main beam axis.

* DATTS: data acquisition, telecommand and tracking station
PDUS: primary data user station
SDUS: secondary data user station.

The nominal received signals, carrier frequencies and power flux-densities are summarized in Table XIII.

TABLE XIII – *DATTS reception from Meteosat*

Nominal signal received at DATTS	Frequency (MHz)	Signal bandwidth (kHz)	Nominal pfd at the DATTS (dB(W/m²))
Raw image – nominal mode	1686.833	660	–156.6
Raw image – real-time mode	1686.833	5400	–142.8
Dissemination channel 1	1691.000	660	–141.8
Dissemination channel 2	1694.500	660	–141.8
Data collection reports	1675.281	200	–190.5(1)
Housekeeping telemetry	1675.929	30	–179.3

(1) Pfd per channel, 66 adjacent channels.

2.2 *Radiosondes in the meteorological aids service*

For the purpose of this analysis only three characteristics of a meteorological radiosonde are relevant:

– RF transmission system parameters;
– trajectory and lifetime;
– typical launch schedule.

Typical transmission system parameters are given in Table XIV.

TABLE XIV – *Radiosonde parameters*

Type of sonde	Transmitter output power (W)	Antenna gain (dB)	Emission
Non-ranging	0.25 to 1	0	15K0G7DXN
Ranging	0.25 to 1	0	400KG7DXN to 1M00G7DXN

Radiosonde transmitters, which are used in great quantities by meteorological authorities, generally use relatively simple technologies, in respect to the design of the modulation system, the temperature compensation of frequency determining components and the initial RF carrier setting. These factors can considerably increase the bandwidth occupied by a series of radiosondes. In fact, the bandwidth within which radiosonde transmissions from a particular series of radiosondes can cause harmful interference may be a multiple of the useful signal bandwidth.

Radiosondes, being in principle balloon-suspended sensors with an RF transmitting system, rise at a rate of 500 metres per minute to a maximum altitude not exceeding 40 km. Their lifetime varies between 1 hour and 2 hours. The distance travelled by a radiosonde during that time can be well in excess of 100 km, depending upon the wind speeds encountered. The direction of its trajectory is a function of prevailing wind directions. Generally four launches are carried out per day, at intervals of 6 hours: 0000, 0600, 1200 and 1800 UTC.

3. Coordination requirements

The basic criteria for the interference study is a bit error ratio in the received METEOSAT signal not exceeding 5 times its nominal value in an interference-free environment. This criterion permits determining the maximum tolerable power flux-densities of the interfering signal at the ground reception station (DATTS or PDUS/SDUS) within the frequency band occupied by the METEOSAT space-to-Earth transmissions.

A simplified presentation of the geometry of the interference problem for the particular case of the DATTS is given in Fig. 2. The trajectory of the radiosondes, the receiving antenna pattern and its main beam azimuth and elevation, result in the definition of areas within which maximum interference levels are applicable. In the definition of the areas the effects of high wind velocities have not been included. Consequently, in the presence of heavy winds blowing from the radiosonde launch station in the direction of the DATTS an allowance has to be made for the distance likely to be travelled by the radiosonde; this can considerably increase the site of the area affected.

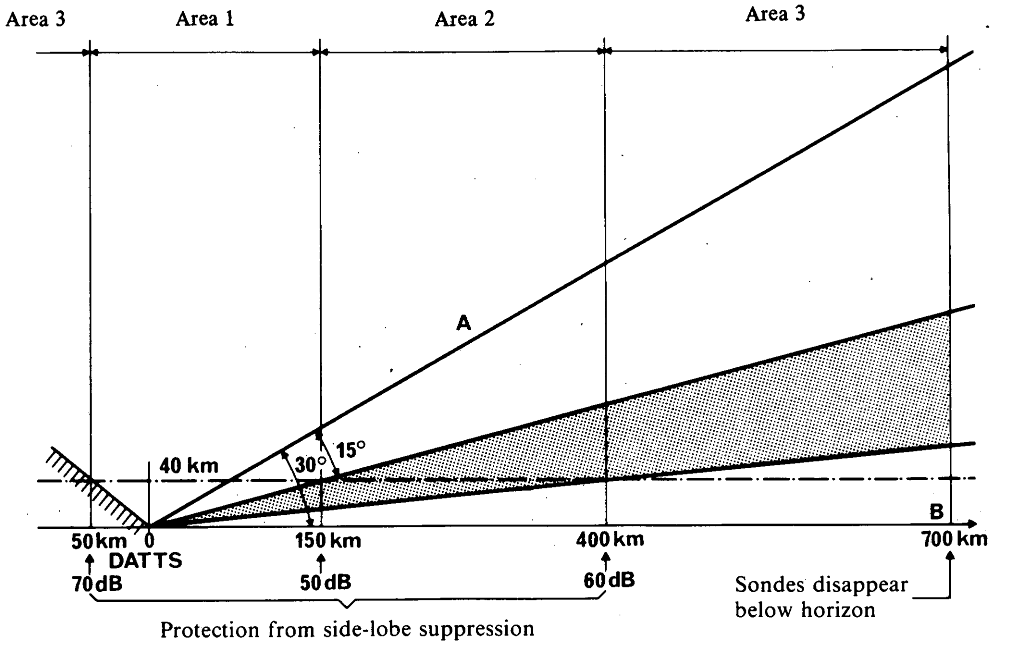


FIGURE 2 – *Coordination areas for METEOSAT DATTS*

A : elevation of antenna main beam

B : satellite azimuth

—·—·— Limiting altitude of radiosonde

In the above case one can distinguish three areas, which are defined for the METEOSAT nominal orbital position ± 10° in longitude (see Fig. 3). For any other orbital position the zones would change as a function of the antenna main beam azimuth and elevation.

Area 1 – In this area radiosonde operations in the 1670 to 1700 MHz band will cause harmful interference, as the receiving antenna pattern does not provide sufficient protection of the useful signal from interfering sources.

Area 2 – Within this area radiosonde operations are possible with certain limitations, which are defined in Fig. 4. It can be seen that, when limiting the e.i.r.p. of a radiosonde transmitter to 0 dBW, three gaps for radiosonde operations are available in the frequency band; from 1670 to 1673 MHz, from 1678 to 1684 MHz, and from 1696 to 1700 MHz.

Area 3 – The same applies as in the case of Area 2, except that the maximum e.i.r.p. has been increased by 10 dB (see dotted curve in Fig. 4).

Beyond Area 3 – No interference caused.

Attention is drawn to the fact that other low-orbiting meteorological satellites may operate in these bands and their reception by interested meteorological services may be subject to interference from the radiosonde transmissions.

The interference situation at the PDUS and SDUS is largely dependent upon the geographical position of the installation (particularly the elevation angle of its antenna beam) and its technical characteristics. Generally, it can be said that the feasibility of sharing the frequency band is somewhat better than for the case of the DATTS. An example of a PDUS and SDUS coordination requirement is given in Fig. 5. It is pointed out, however, that the interference problem should be studied for each installation, on a case by case basis.

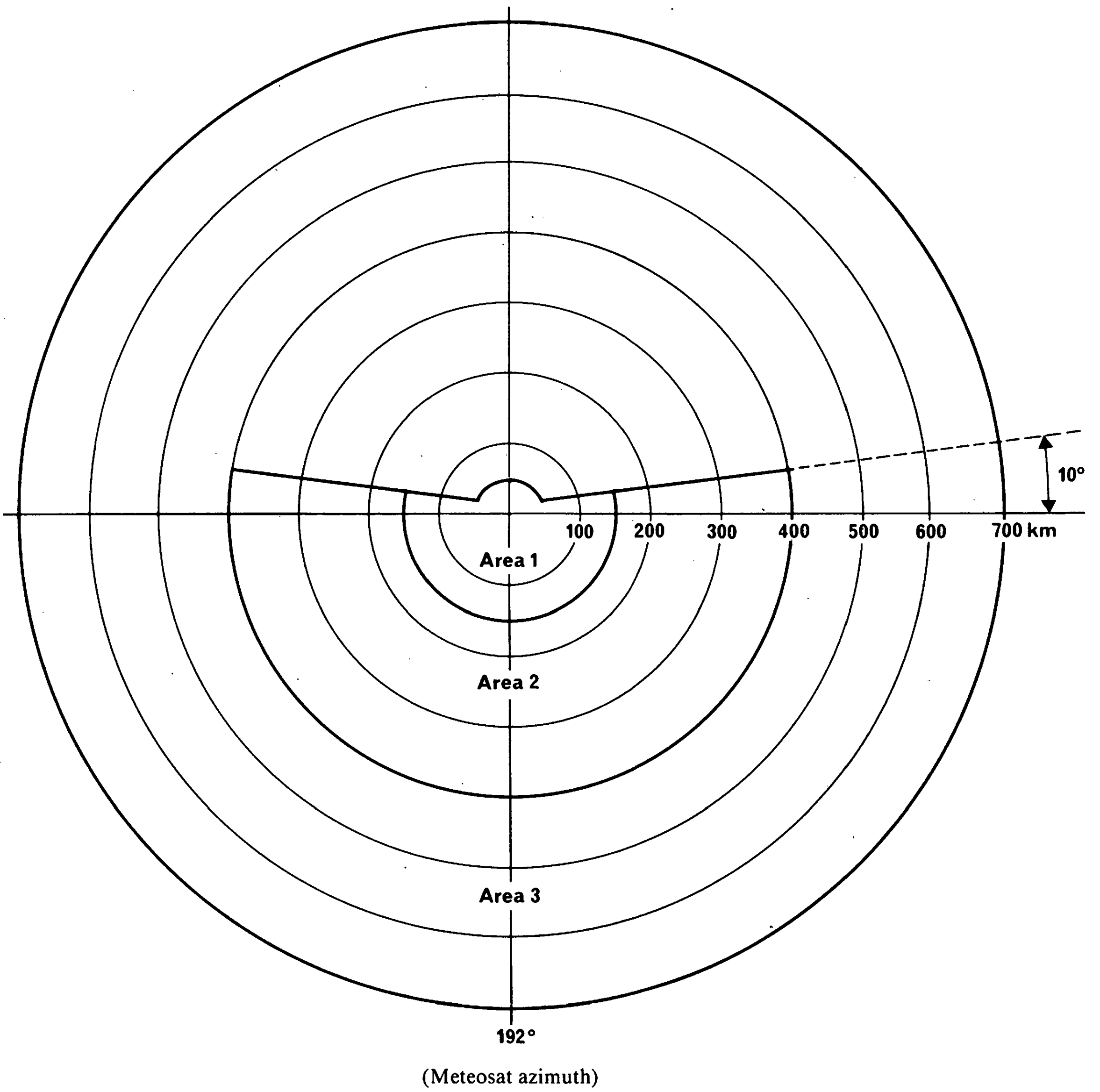


FIGURE 3 – *Coordination areas for METEOSAT DATTS (08°50′E, 49°40′N)*

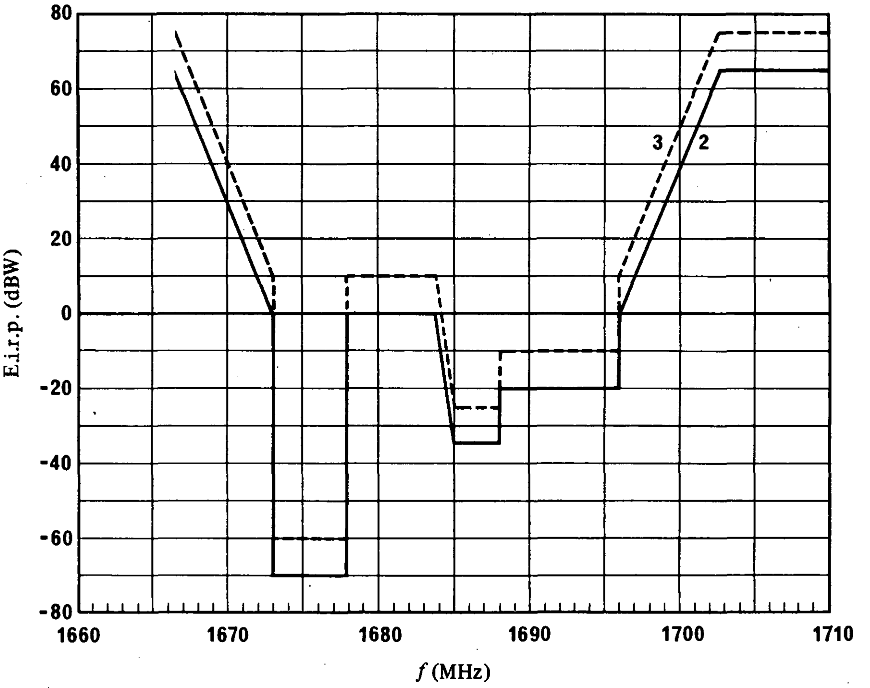


FIGURE 4 – *Maximum radiosonde e.i.r.p. towards DATTS*

——— Area 2

– – – – Area 3

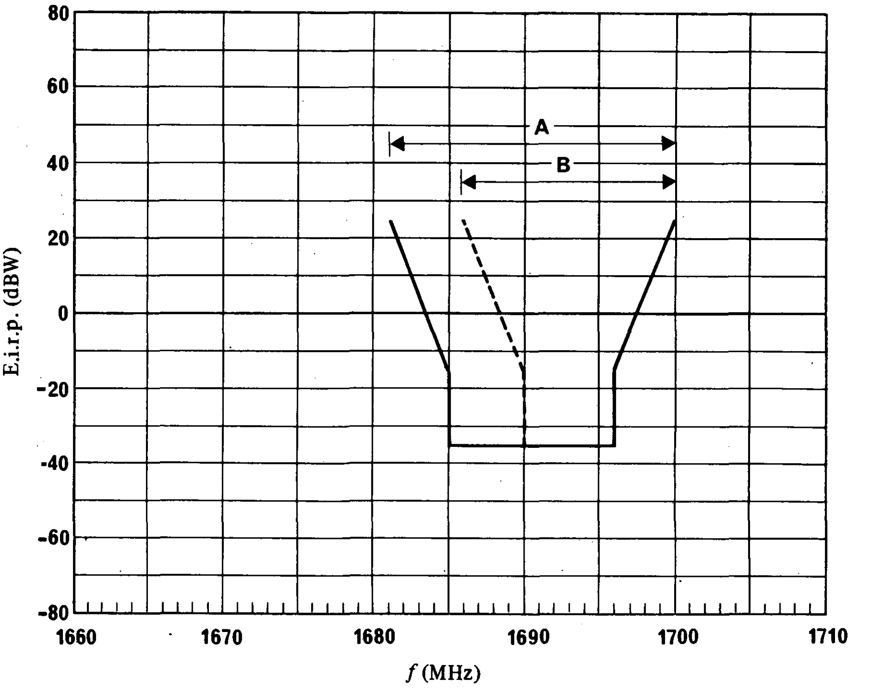


FIGURE 5 – *Maximum radiosonde e.i.r.p. towards data user stations*

Assumptions:
- CCIR standard antenna diagram following Recommendation 465
- Radiosonde outside main antenna beam
- Distance greater than 150 km

A: PDUS Protection

B: SDUS Protection

4. Conclusion

The above interference study leads to the conclusion that sharing of the upper part of band 9 between the "meteorological aids service" and the "meteorological satellites service" is feasible provided that:

– close frequency coordination is effected between the two services;
– radiosonde e.i.r.p. is limited in coordination areas around satellite reception installations;
– efforts are made by radiosonde operators to control the bandwidth occupied by the radiosondes as well as their initial RF carrier setting.

Sharing between the two services can be achieved through an appropriate technical and operational coordination either directly between the authorities responsible for the operations of the satellite(s) and those responsible for the operations of the radiosonde station(s) or through World Meteorological Organization (WMO).

ANNEX II

FREQUENCY SHARING OF THE UPPER PART OF BAND 9 BETWEEN RADIOSONDES AND THE GEOSTATIONARY METEOROLOGICAL SATELLITE (GMS) DOWN-LINK TRANSMISSIONS

1. Introduction

In choosing the site for the command and data acquisition station (CDAS), operating to the Geostationary Meteorological Satellite (GMS (described in Report 395)), it was necessary to undertake a study of the possible interference conditions resulting from frequency sharing of the upper portion of band 9 between the GMS down-link transmission and radiosondes in the meteorological aids service.

This Annex describes the results of experimental investigations of interference levels and consequent bit error ratios in band 9. It also presents the results of the survey of the radiosonde drop points (i.e. balloon burst points) around the CDAS. As a result, frequency sharing between the two services proved to be feasible since radiosondes may drift into the CDAS antenna main beam volume with a very low probability.

2. Summary of relevant characteristics of CDAS and radiosondes

2.1 *CDAS characteristics*

The CDAS is located in Hatoyamamura, Saitama prefecture (35°58′ N, 139°19′ E) which is about 50 km northwest of Tokyo. The station provides the Earth-to-space and space-to-Earth telecommunication links for the GMS. The CDAS is operated for 24 hours a day and performs the following missions:

– VISSR data reception,
– facsimile data dissemination,
– trilateration ranging,
– meteorological data collection,
– telemetry data reception and command data transmission.

Characteristics of the CDAS antenna and each channel are listed in Tables XV and XVI respectively as a reference in the consideration of the interference with the down-link channels.

TABLE XV – *Characteristics of 18 m diameter antenna*

	Receiving	Transmitting
Frequency (MHz)	1670-1700	2015-2045
Gain (dB)	47.9	49.9
Noise temperature (K)	22.3	–
Voltage standing wave ratio	1.3	–
Beamwidth	0.66°	0.56°

TABLE XVI – *GMS telecommunication system of down link*

Function	Centre frequency (MHz)	RF bandwidth (MHz)	Transmitter power (W)	Modulation
DCP interrogation	468.8	0.2	2.5	PCM-PSK
VISSR data transmission	1681.6	20	10	PCM-4Φ PSK
Facsimile				
high resolution	1687.1	1	10	FM-FM
low resolution	1691.0	0.026 or 0.26	1 or 10	AM-FM
Ranging	1684.0	1	1	AM-PM
Ranging	1688.2	1	0.005	AM-PM
Ranging	1690.2	1	0.005	AM-PM
DCP report	1694.5	0.4 (1)	0.05	PCM-PSK
Telemetry	1694.0	0.4	0.2	PCM-PSK-FM-PM
Telemetry/ranging	2286.5	0.2/1	2	PCM-PSK-FM-PM

(1) 133 channels.

2.2 *Radiosondes characteristics*

The characteristics of Japanese radiosondes are listed in Table XVII. Figure 6 shows the location of the radiosonde launching sites (observatories) and the CDAS.

TABLE XVII – *Characteristics of radiosonde RS2 56A which were used for the experiment*

Centre frequency of transmitter	1682.4 MHz (1)	
Transmitting power	0.4 W (2)	
Type of emission	A2B	
Modulation frequency	Space time	750 Hz + 20 %
	Mark time	375 Hz + 20 %
	Pulse time	100 μs-450 μs
	Modulation Index	100 %

(1) 1680 ± 4 MHz in specification.

(2) Antenna gain : 0 dB.

3. The interference simulation experiment and the survey of radiosonde drop points

3.1 *Interference simulation experiment*

The following experiment was conducted with the VISSR channel in order to determine the relationship between interference from radiosondes to the GMS telecommunication channels.

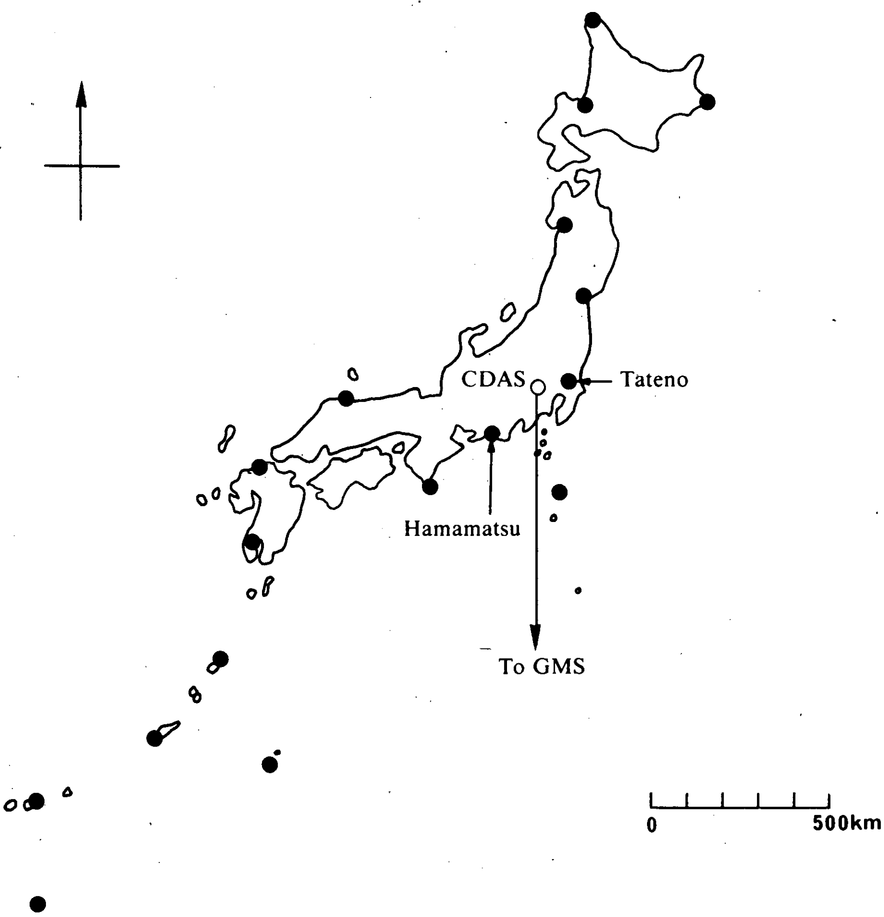


FIGURE 6 – *Location of the radiosonde station and the CDAS in Japan*

● Radiosonde station

3.1.1 *Experimental method*

The experiment was performed by placing a radiosonde with the characteristics shown in Table XVII at a distance of 6.8 km from the CDAS and measuring the effects on the receiving channel. The interfering signal level from the radiosonde was varied by controlling the CDAS antenna azimuth direction and Fig. 7 shows the block diagram of the CDAS configuration.

The interfering signal level from the radiosonde was measured with a spectrum analyzer, and the degradation of the VISSR channel bit error ratio (BER) was obtained from outputs of the synchronizer and data buffer. The influence on the VISSR image quality was noted from the display on the image monitor quick-look facility.

3.1.2 *Results*

Table XVIII presents a summary of the relationship of the interfering signal input level from the radiosonde and the BER, qualitative statement of the effect to the VISSR image quality is also shown. E_b/N_0 in Table XVIII is calculated from:

$$\frac{E_b}{N_0} = \frac{S}{N} \cdot \frac{B}{M} \tag{1}$$

where:

S: VISSR test pattern signal input level to the quadriphase demodulator/demultiplexer (QPDD),

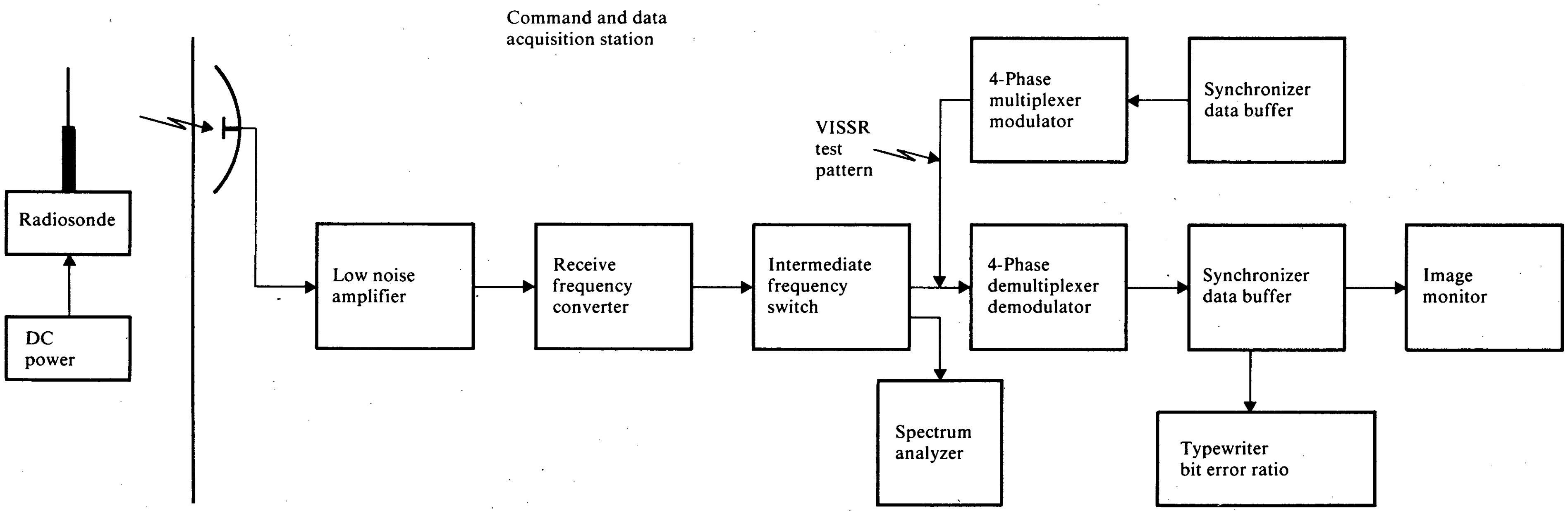
N: total noise (interference) input level to the QPDD,

B: QPDD input band pass filter band width (22.5 MHz),

M: VISSR data bit rate (14 Mbit/s),

E_b: signal energy per bit,

N_0: noise power per Hz.



Position of radiosonde:

distance: 6.8 km
direction: 80.1°

FIGURE 7 – *Block diagram of interference test*

See Fig. 8 for the relation of the E_b/N_0 to BER.

This experiment indicates that the VISSR channel will not be harmfully degraded when the level of the interference entering the CDAS antenna output is below −106.9 dBm.

TABLE XVIII – *The results of the experiment*

Radiosonde signal power entering 18 m antenna (dBm)	4 Φ DEM/DEMX input level (dBm)	E_b/N_0 (dB)	BER	Degree of interference on the VISSR image
− 106.9	− 18.9	13.5	$< 1 \times 10^{-6}$	None
− 105.9	− 17.9	12.5	$\approx 1 \times 10^{-6}$	Noise as recognized on the image
− 104.9	− 16.9	11.5	$\approx 1 \times 10^{-5}$	
− 102.5	− 14.5	9.1	$\approx 1 \times 10^{-3}$	
− 100.0	− 12.0	6.6	≈ 1	It was impossible to receive the image

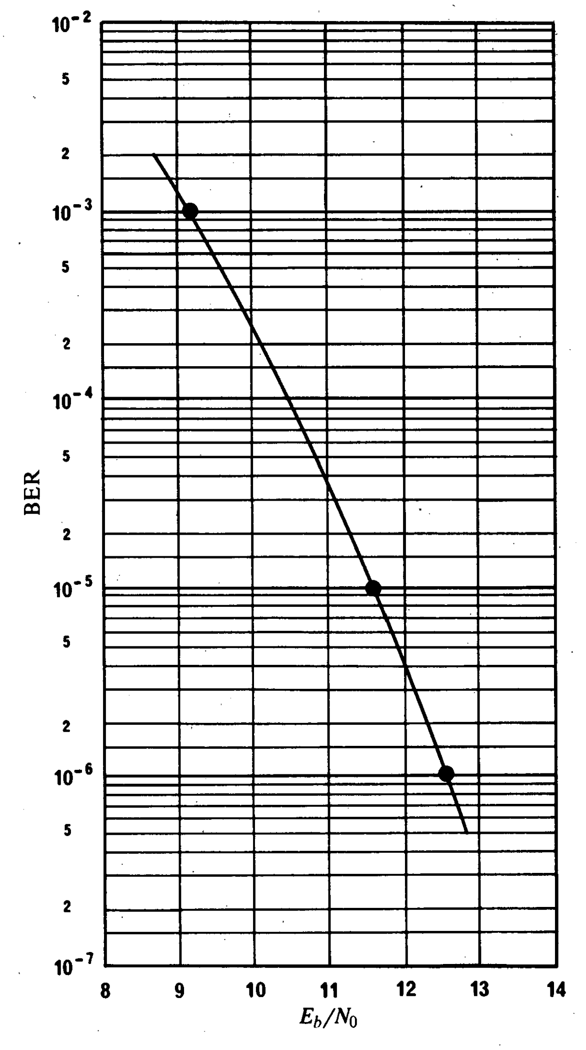


FIGURE 8 – *Relation between the BER and the E_b/N_0*

3.2 *Survey of drop points of radiosondes*

Drop points of radiosondes were surveyed for a year during 1975 in order to quantify the effect on practical radiosonde operations on the GMS-CDAS telecommunication channels. These radiosondes were launched at Tateno, about 74 km distant to the east-northeast of the CDAS, and at Hamamatsu, about 170 km distant to the southeast of the CDAS. Their drop points around the GMS CDAS are plotted in Fig. 9. The area of the pattern marked "interference area" is bounded by the locus of power flux level which will not result in interference to the VISSR imaging (i.e. -106.9 dBm $+$ 47.9 dB $\doteqdot$ -59 dBm) and determined by the following equations. The slant range from a radiosonde to the CDAS antenna d is:

$$d = \left(\frac{P_r}{G_\alpha \cdot P_t}\right)^{-1/2} \cdot \frac{\lambda}{4\pi} \tag{2}$$

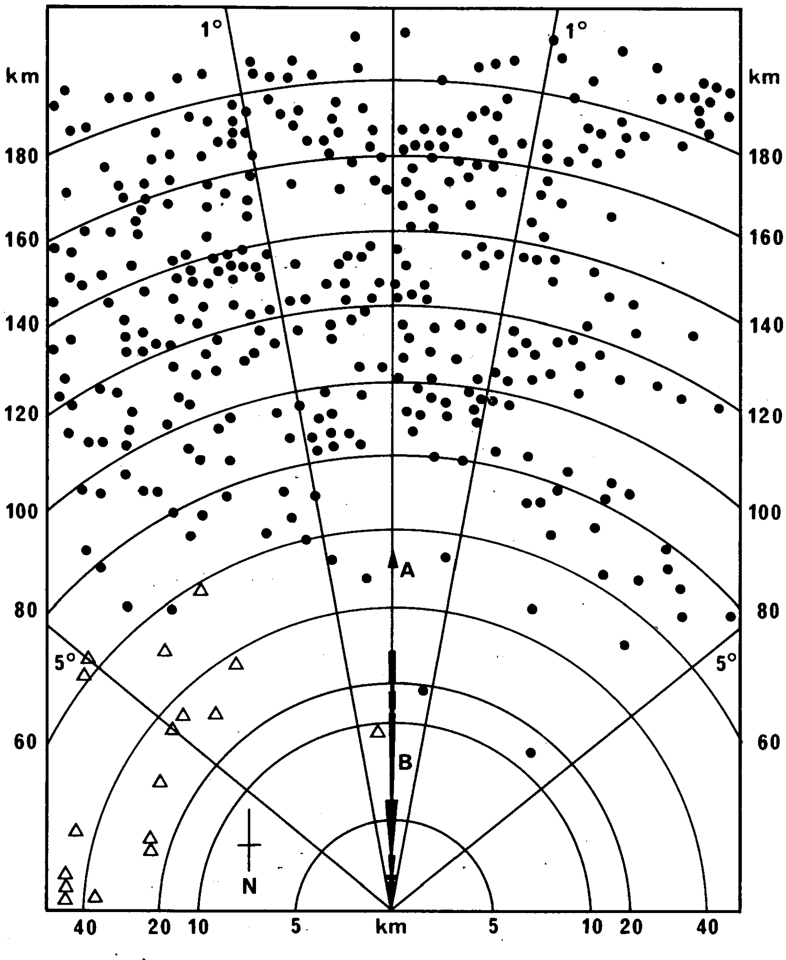


FIGURE 9 – *The relation between the interference area and the radiosonde drop points*

• The drop points of Hamamatsu radiosonde

△ The drop points of Tateno radiosonde

A : to GMS (140° E)

B : interference area

Note 1. – Within the interference area, the radiosonde signal power entering the 18 m diameter antenna is greater than -106.9 dBm.

Note 2. – The drop points were surveyed during 1975.

Note 3. – The drop point is the balloon burst point.

and the distance from the radiosonde sub-point (plumb projection of the radiosonde to the Earth) to the CDAS antenna r is:

$$r = R \cos^{-1} \frac{R^2 + (R + H)^2 - d^2}{2R(R + H)} \tag{3}$$

where:

$$H = H_0 + 1000\, d \sin \theta + 0.0589\, d^2 \cos^2 \theta \tag{4}$$

P_t : radiosonde e.i.r.p.,

P_r : antenna output power,

G_α : antenna gain at α degrees off from the centre axis,

λ : wave length,

R : radius of the Earth,

H : radiosonde height which includes the coefficient of effective radius of the Earth,

H_0 : antenna height from the sea level,

θ : antenna elevation.

4. Conclusions

The results of the interference experiment and survey described above lead to the conclusion that sharing of the upper part of band 9 between the meteorological aids service and the meteorological satellite service is feasible. The basis of this conclusion is the low probability that radiosonde trajectories will pass through the main beam of the 18 m diameter CDAS antenna as a result of careful location of the CDAS site.

In the case of the facsimile data receiving stations (DUS = data utilization station) interference can be minimized by carefully selecting the locations of these stations with respect to the radiosonde launching sites (observatories) and taking into account their trajectories.

REPORT 538-3

EARTH EXPLORATION SATELLITES

Satellites for location of platforms and for data collection

(Study Programme 12D/2)

(1974-1978-1982-1986)

1. Principle and applications

The purpose of data collection satellite systems, is to provide a telecommunication network for users needing information from a variety of sources, which may be located anywhere in the world, including desert regions.

The concept of a data collection satellite system is the following:

- automatic, autonomous platforms installed on land or mounted on a support (boat, aircraft, balloon, anchored or drifting buoy, land vehicle) for the transmission of meteorological (pressure, temperature, humidity, etc.) or geophysical (tsunami warnings, seismic, oceanographic and geodetic data, etc.) parameters. These platforms should, as far as possible, be light and compact, use little power and be inexpensive;
- the information compiled and transmitted by the platforms is received on board a satellite and forwarded through one or more telemetry stations to a system management centre;
- once centralized, the information is carried to users by conventional means (telex);
- if necessary, provision may also be made to distribute information from the management centre to the platforms.

It is obvious that such a system differs from conventional telecommunications in that it cannot be conceived without the use of satellites and is intended for a special category of customers whose needs cannot be met by other means. In general, it favours one direction of transmission and essentially serves to centralize information. It may, however, be backed up by a facility for the distribution of information to the collection platforms. If desired, the information may be retrieved automatically from the platforms. Finally, a requirement that is very important for many users, is that the data collection function may easily be coupled with a location system which determines the coordinates of the transmitting platforms.

A data collection system has many fields of application:

- meteorology;
- Earth resources;
- hydrography;
- seismic observation;
- vulcanology;
- geodesy and geodynamics;
- anchored or drifting oceanographic buoys;
- oil prospecting;
- wild-animal tracking.

2. Data collection systems design

Data collection systems may be classified according to:

- satellite orbital altitude;
- mode of operation of platforms;
- existence or absence of a location function.

2.1 *Types of orbit*

Two types of orbit may be used: the geostationary-satellite orbit or low orbits.

2.1.1 *Geostationary satellites*

The coverage area of a satellite is a spherical cap with a geocentric half-angle of approximately 75°.

TABLE I

Advantages	Disadvantages
Continuous coverage within view of the satellite. The information is transmitted continually and reaches the user very rapidly	At least four satellites are required for world coverage, excluding the polar regions The platforms must be equipped with directional antennas and/or higher powered transmitters The location function is difficult to provide

2.1.2 *Low-orbit satellites*

These are generally placed on circular orbit at altitudes of between 600 and 1800 km, with a period of revolution of approximately 2 h. The whole of the Earth (including the poles) can be scanned with a single satellite, but the number of passes is relatively low (about 3 or 4 per day over the equator). It may be increased by using several satellites e.g. a dozen passes per day over the equator may be obtained with three satellites. Passes are far more frequent near the poles.

TABLE II

Advantages	Disadvantages
World coverage, including the poles Simpler platforms Location function easier to provide	Coverage limited to the overpass of the low-orbit satellite It is generally necessary to store information on board the satellite

2.1.3 *Comparison*

The choice of system will depend on the characteristics of the field of application. A geostationary-satellite system is essential where instantaneous transmission is required either continuously or at set times. A low-Earth satellite system provides global coverage including the polar regions and economically provides platform location.

2.2 *Mode of operation of platform*

Several types of platform are used.

2.2.1 *Interrogated platforms*

These platforms are used principally with geostationary data collection systems. Each platform contains both a transmitter and a receiver.

The system management centre transmits to the satellite a work programme containing the addresses of the platforms to be interrogated and the time at which this operation must be carried out.

The platforms cannot transmit unless they are interrogated. However, they can be designed to request interrogation, e.g. geophysical warning systems.

This mode of operation is very reliable and there is no risk of mutual interference. However, the platform must be equipped with a receiver which increases its cost.

2.2.2 *Platforms operating in a random access mode*

a) In geostationary satellite data collection systems, the platforms are used for transmitting warnings.

The platform normally reports only when a fixed threshold of the phenomenon being measured is met or exceeded. An example is a platform which in monitoring seismic activity only reports if the seismic activity is greater than normal. In practice, separate channels in the allocated band are reserved for random-access platforms in order to reduce the probability of interference with the other types of platform.

b) In low-orbit satellite data collection systems, each platform repeats its message separately from the others and at given intervals. Interference may therefore occur between platforms which are in line-of-sight of the satellite at the same time.

Conversely, the satellite can work with only a limited number of platforms in line-of-sight at the same time.

2.2.3 *Self-timed platforms*

These platforms are used principally with geostationary data collection systems. Each platform transmits its message automatically within pre-set times. The reporting intervals are determined at pre-set times by a clock internal to the platform. Each platform is identified by its address and the frequency (assigned channel) on which it transmits its report. In practice, satellite operators manage the assignment of the time slots and the broadcast channels of the platforms.

2.3 *Platform location*

Mobile platforms (balloons, drifting buoys, wild animals, etc.) are used for a great many applications and their movements, which are unpredictable, need to be tracked in order to carry out the mission (wind determination, study of marine currents, study of migratory movements, etc.). In such cases, the location and collection functions are performed simultaneously.

Either the range or the range rate (Doppler effect), or both, may be measured. A number of measurements are taken and processed in order to locate the transmitting platform with an accuracy ranging from a few metres to a few kilometres. High-precision position determination to sub-metre accuracy is required for geodetic and geodynamic missions. Corresponding systems are described in Rapport 588.

The Doppler method of location is not applicable to geostationary satellites. Location from geostationary satellites may be achieved by interferometric data from a single satellite or by ranging within the overlap area of two satellites.

3. Examples of satellite data collection and location systems

An example of a low-orbit satellite system is given in Annex I. An example of a geostationary-satellite system is presented in Annex II. Annex III describes the aircraft to satellite data relay (ASDAR) system. Annex IV presents an example of a planned geostationary-satellite system in the radiodetermination satellite service for remote platform location and data collection.

Other systems, no longer operational or no longer planned, are described in Report 538 (Geneva, 1982): they are OPLE, IRLS, LANDSAT-1 and 2, RAMS and GEOLE.

ANNEX I

PRINCIPLE AND CHARACTERISTICS OF THE ARGOS SYSTEM

1. Introduction

ARGOS is a data collection and location system designed and developed by CNES (France) in cooperation with NASA and NOAA (United States of America). It has been operated under the aegis of these three agencies since 1978. The system is used nowadays by numerous countries and an average of 600 platforms are in routine operation. In 1985, the three agencies decided to keep the system in operation until at least 1995.

The ARGOS system uses low-orbit satellites and platforms operating in a random access mode. Location is determined by measuring the one-way Doppler shift.

2. Orbit of the satellites

The system comprises two satellites in orbit simultaneously. The nominal orbit characteristics are:

Inclination: 98°

Altitude: 830 km

Period of revolution: 102 minutes

The ascending nodes of the two orbits form an angle of 120°.

3. Platforms

Each platform emits sporadically. Each emission consists of two successive parts: during the first part, a pure carrier is emitted; during the second part, the signal is modulated by the message to be transmitted.

Unmodulated part: duration of the order of 160 ms.

Modulated part: includes 48 service bits followed by the data from the sensors. Depending on the number of sensors the total duration of the modulated part ranges between 200 ms and 760 ms.

Period of repetition:

- platforms to be located: chosen between 40 and 60 s,
- platforms to be used only for data collection: chosen between 100 and 200 s.

Bit rate: 400 bit/s.

Encoding: two-phase Manchester code.

Carrier: 401.65 MHz ± 3.2 kHz.

Emitted power: about 3 W.

Frequency stability (to obtain a location accuracy of 1 to 3 km):

– short-term drift (20 min) not to exceed 0.5×10^{-9}/min,
– jitter (120 ms): 10^{-9}.

Note. – The location accuracy depends to some extent on the stability of the platform oscillator; this specification may vary according to the objective sought.

4. Satellite

Minimum power level of an individual received signal: −131 dBm;

Maximum power level of an individual received signal: −109 dBm;

Noise power: −171 dB(mW/Hz), which corresponds to an antenna temperature of 300 K and to a receiver noise factor of 3 dB;

Analysis bandwidth at reception: 24 kHz;

Number of processing channels: 4;

Estimated service life: 2 years, hence the duplication of some equipment: receivers, ultra-stable oscillators, spectral analysis system.

5. Performance

Capacity:

– for data collection with location:

  230 platforms equipped with four sensors in the same circle of visibility, i.e. 4000 platforms for the total surface of the globe, 99% of these 4000 platforms being located every 24 hours;

– for data collection without location:

  920 platforms equipped with four sensors in the same circle of visibility, i.e. 16 000 stations spread over the surface of the globe, 99% of which will have at least one message processed every 12 hours.

Precision of location:

– about 3 km for balloon-type mobile platforms, the altitude of which is known at ± 500 m:
– about 1 km for drifting-buoy type mobile platforms with slow and regular drift:
– different levels of precision (from some hundreds to some tens of metres) are attainable when the movement is at constant speed and when the stability of the platform's oscillator is sufficiently high, the uncertainty of the satellite orbit parameters then becomes the main source of error.

ANNEX II

CHARACTERISTICS OF THE GEOSTATIONARY METEOROLOGICAL SATELLITE DATA COLLECTION SYSTEM

1. Introduction

The international geostationary meteorological satellite data collection system (IGMSDCS) is comprised of data collection platforms (DCPs) and data relay transponders deployed aboard four geostationary meteorological satellites: METEOSAT, located at 0° W longitude operated by the European Space Agency (ESA); GOES-East (75° W) and GOES-West (135° W), operated by the United States of America; and the geostationary meteorological satellite (GMS) (140° E), operated by Japan. A fifth IGMSDCS satellite is projected for launch by the USSR for operation near 70° E.

Each of the satellites listed above has reserved one band of frequencies for operation of so-called international DCPs, that is, for data collection platforms which may move from the operational area of one satellite, to that of another. Another band of frequencies is reserved for DCPs operating within the coverage area of each of the satellites.

Through coordination, satellite operators share domestic DCP frequencies: the United States of America and the USSR share one band (401.7-402.0 MHz) while ESA's METEOSAT and Japan's GMS share use of a second band (402.1-402.4 MHz). This coordination obviates the need for additional bandwidth for each satellite operator.

2. Coverage areas

The system design of the geostationary meteorological satellite data collection system permits the operation of low-cost, low-power platforms from locations anywhere within the geometric field of view of each spacecraft. For geostationary spacecraft, the geometric horizon is almost 83 great-circle degrees (i.e. 9000 km) from each satellite's sub-point. Since the participating satellites are separated by 75, 60, 85 and 140 great-circle degrees (measured along the equator), this results in large field-of-view overlaps, covering much of the Earth outside the polar regions.

3. Platforms

DCP reports are transmitted at 100 bit/s, and consist of:

- an unmodulated carrier,
- a bit preamble,
- a synchronization code,
- a platform address,
- environmental data,
- an end of transmission sequence.

The details of these transmissions vary between domestic and international services; in the United States system, the minimum required introductory transmissions are shorter for domestic transmissions but longer headers would not be rejected. The following information pertains to transmissions for the international system.

Report format: international platform reports include the following contiguous elements:

- unmodulated carrier for 5 s,
- a 250 bit alternate "0" and "1" preamble,
- a 15 bits maximal linear sequence (MLS) code synchronization word,
- the UCP address which is a 31 bits Bose-Chaudhuri-Hocquenghem (BCH) coded word,
- the environmental data which are a maximum of 649 words, each word being 8 bits long,
- the 31 bits end-of-transmission sequence.

Bit rate: 100 bit/s.

Encoding: non-return to zero (NRZ) split-phase Manchester encoding.

Carrier: the International DCS includes 33 channels filling the band from 402.0-402.1 MHz. GOES United States domestic channels lie between 401.7 and 402.0 MHz (200 channels). Transmissions are phase-shift modulated.

Platform power: approximately 10 W for a platform with a high-gain (helical) antenna; about 80 W for a semi-isotropic (full horizon to zenith) antenna. Antenna polarization is right-hand circular.

Frequency stability: 1.5×10^{-6}/year, including temperature changes from $-20\,°C$ to $+50\,°C$. Phase jitter on an unmodulated carrier shall not exceed 3° r.m.s. when measured with a phase-lock loop two-sided noise bandwidth of 20 Hz within a 2 kHz band.

4. Satellite

Power level of an individual received signal:	-145 dB(W/m^2) $\pm$ 5 dB
Signal/noise level: gain/temperature:	-18.5 dB(K^{-1})
margin:	6.5 dB
Data relay bandwidth:	0.4 MHz
Number of channels:	33 (international); 200 (GOES, domestic)
Estimated service life:	5 years

5. Performance

5.1 *Capacity*

Utilization of any one channel requires availability of the channel in the satellite's transponder, and availability of a demodulator (i.e. a narrow-band receiver) for that channel at the ground control station. The ultimate platform capacity is determined by the total number of channels, and by the total message length (including a guard band of time between messages). For platforms that need not report at regular intervals, but only when some environmental threshold is reached (such as river height, or rainfall rate), the total number of platforms served can be quite large.

5.2 *Data availability*

IGMSDCS reports include environmental data of general use, as well as of value to the platform operator. Most reports are processed and are made available to such users as regional and local centres for numerical weather prediction and short-term forecasting. However, platform operators are not limited to receipt of their data by way of central processing facilities. If they wish, they may install ground station facilities for receiving the channel(s) on which their platform reports are carried.

ANNEX III

THE ASDAR DATA COLLECTION SYSTEM

1. Introduction

The aircraft to satellite data relay (ASDAR) system, first operational in 1979, is an international fixed-time data collection system (DCS) engineered for deployment aboard wide-bodied jet aircraft, for the collection of in-flight meteorological reports. Although engineered by a United States National Aeronautics and Space Administration (NASA) laboratory for use aboard commercial wide-bodied aircraft having digital navigation and flight-control data streams, the ASDAR package proved capable of modification for flight aboard other modern aircraft designs.

2. Operation

In operation, the ASDAR unit monitors the data streams within the host aircraft and, on schedule, selects values for altitude and location,, wind speed and direction, and outside air temperature. Once an hour, eight timed ASDAR reports are transmitted (as a single batch message) for satellite relay. ASDAR messages, including preface and end-of-transmission signals, are about 50 s long. This allows each message to be assigned a two minute time-slot, with a 35 s guard band of time at each end. Data users include centres for large-scale numerical weather prediction, regional weather forecasters, aircraft in-flight controllers, and airline flight planners.

A single micro-processor oversees all ASDAR functions, including message formation, and command of the ASDAR 80 W transmitter. This design feature ensures that any malfunction of the message data-processor will also guarantee that no messages are transmitted. Other design features include fail-safe isolation between the ASDAR box and its sources of data, notably the aircraft's inertial navigation system and central air data computer. Additional circuits were installed to disable the transmitter permanently should any transmission take place after the time for a message broadcast.

3. Satellite considerations

Cooperation among operators of four geostationary meteorological satellites, who established a radio-frequency band for "international" data relay, permit ASDAR data relay from virtually any location on Earth. Where the fields of view of adjacent data relay satellites overlap, processing areas are delineated to reduce the number of redundant ASDAR reports which might originate from data processing centres in Europe and America, or America and Japan.

4. Quality control

An ASDAR message suffers considerable Doppler shift of its transmitter frequency as the host aircraft either approaches or departs from a satellite sub-point. For this reason, it is necessary to monitor closely the receipt of data from ASDAR packages, in order to assure transmitter stability. United States satellite operators spot-check ASDAR signal quality, and report their findings to the ASDAR control staff. Monitors observe the transmitter centre frequency, the signal strength, and the quality of signal modulation on the transmitter carrier. The demonstrated value of this overall quality monitoring has led United States satellite operators to implement fully automated quality monitoring of all DCPs, both in its domestic and international bands.

5. Future plans

A re-engineered ASDAR package is currently planned for future deployment. (A system called ACARS is also now in use, but involves direct radio transmission of data, sometimes including meteorological reports, from an aircraft in flight to a ground radio station.)

ANNEX IV

GEOSTAR POSITIONING AND COMMUNICATIONS SYSTEM

1. Introduction

The GEOSTAR is a proposed radiodetermination satellite service system being developed for use in the United States of America for implementation in the 1987-1988 time-frame which will provide position information and message service to aeronautical, maritime and terrestrial users. The user transceivers utilized with the GEOSTAR are being designed to be low cost, light weight, physically small units. In addition to determining the position of the user transceiver to an accuracy of 2-7 m, the GEOSTAR will be capable of relaying short digital messages between user transceivers and the central control earth station.

2. Potential applications

A potential application of the GEOSTAR transceiver is for the automatic collection of environmental data. Using the GEOSTAR, remote measurements similar to those gathered by data collection platforms (DCPs) can be collected and distributed to any desired pre-determined earth location. As such, the GEOSTAR can support DCP functions and may be an attractive alternative for some DCP applications, particularly those in which knowledge of the location of moving data collection platforms is required.

In addition to relaying data, the GEOSTAR system has the potential to be used for generating wind velocity data. The true course of an aircraft can be determined by the GEOSTAR control centre by comparing its current position to its position at the previous request for position determination. If the aircraft transmits its true heading and air speed to the GEOSTAR satellite, which then relays these data to the central control earth station, the control centre computer can calculate the velocity and direction of winds aloft by comparing the true course of the aircraft to its true heading. This information, if obtained from a large number of aeronautical users, could be used to develop a detailed 3-dimensional data source for winds aloft. The data have the potential for producing large fuel savings in the airline industry as well as providing a real-time data source for meteorological studies.

3. Orbit of the satellites

The system will be comprised of three geostationary satellites at longitudes 70° W, 100° W, and 130° W.

4. Platforms

Bit rate:	16 kbit/s
Coding:	pseudo-random noise
Transmit carrier:	1618.25 MHz
Receive carrier:	2491.75 MHz
Emitted power:	40 or 80 W
Modulation:	spread spectrum, 2-PSK
Chip rate:	8.192 Mchip/s
Chip period:	122.07 ns
Signal format:	SS/TDMA

5. Satellite

Received power level:	−170.7 or −167.7 dBW
Thermal noise density:	−200.8 dB(W/Hz)
Bandwidth:	16.5 MHz
Number of beams:	8
Estimated service life:	10 years

6. Performance

6.1 *Capacity*

The system will be capable of processing an average of 10 simultaneous user accesses within each of the 8 beams.

6.2 *Positioning*

- Primary method: two satellites used with a digital terrain map or encoded altimeter readings
- Back-up positioning: tri-lateration of three satellites if no terrain map or altimeter reading is used
- Accuracy: 2-7 m (primary)
  50-100 m (back-up).

REPORT 988

SATELLITE SYSTEMS FOR GEODESY AND GEODYNAMICS

(Question 12/2 and Study Programme 12/2)

(1986)

1. Introduction

Space techniques, which enable more and better information to be obtained about the Earth (shape, motions, gravitational field and their temporal variations), have made a significant contribution to geodesy and geodynamics since the placing in orbit of the first artificial earth satellites. Since 1964, more than 20 dedicated geodetic satellites have been launched including Explorer-22, Explorer-27, GEOS-1, Pageos-1, GEOS-2, GEOS-3 and LAGEOS. A typical representative of that generation of geodetic satellites is GEOS-3. It was launched in 1975 and carried a radar transponder, a range and range-rate system, a laser retro-reflector, a radar altimeter, and a two-frequency Doppler beacon system. This combination of instruments was used for a variety of measurements related to geodesy and geodynamics. An inter-comparison of geodetic and geophysical measuring systems was also made and a satellite-to-satellite tracking experiment was carried out. More details of most of these satellites can be found in Annex III to Report 535 (Geneva, 1982).

New satellite systems for geodesy and geodynamics are under consideration by several countries and agencies for launch in the late 1980s or early 1990s. Some of them are described in Annexes I to III.

This Report concerns satellite systems in which one or more satellites are linked to earth stations and/or to each other by means of high-precision range and range-rate measurements, using radio waves.

There are other satellite systems which contribute to the advancement of geodesy and geodynamics. Examples are:

- ocean altimetry using satellite-borne radar (see Reports 535 and 693);
- range measurement by pulsed laser (see Report 680);
- microwave radiometry (see Report 693) for determining the composition of the troposphere and so correcting other measurements.

2. Telecommunication requirements for space geodesy and geodynamics

2.1 *General*

Space telecommunication systems for geodesy and geodynamics are generally required to perform three functions:

- high-precision orbit determination;
- high-precision positioning of points on the Earth's surface;
- rapid data distribution (preferably, this function is performed by the system itself).

The first and second functions are closely linked. In order to position points in a geocentric reference system, it must be possible to predict or restore the satellite orbit in that reference system with a degree of accuracy comparable to that required for the positioning. Consequently, the orbit determination system used for the tracking of geodetic satellites must have better accuracy than that which is generally required for application satellites. Such an orbit determination system typically uses a fairly large number of earth stations (e.g. 10-50) distributed geographically so as to ensure continuous tracking of the satellite(s) which should always be visible from two or more stations. This network may be used also for geodetic applications, i.e. to determine parameters relating to the Earth's rotation, the geocentric coordinates of stations and the base lines linking pairs of stations.

The second function (precise absolute and relative point positioning) is generally performed with transportable ground stations or networks to be established temporarily in areas of geographical interest, sometimes in clusters of more than 20 stations within a limited region.

With respect to the third function, certain geodetic and satellite orbital parameters must be recovered within a relatively short time (approximately one day). It may also be necessary to distribute *in situ* data gathered locally and orbit prediction data generated at a central facility.

2.2 *Types of telecommunication required*

Two main types of telecommunication are required to perform the functions described above:

- measurement telecommunication (between the earth stations and satellites or between satellites);
- data communication.

These may be used in conjunction or separately.

2.2.1 *Measurement telecommunication*

Determination of the relative positions of earth stations and satellites or of their variation in relation to the movement of the spacecraft, using electromagnetic wave propagation, has thus far been based on the measurement of:

- range rate;
- range;
- range difference.

These values may be obtained by various methods, which may be classified as either one-way or two-way.

2.2.1.1 *One-way measurements between earth stations and satellites*

One-way measurements are used in the space-to-Earth direction as, for example, in the TRANSIT and GPS-NAVSTAR systems [Stansell, 1971; Milliken and Zoller, 1978]. The measurements are taken in this case on the ground, at each station. Such systems facilitate data distribution to a large number of users. They cannot be used directly for the determination of the base lines linking pairs of stations.

One-way measurements may also be used in the Earth-to-space direction as for example, in the planned DORIS system (see Annex I). This system offers the possibility to collect data at a central point.

Whatever direction the one-way measurements are performed, they require very high frequency stability at both the transmitter and the receiver local oscillator. For example, a relative frequency shift of $\delta f/f = 10^{-11}$ introduces an error of $\delta v = 3$ mm/s in range-rate measurements. In one-way range measurements systems, such as GPS-NAVSTAR, where phase stability must also be maintained, when higher frequency stability is necessary.

On the other hand, one-way systems have the advantage of requiring only a transmitter at one end of the link and a receiver at the other.

2.2.1.2 *Two-way measurements between earth stations and satellites*

Systems employing two-way measurements have considerably lower requirements on the stability of their oscillators. Depending upon operational conditions, the measurement signal can either be generated on board a satellite or in the ground terminals with one of the link elements operating as a simple transponder. If suitable modulation schemes are used, these systems can serve several stations simultaneously permitting the precise determination of relative distances (base lines) between pairs of stations. The planned POPSAT system (see Annex II) and the Precise Range and Range-Rate Experiment PRARE (a payload of the European remote-sensing satellite ERS-1, see Annex V to Report 535) are two-way measurement systems.

2.2.1.3 *Satellite-to-satellite tracking (SST)*

Space techniques can provide the key to the determination of the short and medium wavelength components of the Earth's gravitational field. One particular method is the measurement of the relative velocity between two satellites. The principle of SST has been successfully demonstrated in a mission where a geostationary satellite (ATS-6) tracked a satellite in low orbit (GEOS-3). Another possibility is to perform satellite-to-satellite tracking with both satellites in the same low orbit, but separated by up to 300 km. The proposed Geopotential Research Mission (see Annex III) represents such a configuration.

2.2.2 *Data telecommunications*

The measurement systems described above provide their results at one end of the system. In the case where these data are not extracted at the point where they are needed for further processing or dissemination, they have to be transmitted back to the other end of the system. Furthermore, processing the raw data might entail the addition of auxiliary data available at the other end of the link, for example:

– data on propagation conditions measured in the vicinity of the earth stations (atmospheric pressure, temperature, humidity), and added to the up-link signal;
– ephemeris data of the satellites, information on the state of the ionosphere, etc. to be distributed to the earth stations.

Three types of information can be transferred within the system:

– measurement signals;
– measurement results;
– auxiliary data.

The latter two could be multiplexed with the measurement signal or use separate links for re-transmission.

3. Preferred frequency bands

3.1 *RF spectrum constraints due to propagation characteristics*

The usable frequency bands are limited by the characteristics of the media through which the signals pass.

– The troposphere causes both absorption loss and signal delay. Although tropospheric delay causes errors which exceed the accuracy goals of satellite geodesy and which have to be corrected in the parameter recovery process, it is not a criterion for the choice of preferred frequencies. Absorption loss significantly affects link budgets only above about 20 GHz.
– The ionosphere causes negligible absorption above about 100 MHz. The lower limit of usable frequencies is determined by the phase shift and group delay of the signals used for measurement.

Report 263 describes in detail the ionospheric effects on Earth-to-space and space-to-Earth propagation. A simplified description is given in § 3.1.1 of Report 845.

In order to reduce measurement errors caused by inadequate knowledge of the ionosphere, it is necessary either to use fairly high frequencies or to merge the measurement data obtained simultaneously at a number of coherent frequencies. Reference is made to a study [Saint-Etienne, 1981] which assesses measurement errors due to the ionosphere in single or dual-frequency systems.

Tables I and II are taken from this study and show typical error values for Earth-to-space or space-to-Earth links. Table II shows a significant improvement when a dual-frequency system is used, but it is important to note that the two measurements are assumed to be simultaneous. Sequential measurements would produce far less satisfactory results.

As shown in Table II, the combination of dual-frequency measurements considerably reduces the ionospheric error. However, if in dual-frequency systems these frequencies are not sufficiently spaced in the radio spectrum, the non-ionospheric errors grow by a factor which is, for example, between 1.2 and 1.6 for the pair 150/400 MHz and attains 3-4 for the pair 1227/1575 MHz.

One major conclusion that can be drawn from the above considerations is that single-frequency measurement systems are generally inadequate for high-accuracy satellite geodesy and geodynamics missions. Measurement systems for such missions require at least two frequency bands sufficiently spaced in the radio spectrum.

3.2 *Necessary bandwidth*

3.2.1 *Necessary bandwidth for Doppler effect measurements*

Owing to the Doppler shift, the received frequency differs from the emitted frequency by a quantity $+\Delta f$ or $-\Delta f$ depending upon whether the slant range is decreasing or increasing.

$$\Delta f = \frac{v}{\lambda} \text{ for one-way measurements,}$$

$$\Delta f = \frac{2v}{\lambda} \text{ for two-way measurements,}$$

v being the range rate and λ the wavelength.

TABLE I – *Ionospheric error in single-frequency systems*

Measurement	Error \ Frequencies (MHz)	400	1600	2000	8000
Range (m)	Average Exceeded < 10% of cases Maximum	50 250 500	3 15 30	2 10 20	0.12 0.6 1.2
Range rate (cm/s)	Average Exceeded < 10% of cases Maximum	17 85 170	1 5 10	0.7 3.5 7	0.04 0.21 0.43

TABLE II – *Ionospheric residual errors in dual-frequency systems*

Measurement	Error \ Frequencies (MHz)	150/400	400/2000	1227/1575	2000/8000
Range	Average Exceeded < 10% of cases Maximum	0.6 m 10 m 36 m	0.9 cm 6.6 cm 22 cm	0.3 cm 1.7 cm 4.5 cm	0.01 cm 0.05 cm 0.11 cm
Range rate (cm/s)	Average Exceeded < 10% of cases Maximum	0.3 6 23	3×10^{-3} 0.04 0.14	2×10^{-3} 0.02 0.06	3×10^{-5} 4×10^{-4} 10^{-3}

Note. – Values in Tables I and II were calculated for a zenith pass at an elevation angle of 24°. Range-rate error calculations assume a satellite altitude of 1000 km.

Table III gives the necessary bandwidth $2\Delta f$ for $v = 9$ km/s.

TABLE III – *Necessary bandwidth for measuring the Doppler effect corresponding to a range rate of 9 km/s*

		150	400	2000	8000
f (MHz)		150	400	2000	8000
λ (m)		2	0.75	0.15	0.0375
$2\Delta f$ (kHz)	one-way	9	24	120	480
	two-way	18	48	240	960

3.2.2 *Necessary bandwidth for ranging*

Radio ranging consists of measuring the propagation phase or group delay of signals between the spacecraft and the earth station. However, the measurement is generally not taken on the carrier because of the ambiguity of $n\lambda$ (one-way) or $n\lambda/2$ (two-way). In order to remove the ambiguity, measurements are taken on signals which modulate the carrier.

Two main types of modulation are used. In one case, the phase delay of several sinusoidal signals or tones, modulating the carrier simultaneously or sequentially, is measured. The lowest frequency tone is used to remove the ambiguity, while the highest determines the range resolution. Highest modulating frequencies are typically about 1-10 MHz. However, this technique has the disadvantage of concentrating RF energy on spectrum lines and therefore its use may be difficult in some of the bands shared with services requiring protection defined in terms of a spectral power-density limit.

In the other case, the group delay of a pseudo-noise code, modulated on the carrier, is measured. Here the energy is spread over a band of some 1-10 MHz.

In both cases, after modulation of the carrier, the RF bandwidth is between about 2-20 MHz. Larger bandwidths might be used in the future.

The Doppler frequency shift (see Table III) must be added to these values.

3.2.3 *Necessary bandwidth for data communications*

The data rate of the auxiliary data is in the region of some tens of bit/s. This information may be multiplexed with ranging signals.

3.3 *Usable frequency bands*

Telecommunication systems for satellite geodesy and geodynamics are relevant to the space research service and to the earth exploration-satellite service. Furthermore, some systems operated by the radionavigation-satellite service can also be exploited for geodesy or geodynamics.

Table IV shows some of the frequency bands currently used or envisaged for satellite geodesy and geodynamics applications.

TABLE IV – *Frequency bands currently used or envisaged in satellite telecommunication systems for geodesy and geodynamics*

Frequency band (MHz)	Direction	Allocation
149.9-150.05	Not specified	Radionavigation satellite
399.9-400.05	Not specified	Radionavigation satellite
401-403	Earth-to-space	Earth exploration satellite
1215-1260	Space-to-Earth	Radionavigation satellite
1559-1610	Space-to-Earth	Radionavigation satellite
2025-2110	Earth-to-space	Space research and earth exploration satellite
2200-2290	Sparce-to-Earth	Space research and earth exploration satellite
7190-7235	Earth-to-space	Space research
8025-8400	Space-to-Earth	Earth exploration satellite
8450-8500	Space-to-Earth	Space research

Note. – For geodesy and geodynamics purposes the bands allocated to the radionavigation-satellite service should only be for reception.

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ANNEX I

DORIS SYSTEM OF FINE POSITIONING AND TRACKING

1. Introduction

The DORIS system of fine positioning and tracking is being developed in France. It is intended to be used mainly for geodynamics and, in conjunction with a radar altimeter, for physical oceanography missions. Its first application is planned on the SPOT-2 satellite (1987).

2. Technique and objectives

2.1 *Principal mission*

The DORIS system offers a means of precisely determining the orbit to any number of user satellites. It will comprise about 40 tracking beacons distributed uniformly around the Earth. These beacons will all emit the same signals with very high frequency stability for measurement purposes. Each beacon will also emit specific auxiliary data.

Each user satellite will carry receiving and measuring equipment, driven by a local oscillator, with very high frequency stability. This equipment will permit one-way measurement of the Doppler effect and the reception of auxiliary data from which the orbit will be derived.

2.2 *Secondary mission*

It is planned to install additional, geophysical beacons for studies of the movements of the Earth's crust. These beacons will be placed in active seismic zones for durations of a few weeks. Since the satellite orbit is determined in the context of the principal mission, the positions of the geophysical beacons can be deduced from the Doppler effect measurements.

3. Technical characteristics

3.1 *Frequency stability*

The signals emitted and the signal of the receiver local oscillator should have a frequency stability, $\delta f/f$ of 10^{-12} per 500 s and of 10^{-11} per 24 h.

3.2 *Frequency bands used*

- Main link: 2025-2110 MHz,
- Ionospheric correction link: 401-403 MHz.

3.3 *Auxiliary data*

These data include the identification number of the beacon and meteorological information collected *in situ* which are used to correct the tropospheric measurement error. The data will be transmitted continuously at a rate of 200 bit/s and with a format of 0.8 s duration which repeats every 10 s.

3.4 *Occupied bandwidths*

The bandwidth of the signals transmitted by the beacons is 5 kHz on each of two frequencies.

Owing to the Doppler effect, the necessary bandwidth of the satellite receivers is much wider (see, for example, Table III).

3.5 *Link performance*

With a transmitting power of 7 dBW at 400 MHz and 10 dBW at 2 GHz, and using hemispheric radiation pattern antennas on board and on the ground, the error due to total noise (thermal and interference noise) will be about 0.15 mm/s after processing, for an integration time of 10 s and a satellite distance of 1600 km. Noise due to interference from terrestrial stations is assumed to exceed thermal noise by 4 dB at 400 MHz and 7 dB at 2 GHz.

3.6 *Accuracy*

The system is designed so that the overall error of satellite-beacon range-rate measurement due to the instrument (including ultra-stable oscillators), to interference and to propagation does not exceed 0.4 mm/s.

Depending on the application and the data processing method, the relative satellite-beacon equivalent range measurement precision should be between 2 and 10 cm.

ANNEX II

PRECISE ORBIT POSITIONING SATELLITE (POPSAT)

1. Introduction

An active geodetic satellite system named POPSAT is currently being investigated comprising all elements of an operational system for continuously monitoring the absolute and relative positions of points on the Earth's surface, the spin-axis motion and the Earth's rotation rate. The essential elements of the system are: all-day, all-weather self-tracking capability, data collection/transmission capability, ionospheric path delay correction capability, possibility to serve unattended automated user stations, simultaneously tracking to four ground transponders in the two-way mode, and unlimited access to orbit ephemeris for real-time positioning in receive-only mode.

POPSAT is being studied for a launch in the early 1990s. Its mission is expected to permit determination of earth kinematics parameters and the absolute position of points with sub-decimetre accuracy. For relative positioning (baseline determination), the achievable precision will be in the 2-3 cm range.

2. System description

The POPSAT system is conceived to comprise:

- a single satellite orbiting at a nominal altitude of 7000 km with an inclination of 98.6°, and
- a network of about 10-20 fixed ground terminals.

The spacecraft will have a mass of between 500 and 700 kg, and its principal payload is a microwave tracking system for precise range and range-rate measurements performed in the 8 GHz and 2 GHz frequency bands.

The system offers unlimited access by the world-wide community of geodesists and geophysicists by means of transportable transceiver stations or simpler receive-only user terminals.

In order to achieve the geodetic objective mentioned above, the system is conceived for range and range-rate accuracies of 10-20 cm and 0.1 mm/s, respectively.

A special feature of the system is that it allows for data transmission from the user stations to a coordination centre via the tracking link.

POPSAT will also be equipped with a retro-reflector array as a target for laser-tracking stations. Since the orbit of POPSAT can be predicted to a high degree of accuracy with the use of its microwave payload, the addition of such a supplementary payload offers the possibility of geodetic laser tracking operations and of contributing to orbit determination.

3. Frequency bands used

The range measurement is performed electronically by digital code correlation techniques. The actual parameter observed is the time shift measured in the spacecraft between an emitted code sequence and its received replica after two-way transmission, where the ground terminal acts as a transponder.

The carrier frequencies will be assigned either in the 7/8 GHz bands or in the 13/15 GHz bands. The spectral characteristics of these links are dominated by a digital NRZ modulation with a pseudo-random ranging code at a chip rate of 10 MHz, modulated in PSK, to achieve spectrum spreading over a bandwidth of 20 MHz. An auxiliary down link modulated with a 1 MHz PN pseudo-noise ranging code is foreseen in the 2 GHz band for ionospheric delay correction. This link is coherent in carrier and modulation with the 8 GHz down link. With transmitter powers of 5 W and 20 W for the down and up links, respectively, the nominal signal-to-noise density ratio (S/N_0) is about 66 dB(Hz); the system thus operates at receiver input S/N ratios of -7 to -10 dB.

Since the transponder is of the regenerative type, a data code can be modulated on the same carrier together with the PN ranging signal.

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ANNEX III

GEOPOTENTIAL RESEARCH MISSION (GRM)

1. Mission description

The geopotential research mission (GRM), formerly known as GRAVSAT/MAGSAT, is being studied for launch in the early 1990s. The objective of the GRM is to determine the Earth's gravity and magnetic fields to provide accurate mathematical models for studies of the structure, composition and movement of the solid Earth and oceans, resource exploration, orbit determination, and navigation. GRM is expected to permit determination of the gravity field to 2 milligal, the geoid to 10 cm, with a 100 km horizontal resolution. Determination of the magnetic field anomaly map to 1 nanotesla (nT) with a 100 km resolution is expected.

2. System description

The GRM will consist of two spacecraft orbiting at a 160 km altitude and separated in orbit by about 300 km. The two spacecraft differ in that one of them (A1) will carry the magnetometers and the star cameras (required for precise measurement of the orientation of the magnetometers). The two spacecraft are alike with respect to the gravity field detection system. An interesting feature of the gravity measurement system is that the spacecraft themselves serve as the detecting instruments. The supporting instrumentation, the Doppler tracking, and the disturbance compensation system (DISCOS) measure the spacecraft response to the variations of the Earth's gravity field.

3. Spectrum considerations

3.1 *Doppler tracking instrument*

The Doppler frequency shift due to changes in the relative velocity between the two spacecraft will be measured at two frequencies, near 95 GHz and near 40 GHz. A continuous wave signal is radiated by the A1 spacecraft to the A2 spacecraft which receives it and compares it to an on-board signal. At the same time, the A2 spacecraft is radiating an incrementally frequency-shifted signal to the A1 spacecraft where it is compared. The resultant continuous comparison of the signals serves to measure the velocity changes to a precision of 10^{-6} m/s.

3.2 *Communications and data handling system*

Command, telemetry, and tracking will use the TDRS multiple-access system which operates in band 9 (see Report 848). In addition, a ground-based precision Doppler tracking system will provide spacecraft-to-ground tracking data which will be processed in conjunction with the spacecraft-to-spacecraft tracking data to determine the gravity field. The ground-based Doppler tracking system operates in band 9.

SECTION 2G: RADIOASTRONOMY AND RADAR ASTRONOMY

Recommendations and Reports

REPORT 852-1

CHARACTERISTICS OF THE RADIOASTRONOMY SERVICE AND PREFERRED FREQUENCY BANDS

(Question 5/2)

(1982–1986)

A. CHARACTERISTICS OF THE RADIOASTRONOMY SERVICE

1. Introduction

The science of astronomy concerns itself with the study of the Universe. With very few exceptions, such as meteorites, particles ejected by the Sun and space probes, all the available information about the Universe is conveyed by electromagnetic waves.

Radioastronomy and the radioastronomy service are defined in Article 1, Nos. 14, 55, and 91 of the Radio Regulations as being astronomy based upon the reception of radio waves of cosmic origin. Since it uses receiving techniques only, the radioastronomy service does not cause interference to any other service. Radioastronomy at present utilizes the electromagnetic spectrum ranging from 1 MHz to about 700 GHz. However from the point of view of availability of equipment, the entire radio spectrum can now be employed for astronomical measurements.

Radar astronomy, which involves the transmission of a signal at a high power-level and the detection of that signal after reflection from celestial bodies, man-made satellites, or meteor trails, is a quite different activity, and is covered in Question 6/2 and Report 226.

Radioastronomy began with the discovery in 1932, by Karl Jansky, of radio waves of extra-terrestrial origin [Jansky, 1935]. The cosmic emissions with which the radioastronomy service is concerned constitute the "cosmic background noise" of communications engineering.

Since Jansky's original observations, remarkable progress has been made in identifying the nature of these emissions, and radioastronomy is now firmly established as an important branch of astronomy. It is a new field of science, but it has already made important contributions to our knowledge of the measurement of atmospheric absorption at radio frequencies and also to our knowledge of the composition and nature of the Sun, the planets, interplanetary space and, in particular, the major disturbances in the solar atmosphere which are often the forerunners of interruptions to radiocommunication circuits and of radiation hazards to man in space. Further afield, studies of individual sources over a range of frequencies, and of the "line" emissions at precise frequencies resulting from transitions within certain atoms and molecules, provide information basic to our understanding of the physical processes responsible for the emissions of plasmas, and of the structure and evolution of galaxies and of the Universe as a whole. The radioastronomy service offers means for studying magnetic fields in distant regions of the Universe, and much of the information it provides is unique in that it is unobtainable by optical or other methods; one of its most spectacular characteristics is the ability to probe even further into the depths of space than is possible with the largest optical telescopes.

In addition to providing new knowledge and understanding of great significance to astrophysics and cosmology, radioastronomy is repaying, in a practical way, some of the investment of specialized radio techniques that helped to bring it into being. It supplied a major stimulus to the development of maser and parametric amplifier techniques, and hence to an increase, by orders of magnitude, in the sensitivity attainable in radio receivers. It has also made, and is continuing to make, significant contributions to the design of large steerable antennas and feed systems. The techniques of very long base-line interferometry (VLBI) are becoming of increasing importance for geodetic measurements of global distances. Radioastronomy methods are now being employed for radionavigation and are finding applications in the medical field.

The cosmic emissions with which the radioastronomy service is concerned are characterized by low power flux levels at the Earth. Most emissions show no modulation, other than random noise; an exception is the pulsars, which emit pulses of radio energy at extremely regular repetition rates. For many sources, the best times for observation are dictated by natural phenomena over which the observer has no control, and so radio astronomers are not generally able to observe over any chosen limited time interval at their own convenience. Furthermore, the radio astronomer is unable to change the character of the "signal" he wishes to receive; he cannot increase the transmitter power nor code the transmitted signal to increase its detectability. Recent discoveries of discrete line emission from molecules at frequencies other than those currently allocated to radioastronomy cause radio astronomers to be faced with interference situations over which they have no control.

Studying radiation, the radio astronomer observes and measures all the properties of the electromagnetic emission. These are:

- intensity,
- frequency,
- polarization,
- the position in the sky, and
- the variation of these parameters with time.

The results are combined in order to gain an understanding of the physical processes in the Universe.

2. Origin and nature of the emissions

2.1 The radio waves with which the radioastronomy service is concerned are generated in extra-terrestrial sources by three distinct mechanisms:

- thermal emission from hot ionized gas, solid bodies, and the universal microwave background;
- non-thermal processes, mainly synchrotron emission from relativistic electrons spiralling in a magnetic field, but including also emission from plasmas (as in the solar atmosphere); and the pulses emitted by pulsars;
- "line" emission resulting from transitions within individual atoms and molecules.

These combine to produce:

2.1.1 *A continuum of radiation*, which extends relatively smoothly over the whole frequency range accessible to observation.

The continuum is composed of a background together with numerous small "bright" regions, the discrete radio sources (see Report 720). The background shows a general distribution over the whole sky with a broad maximum in the direction of the galactic centre, together with a ridge of intense emission around the galactic equator (the Milky Way), showing a marked maximum in the direction of the centre.

The discrete sources, often referred to as radio stars, are, with a few exceptions, (notably the Sun, and special types of nearby stars), not stars but radio "nebulae". They are of two kinds, those of extra-galactic origin and those originating within our galaxy. The extra-galactic sources are, in general, distributed randomly over the sky while the galactic sources are for the most part confined to within a few degrees of the galactic equator.

2.1.2 *"Line" emission* which, though occurring at the source at one or more precise frequencies determined by the transitions involved, is observable over a band of frequencies, the result of Doppler shifts due to relative motions in the line-of-sight. Spectral lines are also observable in absorption when a strong source of continuum emission is viewed through an intervening gaseous medium.

2.1.3 *Intermittent emission* ("bursts") of durations which may vary from seconds to hours. They are most intense in the HF and VHF bands, and those from disturbances in the solar atmosphere may vary progressively in frequency, from high to low, during their lifetime. Those so far detected originate in localized areas on the Sun, some types of stars, the planet Jupiter and (at a lower level) X-ray sources.

2.1.4 *Pulsating emission* (from pulsars) was discovered in 1967 [Hewish *et al.*, 1968] and is believed to be radiation from stars composed only of neutrons and thus to be matter in its most highly condensed state. The neutron star rotates and the interaction of its magnetic field with the surrounding plasma generates the pulses of radio waves. The rate of emission of these pulses varies in different pulsars from about 30 per second to about one pulse every 4 seconds. Some pulsars are slowing down; cases have occurred where the pulse recurrence frequency has changed suddenly. A general description of pulsars has been published [Radhakrishnan, 1969]. Pulsars are not only important astrophysical objects but they often serve for the investigation of the interstellar and interplanetary media. Furthermore, observation of a pulsar member of a binary star system offers a possible new technique for investigating the general theory of relativity.

2.2 *Continuum radiation and discrete sources*

The discovery of the largest class of radio sources and the bulk of current knowledge about their nature and distribution, and the processes responsible for the radio emission from them, has come about through observations of the continuum radiation, made at a limited number of frequencies at the lower end of the band transmitted by the ionosphere. Observations of intensity need to be made at a number of frequencies to determine the characteristic "spectra" of sources, but, because the distribution of continuum radiation with frequency is relatively smooth, observations of this kind do not need to be made at specific or closely adjacent frequencies. For many types of observation, bands spaced at intervals of an octave are satisfactory. However, there are some unusual sources, for example those showing self-absorption, newly-created sources such as novae and pulsars for which observations at intervals of less than half an octave are desirable. In addition the study of polarization often requires observations at closely spaced frequencies.

The detailed structure of many radio sources is an important feature which can lead to a better understanding of the ways in which radio energy is generated. To observe this structure, high angular resolutions are needed. Antenna systems (arrays) capable of producing details with a resolution of a few seconds of arc have very large dimensions (100 000 wavelengths or more). Much finer detail can be observed by using very long base line interferometers with antennas separated by thousands of kilometres or by observing when the Moon occults the source. World-wide protection of the continuum bands is needed to ensure that no transmitter in the protected bands will illuminate the Moon or be able to interfere via any antenna of an interferometer system which often extends over different countries or different continents.

The continuum radiation from most discrete sources and from parts of the background is partially plane polarized. A study of this polarization over a range of frequencies can be used to deduce the Faraday rotation, and hence the magnetic field conditions in the radiation source, the ionosphere and the interstellar regions of the Milky Way. For this work, observations at more closely spaced frequency intervals than the normally adequate octave separation are desirable at frequencies below about 2 GHz.

The bands made available to the radioastronomy service, in accordance with the Final Acts of the World Administrative Radio Conference, Geneva, 1979, represent a significant improvement over previous international allocations made to the service, and are a partial fulfilment of the requirements of the service. However, many of the allocated bands have insufficient bandwidths; they are in most cases shared with other services; many apply to limited areas of the world; and there are large intervals between some of the allocated bands. Table I indicates the allocated bands considered important for continuum measurements.

2.3 *Line radiation*

Using interstellar radio spectroscopy, a number of phenomena are observed which convey information on the evolution, composition and kinematics of gaseous clouds in interstellar space.

There are many discrete spectral lines called "recombination lines" that arise when atoms of hydrogen, helium, carbon, etc. gain or lose energy as their electrons jump from one orbit to another under different conditions of atomic excitation. The first of these lines was discovered in space in 1964 by radio astronomers in the USSR [Sorotchenko *et al.*, 1964]. These lines are numerous and spread throughout the radio spectrum [Lilley and Palmer, 1968]. Through careful observation of the strengths and shapes of these lines, radio astronomers are able to determine the physical conditions such as temperature, density and the extent of ordered or random motions of any celestial object in which recombination lines are found.

TABLE I – *Frequency bands allocated to the radioastronomy service that are preferred for continuum observations*

(Secondary allocations are contained within brackets)

Frequency band (MHz)		Bandwidth (%)		Frequency band (GHz)	Bandwidth (%)
13.360-13.410		0.37		10.6-10.7	0.94
25.550-25.670		0.49		15.35-15.4	0.33
	(37.5-38.25)		(1.98)	22.21-22.50	1.30
73-74.6 (1)		2.17		23.6-24.0	1.68
150.05-153 (2)		1.95		31.3-31.8	1.58
322-328.6		2.03		42.5-43.5	2.33
406.1-410		0.96		86-92	6.74
608.614 (3)		0.98		105-116	9.95
1400-1427		1.91		164-168	2.41
2690-2700	(2655-2690)	0.37	(1.31)	217-231	6.25
4990-5000	(4800-4990)	0.20	(3.88)	265-275	3.70

(1) Allocation (primary) in Region 2, protection recommended in Regions 1 and 3.

(2) Allocation (primary) in Region 1, Australia and India.

(3) Allocation (primary) in Region 2, China and India.

There have also been discoveries of emission or absorption lines arising in interstellar space due to neutral atomic hydrogen and many inorganic and organic molecules. Following the first observation of the hyperfine spin-flip transition of hydrogen in 1951 [Ewen and Purcell, 1951], it was not until 1963 that the first molecular line (OH) was detected in the radio spectrum [Weinreb *et al.*, 1963], and not until 1968 that other molecules were observed. Since then, lines from more complex molecules and their isotopes have been discovered at a remarkable rate, e.g., water, ammonia, carbon monoxide, cyanogen, hydrogen cynanide, formaldehyde, formic acid, methyl alcohol and cyano-acetylene are all now known to exist in interstellar space. More than five hundred and fifty radio spectral lines from forty-six different molecules have been detected in the frequency range 0.8 to 350 GHz from interstellar space, and a list which is current to 1978 is given by Lovas *et al.* [1979]. It is realized that all of these lines cannot be afforded protection in the Radio Regulations by frequency allocation, but protection should be sought for those lines, which are considered astrophysically most important (see § 4.3).

Annex I describes some of the types of spectral line observations that are being conducted at observatories throughout the world. The description concentrates on lines of atomic hydrogen, hydroxyl, formaldehyde, and carbon monoxide because these are common to a wide range of astrophysical problems. The Annex is intended to show the kinds of spectral line observations that are made, and the variety of results obtained, and to demonstrate how interstellar radio spectroscopy contributes to an understanding of the nature of the Universe.

Integration times of many hours are commonly required in order to obtain the signal-to-noise ratios necessary to draw conclusions of astrophysical interest from the observations. Hence, freedom from harmful interference is necessary over bandwidths which include broadening and shifting of the emission due to Doppler effects together with comparison or reference bands bordering the line emission.

2.4 *Bursts, pulsars and variable sources*

The Sun is an outstanding source of short-period bursts of radio energy of many types which give important knowledge of processes of solar and plasma physics [Wild *et al.*, 1963]. Some stars seem, like the Sun, to show large increases in their output in the form of flares of optical and radio waves together, and these short duration flares can be detected by radio astronomers. Jupiter is a source of large bursts of radio energy, observed sporadically at frequencies below about 30 MHz [Roberts, 1963].

Pulsars are sources which emit pulses of remarkably regular periodicities, in the approximate range from 30 pulses per second to one pulse every four seconds. The emissions can be observed in the frequency range between 30 MHz and 15 GHz, and observation at several frequencies in this range are needed. Only for strong pulsars is the detection of single pulses possible. For weak sources pulse-averaging techniques with integration times of up to some hours are used to detect the mean pulse profile. Pulse arrival time measurements, extending over some years give not only information about proper motions of the pulsars and their positions, with an accuracy of 0.01 arc second, but also about the long-term stability of the pulsar period.

Some radio sources, particularly the quasars, show variability of their radio emission over a time scale of a few weeks, and novae and X-ray sources have been found to emit a changing level of their radio noise as their optical brightness changes.

2.5 *Observations below 30 MHz*

Several phenomena of astrophysical interest manifest themselves only at observations at wavelengths of the order of 10 m or longer. "Free-free" absorption in ionized regions of the galaxy, self-absorption in radio galaxies and in quasars, and low-frequency emission from tenuous plasmas in clusters of galaxies are a few which require extensive investigation.

2.6 *Summary*

This outline of the nature of radio signals in radioastronomy shows two general facts. First, there is a wide variety of phenomena to be studied over the whole accessible range of radio frequencies. Second, the science is still growing at a rapid rate and enormously increasing our knowledge. These two facts demonstrate clearly the difficulties which face both the astronomer and the frequency allocation authorities in their search for the best solution to the problem of achieving the right degree of protection for a radioastronomy service.

3. Details of radioastronomy observatories

Appendix 3 (Section F) of the Radio Regulations describes the information on observatories and on the observations in progress or planned, which administrations should furnish to the IFRB for incorporation in the Master International Frequency Register. This information is published by the ITU from time to time, in the form outlined in the revision of Appendix 9 of the Radio Regulations (List VIII A). Collected information and the activities of radioastronomy and radar observatories can be obtained upon application to the Committee on Radio Frequencies, National Academy of Sciences, 2101 Constitution Avenue, NW, Washington DC, USA. This publication is intended to list radioastronomy stations of all countries and is revised from time to time to include information that has been provided by national radioastronomy organizations or observatories.

B. PREFERRED FREQUENCY BANDS

4. Frequency considerations of the radioastronomy service

4.1 *General considerations*

The choice of wavelength for astronomical observations naturally depends on the phenomena to be observed, but it may also be strongly influenced by the Earth's atmosphere (troposphere and ionosphere). The ionosphere strongly affects astronomical observations below 20 MHz; measurements suggest that the lowest practical frequency for ground-based observation is 1.5 MHz (see Report 699). The troposphere affects observations by absorption, primarily by oxygen and water vapour. The attenuation due to resonances of these molecules is shown schematically in Fig. 1, based on Report 719 (Geneva, 1982). The effects of other atmospheric constituents, for example, CO, NO, NO_2, etc., are negligible.

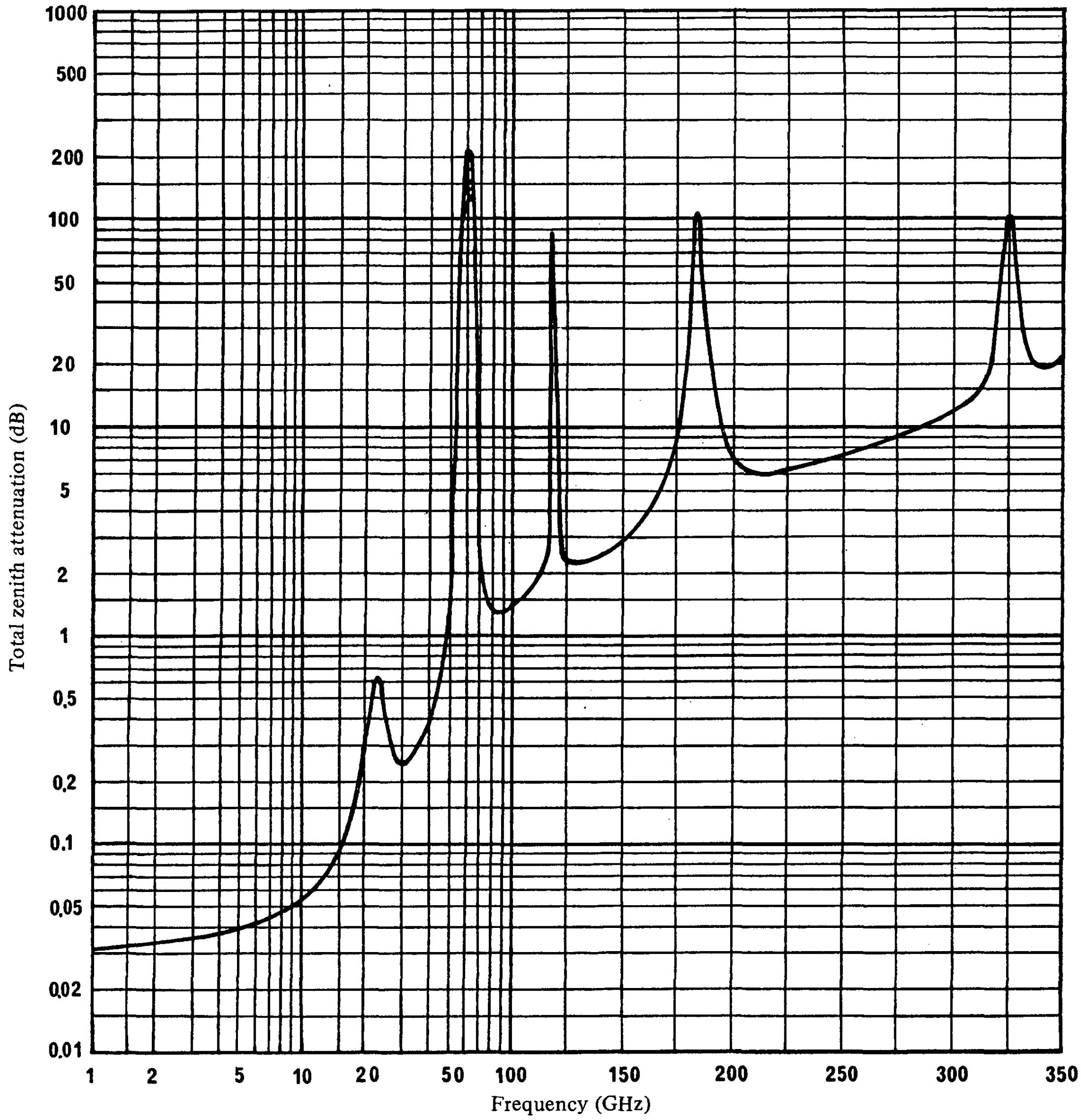
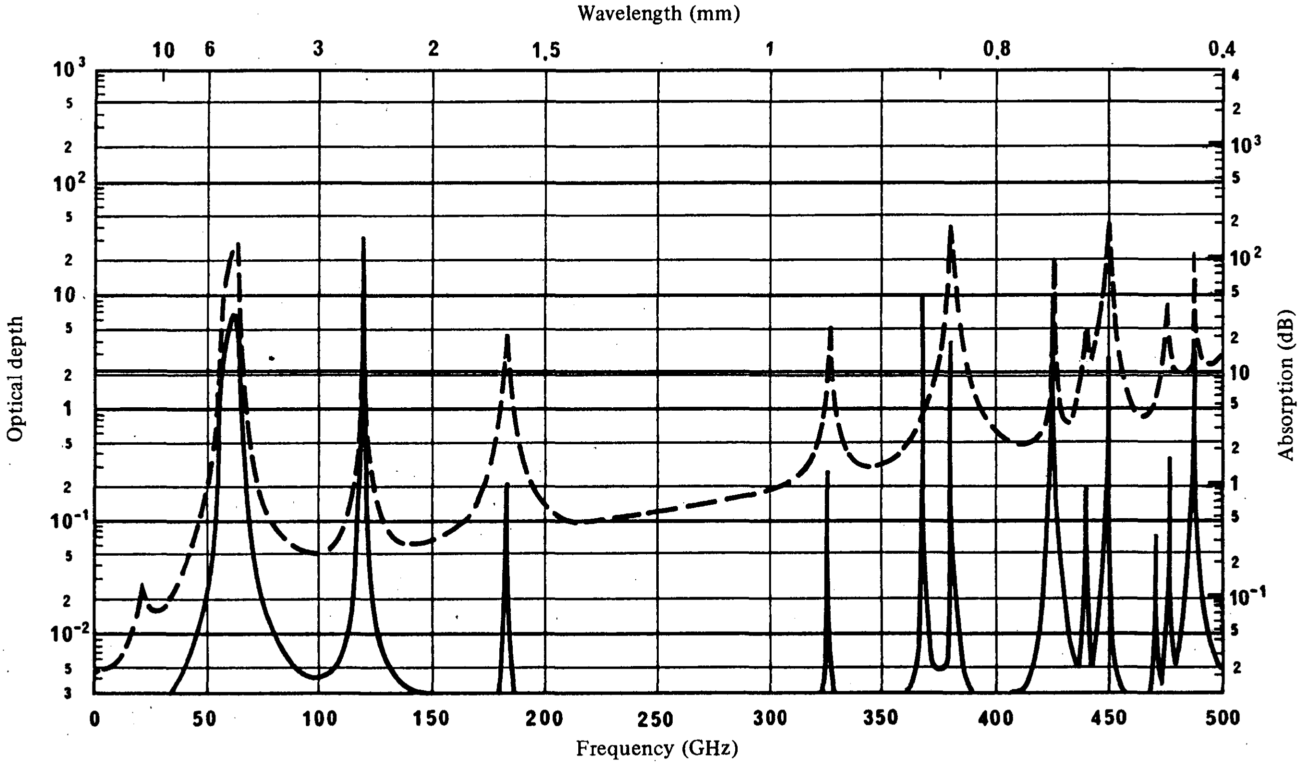


FIGURE 1 – *Total zenith attenuation*

Pressure:	1 atm	at ground level
Temperature:	20 °C	
Water vapour concentration:	7.5 g/m^3	

The curve in Fig. 1 shows the total one-way absorption in the vertical direction for an atmosphere with water vapour concentration of 7.5 g/m^3 at the Earth's surface. This curve is based partly on theoretical calculations and partly on measurements. The model atmosphere adopted is one in which the water vapour concentration decreases exponentially with increasing height, the scale height being 2 km. Thus, the effects of absorption can be reduced by choosing observing sites at high altitudes. Figure 2 shows the total zenith attenuation for a high altitude site (Mauna Kea, Hawaii) with water vapour concentration 0.75 g/m^3 and from an aircraft at an elevation of 12 500 m (water vapour concentration 0.003 g/m^3) [JPL, 1978].

Radioastronomers are pioneers in the use of frequencies above 100 GHz. Observations have been made above 300 GHz but the preferred frequencies have not yet been fully identified.



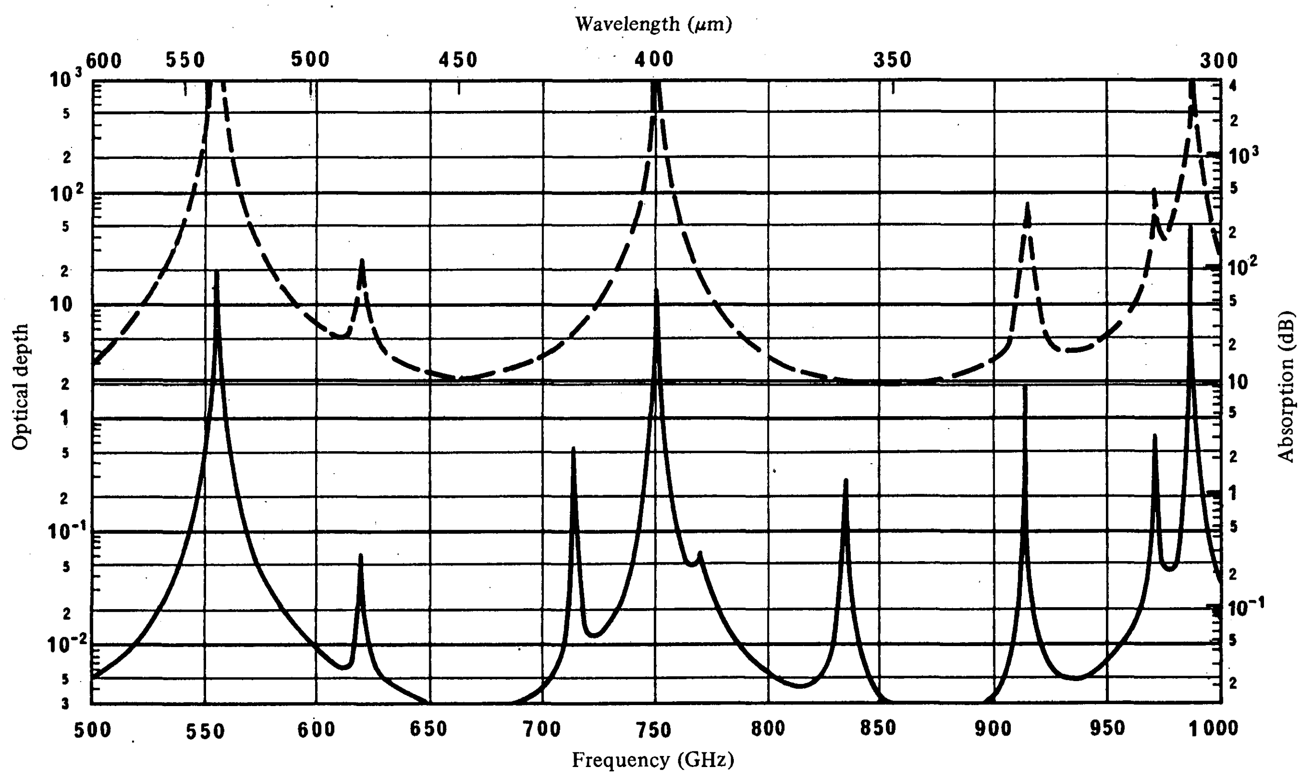


FIGURE 2 – *Vertical atmospheric attenuation for precipitable water vapour of 1.5 mm (dashed curve – Mauna Kea, Hawaii) and 6 μm (solid curve – C141 aircraft)*

4.2 *Continuum observations*

One purpose of continuum observations in radioastronomy is to define the frequency variation of the radiation in sufficient detail to draw conclusions concerning the physical mechanisms responsible. The experience has been that observations in each octave of the spectrum are, in general, adequate for this purpose although closer spacings may be needed for some specialized types of observation (see § 2.2). The set of observations spaced in frequency by factors of approximately 2 should extend from the lowest frequency to the highest frequency at which ground-based observations are possible; that is, from about 1.5 MHz (see Report 699) to beyond the 275 GHz limit of the frequency allocations in the Radio Regulations. At frequencies above 20 GHz the need to avoid the maxima in atmospheric absorption due to O_2 and H_2O must take precendence over the desire to maintain the octave spacing. Thus, frequencies for continuum observations must be chosen to lie within the atmospheric absorption minima near 30 GHz, 90 GHz, 150 GHz, 240 GHz, 340 GHz, 410 GHz, 470 GHz, 670 GHz and 850 GHz.

In Report 224, equation (3), it is shown that for continuum observations, the minimum detectable signal is inversely proportional to the square root of the bandwidth. Therefore, in the absence of interference, radioastronomers can profit from the widest bandwidth that can be used without degradation of receiver noise temperature. In fact radioastronomers have found 1% to 2% bandwidths to be practical and realistic. For paraboloidal telescopes, wider bandwidths and consequent better sensitivities lead to improved efficiency in the use of these major astronomical instruments. The same is true of telescopes with unfilled apertures (such as the T or cross antennas). However in this case bandwidth can have a direct effect on the cost of the telescope. If the required sensitivity is not achieved because of an insufficiently wide bandwidth then it may be necessary to fill in more of the aperture at a very large cost.

Table I gives a list of bands allocated to the radioastronomy service that are preferred for continuum observations. The nature of the protection accorded radioastronomy is not the same in each of these bands and in some cases would be considered inadequate to permit full use of the band by radioastronomers. The sharing problems are considered in Report 696. However, the array of bands listed if they had adequate protection would satisfy most of radioastronomy requirements for frequency coverage. The exceptions are that the allocations at 13 MHz and 25 MHz do not meet the bandwidth criterion and the interval between 74 MHz and 322 MHz, while adequately covered in Region 1 with the band at 150 MHz, has no recognized frequency bands in Regions 2 and 3. In addition the bandwidths of the primary allocations at 2695 MHz and 4995 MHz are much too narrow. Also there is no band listed below 13 MHz. Report 699 specifies 1.5 MHz as the low frequency limit for ground-based radioastronomy. Thus there are 2 octaves below 13 MHz in which ground-based radioastronomy observations are possible but in which radioastronomy has not been recognized in the Radio Regulations.

4.3 *Spectral line observations*

Spectral line observations must be made at the specific frequency or frequencies set by nature for the spectral emission of the atoms or molecules of interest. Those lines which are considered of greatest astrophysical importance are listed in Tables I and II and also in Recommendation 314. These most important lines were selected by members of the International Astronomical Union [IAU, 1982] from among the hundreds of lines from interstellar space which have been observed. Table III, which lists lines above 275 GHz, will undoubtedly need modification as astronomers explore this newly-opened region of the radio spectrum. The bandwidths required for observations of the lines in both tables are determined by Doppler frequency shifts in the rest frequencies of the lines caused by the velocity of the emitting region relative to that of the observer on Earth. The velocity range is ± 300 km/s for sources within our own galaxy which can be accommodated by ± 0.1% of the rest frequency. For extra-galactic sources, velocities of + 1000 km/s and − 300 km/s require bandwidths of − 0.33% to + 0.1%.

An examination of the Frequency Allocation Table of the Radio Regulations reveals that most bands listed in Table I of Recommendation 314 have been recognized in the Radio Regulations as being of astronomical interest. In many cases, the recognized bandwidths are at least the equal of those specified in the table although little or no protection may be accorded by the recognition. For the hydroxyl lines at 1612 MHz and 1720 MHz, the three CH lines near 3300 MHz, the formaldehyde line at 4830 MHz, and the water vapour line at 22.235 GHz, the recognized bandwidths are adequate for observations within our own galaxy but do not show the downward extension of the lower frequency limit as required for observations of distant galaxies as shown in Table II.

TABLE II – *Radio-frequency lines of the greatest importance to radioastronomy at frequencies below 275 GHz*

Substance	Rest frequency	Suggested minimum band	Notes (1)
Deuterium (DI)	327.384 MHz	327.0- 327.7 MHz	
Hydrogen (HI)	1420.406 MHz	1370.0- 1427.0 MHz	(2) (3)
Hydroxyl radical (OH)	1612.231 MHz	1606.8- 1613.8 MHz	(3) (4)
Hydroxyl radical (OH)	1665.402 MHz	1659.8- 1667.1 MHz	(4)
Hydroxyl radical (OH)	1667.359 MHz	1661.8- 1669.0 MHz	(4)
Hydroxyl radical (OH)	1720.530 MHz	1714.8- 1722.2 MHz	(3) (4)
Methyladyne (CH)	3263.794 MHz	3252.9- 3267.1 MHz	(3) (4)
Methyladyne (CH)	3335.481 MHz	3324.4- 3338.8 MHz	(3) (4)
Methyladyne (CH)	3349.193 MHz	3338.0- 3352.5 MHz	(3) (4)
Formaldehyde (H_2CO)	4829.660 MHz	4813.6- 4834.5 MHz	(3) (4)
Formaldehyde (H_2CO)	14.488 GHz	14.439- 14.503 GHz	(3) (4)
Water vapour (H_2O)	22.235 GHz	22.16 - 22.26 GHz	(3) (4)
Ammonia (NH_3)	23.694 GHz	23.61 - 23.71 GHz	(4)
Ammonia (NH_3)	23.723 GHz	23.64 - 23.74 GHz	(4)
Ammonia (NH_3)	23.870 GHz	23.79 - 23.89 GHz	(4)
Silicon monoxide (SiO)	42.821 GHz	42.77 - 42.86 GHz	
Silicon monoxide (SiO)	43.122 GHz	43.07 - 43.17 GHz	
Carbon monosulphide (CS)	48.991 GHz	48.94 - 49.04 GHz	
Deuterated formylium (DCO^+)	72.039 GHz	71.96 - 72.11 GHz	(3)
Silicon monoxide (SiO)	86.243 GHz	86.16 - 86.33 GHz	
Formylium ($H^{13}CO^+$)	86.754 GHz	86.66 - 86.84 GHz	
Ethynyl radical (C_2H)	87.3 GHz	87.19 - 87.54 GHz	(5)
Hydrogen cyanide (HCN)	88.632 GHz	88.34 - 88.72 GHz	(4)
Formylium (HCO^+)	89.189 GHz	88.89 - 89.28 GHz	(4)
Hydrogen isocyanide (HNC)	90.664 GHz	90.57 - 90.76 GHz	
Diazenylium (N_2H^+)	93.17 GHz	93.07 - 93.27 GHz	
Carbon monosulphide (CS)	97.981 GHz	97.88 - 98.08 GHz	
Carbon monoxide ($C^{18}O$)	109.782 GHz	109.67 -109.89 GHz	
Carbon monoxide (^{13}CO)	110.201 GHz	110.09 -110.31 GHz	
Carbon monoxide (CO)	115.271 GHz	114.88 -115.39 GHz	(4)
Formaldehyde (H_2CO)	140.840 GHz	140.69 -140.98 GHz	
Carbon monosulphide (CS)	146.969 GHz	146.82 -147.12 GHz	
Formaldehyde (H_2CO)	150.498 GHz	150.34 -150.65 GHz	(3)
Water vapour (H_2O)	183.310 GHz	183.12 -183.50 GHz	
Carbon monosulphide (CS)	195.962 GHz	195.76 -196.16 GHz	(6)
Carbon monoxide ($C^{18}O$)	219.560 GHz	219.34 -219.78 GHz	
Carbon monoxide (^{13}CO)	220.399 GHz	220.17 -220.62 GHz	
Carbon monoxide (CO)	230.538 GHz	229.77 -230.77 GHz	(4)
Carbon monosulphide (CS)	244.953 GHz	244.71 -245.20 GHz	(6)
Hydrogen cyanide (HCN)	265.886 GHz	265.62 -266.15 GHz	
Formylium (HCO^+)	267.557 GHz	267.29 -267.83 GHz	
Hydrogen isocyanide (HNC)	271.981 GHz	271.71 -272.25 GHz	

(1) If Notes (4) or Note (2) are not listed, the band limits are the Doppler-shifted frequencies corresponding to radial velocities of ± 300 km/s (consistent with line radiation occurring in our galaxy).

(2) An extension to lower frequency of the allocation of 1400-1427 MHz is required to allow for the higher Doppler shifts for HI observed in distant galaxies.

(3) The current international allocation is not primary and/or does not meet bandwidth requirements. See the Radio Regulations for more detailed information.

(4) Because these line frequencies are also being used for observing other galaxies, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1000 km/s.

(5) There are six closely spaced lines associated with this molecule at this frequency. The listed band is wide enough to permit observations of all six lines.

(6) This line frequency is not mentioned in the Radio Regulations as being of astronomical interest.

TABLE III – *Radio-frequency lines of the greatest importance to radioastronomy at frequencies between 275 and 700 GHz (not allocated in the Radio Regulations)*

Substance	Rest frequency (GHz)	Suggested minimum band (GHz)
Diazenylium (N_2H^+)	279.511	279.23-279.79
Carbon monoxide ($C^{18}O$)	329.330	329.00-329.66
Carbon monoxide (^{13}CO)	330.587	330.25-330.92
Carbon monoxide (CO)	345.796	345.45-346.14
Hydrogen cyanide (HCN)	354.484	354.13-354.84
Formyl ion (HCO^+)	356.734	356.37-357.09
Diazenylium (N_2H^+)	372.672	372.30-373.05
Water vapour (H_2O)	380.197	379.81-380.58
Carbon monoxide ($C^{18}O$)	439.088	438.64-439.53
Carbon monoxide (^{13}CO)	440.765	440.32-441.21
Carbon monoxide (CO)	461.041	460.57-461.51
Carbon (CI)	492.162	491.66-492.66
Water vapour (H_2O)	556.936	556.37-557.50
Ammonia (NH_3)	572.498	571.92-573.07
Carbon monoxide (CO)	691.473	690.78-692.17

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ANNEX I

INTERSTELLAR RADIO SPECTROSCOPY

1. Introduction

Direct knowledge of the chemical composition and physical properties of the gas in interstellar clouds comes mainly from radio-frequency observations of atomic and molecular spectral lines. Many atoms and molecules of interstellar significance have transitions at radio frequencies. This Annex describes the characteristics of four species, neutral atomic hydrogen (HI), hydroxyl (OH), formaldehyde (H_2CO) and carbon monoxide (CO), which are widespread throughout our galaxy. Inclusion here does not signify that these are the most important atoms and molecules in radioastronomy, but rather the discussion is intended to convey a sense of the types of information which are available through the observations, and the uses of interstellar spectroscopy in general.

Interstellar clouds contain a substantial fraction of the total mass of the galaxy. Clouds appear in regions where there are no stars at all, where stars are forming, and associated with stars in various stages of their evolution. Studies of the transitions of interstellar atoms and molecules yield information on the densities, temperatures, motions, and radiation fields within these clouds. In the aggregate, interstellar radio spectroscopy provides a view of the structure of our galaxy and the inter-relationships of its various constituents. Given sufficient sensitivity and angular resolution, these same properties can be investigated in other galaxies.

1.1 *Interstellar clouds*

The neutral interstellar medium can be divided into four categories:

1.1.1 *Diffuse interstellar clouds*

These clouds have densities which range from about 20 to 1000 gas atoms per cm^3. Clouds at the low end of this density range would essentially have zero molecular content, and observations of the 21 cm line of neutral atomic hydrogen (HI) would be used to probe these clouds. At the high end of the density range, much of the hydrogen would be in its molecular form (H_2), and molecules, such as OH, H_2CO, and CO, with transitions at lower excitation energies would be observed.

1.1.2 *Isolated dark clouds*

The density ranges between 500 and 10 000 atoms per cm^3. This category includes objects known as dark globules. Isolated dark clouds contain a wide variety of molecules including OH, H_2CO, and CO which are shielded from dissociating radiation. There are no stars embedded in these clouds.

1.1.3 *Dark clouds with associated stellar-type sources*

These are similar to the previous class with the addition that stars have formed or are still forming in the clouds. Many species of molecules are found.

1.1.4 *Giant molecular clouds*

These are the most massive objects in the galaxy. They are associated particularly with formation of massive early type stars. They also contain very high density gas concentrations, i.e. 10^6 to 10^8 atoms per cm^3, which may be the sites of future star formation. They contain the richest and most varied collection of molecular species.

1.2 *Interpretation of observations*

In general, the interstellar clouds which have been categorized above contain many of the same atoms and molecules. However, each cloud has individual properties which make it unique. Different types of observation of a cloud provide a view of different aspects of that cloud as well as different views of the same aspect. This procedure is essential to the derivation of reliable quantitative conclusions.

Although the astrophysical interpretation may differ, there are certain properties of the observations which are common to any interstellar spectroscopy. An observed spectral line profile of an atomic or molecular species is an intensity as a function of frequency. The observed frequency of the line emission (or absorption) may be shifted by the Doppler effect from the natural rest frequency of the transition because of motions of the source relative to the observer, in the line-of-sight. These relative motions will also broaden the observed line. Such frequency shifts are usually converted to radial velocity units. The intensity at a specific frequency is a measure of the number of atoms (or molecules) along the line-of-sight at a specific velocity. The shape of the line is governed by the kinematics of the material along the line-of-sight. With the velocity information, interstellar spectroscopy adds effectively a third dimension to the planar projection of the spatial distribution of a cosmic source.

2. Neutral atomic hydrogen (HI)

2.1 *General*

Emission from the neutral atomic hydrogen transition at 1420.4 MHz, commonly referred to as the 21 cm HI line, was first detected in interstellar space in 1951 [Ewen and Purcell, 1951]. In fact this was the first interstellar spectral line to be detected at radio frequencies. In 1954 this line was detected in absorption against a background continuum radiation source [Hagen and McClain, 1954].

The 21 cm HI line is due to a hyperfine transition of the hydrogen atom in its ground state. The transition occurs when the electron reverses its spin relative to that of the proton; the higher energy state is the one in which the two spins are parallel, the lower energy state when the two spins are anti-parallel. The laboratory rest frequency of this transition has been measured to be 1420.405 751 786 MHz [Allen, 1973].

Hydrogen is the most abundant element in the Universe. Approximately 5% of the mass of our galaxy is in the form of neutral atomic hydrogen. The 21 cm line offers the only means of studying this important constituent of the interstellar medium. HI is so abundant and is distributed so generally throughout the galaxy that the 21 cm line has been detected in emission at every position in the sky. In fact, HI is the principal constituent of the interstellar clouds with densities less than 1000 atoms/cm^3; hyrogen goes into its molecular form (H_2) at higher densities.

Neutral atomic hydrogen observations are used for a wide range of astrophysical problems. These include large scale surveying with the intent of providing an HI "map" of the galaxy and small scale investigations of specific regions of the sky with the intent of studying the physical parameters and kinematics of these regions.

Emission and absorption line observations reveal very different aspects of the HI gas. All of the emission encompassed by the beam of the telescope contributes to the observed spectrum, whereas only the gas directly in front of a background continuum source, whose angular size may be much different from the telescope beamwidth, contributes to the absorption spectrum. Line profiles are often a complex superposition of emission and absorption spectra, and special techniques have been developed to separate the components. The emission is a tremendously useful probe of the large scale structure of the galaxy, but a combination of emission-absorption observations must be used to extract quantitative information on the physical state of the gas.

There is a class of HI sources in our galaxy called High Velocity Clouds. These are objects which have unusually large radial velocities compared to the velocities of those clouds which are inherently part of the galactic dynamical motions.

If a cloud of neutral hydrogen is permeated by a magnetic field, the 21 cm emission line should be split in frequency into two oppositely circularly polarized components (the Zeeman effect). The amount of the splitting depends on the strength of the line-of-sight component of the magnetic field. The splitting is 2.8 Hz per μgauss. Using special differential observing techniques, it is possible to measure interstellar magnetic fields of approximately 10 μgauss, and fields of the order of 10 to 50 μgauss have been observed.

Since hydrogen is such an abundant constituent of the interstellar medium, it is readily observed in other galaxies. External galaxies exhibit the well-known cosmic "red shift", a decrease of the observed from the rest frequency dependent on the distance of the galaxy (Hubble's law). It is quite common to observe the HI line from other galaxies shifted into the frequency range 1300-1420 MHz. In one case an HI absorption line has been detected at $\approx$ 500 MHz toward a quasar. Extra-galactic observations of the HI line provide information on the total hydrogen content of other galaxies, and that varies with galaxy type. Typically certain spiral galaxies contain approximately 1% HI while some types of irregular galaxies consist of over 30% HI.

Deuterium (D), the well-known isotope of atomic hydrogen, has a transition which is the equivalent of the 21 cm line but which occurs at 327.384 MHz. This line has been sought with marginal success. It is clear that any D lines are extremely weak, and integration times of several hundred hours at one position are required for successful experiments. The direct detection of a D transition is very important for the determination of the abundance of deuterium which in turn has direct implications for cosmological theories. Deuterium has been observed at optical frequencies, and it has been detected as a component of several molecules where D is substituted for an H atom. However, in this case deuterium abundances are difficult to determine because of complex corrections related to the molecular formation processes.

2.2 *Techniques*

Since HI emission is so widespread, it can be observed with very modest-sized radio telescopes and less than state-of-the-art receivers. There are facilities equipped to observe these lines in many countries.

Single dish telescopes are used to map the general distribution of the HI gas and to get a general picture of the HI content of other galaxies. Interferometers are used to separate absorption in front of small continuum sources from the extended emission, and to observe the detailed HI structure in other galaxies. Very long baseline interferometer (VLBI) telescopes have been used for special investigations requiring extremely good angular resolution.

Receivers on telescopes are often readily tunable over the range 1330-1430 MHz to observe Doppler-shifted HI. The natural width of the HI line is 4.75×10^{-16} kHz. However, observed profiles typically extend over about 500 kHz due to broadening by thermal motions of the HI atoms, turbulent motions within the HI gas, and large-scale motions in the galaxy.

The great interest in extra-galactic HI has injected renewed enthusiasm for these observations of HI, which then require the exploitation of all the instrumental sensitivity available.

3. Hydroxyl (OH)

3.1 *General*

The hydroxyl radical (OH) was first detected at radio frequencies in interstellar space in 1963 [Weinreb *et al.*, 1963]. OH lines are usually seen in emission but may appear in absorption against background continuum sources. In certain types of sources the emission lines are due to maser action. Lines from excited energy states of the OH molecule have been discovered, as well as from isotopic variations of the common state of ^{16}OH.

The $^2\pi_{3/2}$, J = 3/2 ground state of OH is split by lambda doubling – an interaction between the rotation of the nuclei and the motion of the unpaired electron in its orbit. Two different states of electron motion are possible: an electron distribution either along the axis of rotation or in the plane of rotation. Hyperfine interaction with the unpaired spin of the proton further splits the energy levels. This produces four energy levels which have interconnecting transitions with laboratory rest frequencies of 1612.231, 1665.402, 1667.359, and 1720.530 MHz [Meulen and Dymanus, 1972]. The two centre transitions in this set are sometimes referred to as main lines and the two outer frequency transitions as satellite lines. This is simply spectroscopic terminology and has no relation to the importance of the lines to the astronomer. These four lines are also referred to as the 18 cm lines of OH.

If the ground state OH energy levels were populated according to thermodynamic equilibrium, the 1612, 1665, 1667, and 1720 MHz lines would have the intensity ratios 1 : 5 : 9 : 1 respectively. Many of the OH sources are thermally excited, and these ratios apply. However, there are also important cases where the molecule is excited by external means (e.g. by collisions or by radiation) to significant over-abundances in certain energy levels. This leads to maser emission which is characterized by very intense, very narrow lines.

The "thermal" line emission from OH is very widespread over the plan of our galaxy, but the scale height above the galactic plane is about one fifth that of HI. The OH radical is susceptible to dissociation by ultraviolet radiation, and therefore must be in clouds of gas and dust sufficiently dense to provide adequate shielding. On the other hand OH seems to be associated with the less dense portions of molecular clouds which contain many other molecular species. Since hydrogen is the predominant constituent, the hydrogen density is taken as equivalent to the gas density. An "average" hydrogen density for the OH sources is approximately 1000 H atoms per cm^3. OH lines are seen in absorption when the molecular cloud lies in front of a background continuum source in the line-of-sight to the observer.

Maser emission occurs in any of the four 18 cm OH lines and is closely associated with specific types of cosmic object at both ends of the stellar evolution scale (proto-stellar objects on one end and highly evolved stars on the other end). The sources are point like.

Observations of OH can be used to delineate neutral clouds of gas which are either obscured optically or the hydrogen is in its molecular instead of atomic form. OH sources are often also HI sources and/or H_2CO sources and observations of lines from all three provide independent data on a given area of interstellar space. This is very useful because of the complexities of interpreting the data from only one atomic or molecular species.

The ground state transitions of the ^{17}OH and ^{18}OH isotopes of OH have been observed in our galaxy. The freuqencies of these lines are of course shifted from those of the ^{16}OH molecule because of the mass dependent effects on the energy levels.

Excited state transitions of OH have been detected at 4775 MHz (3 lines), 6030 MHz (3 lines), 8136 MHz (1 line), 13.44 GHz (1 line), and 23 GHz (1 line). The isotope and excited state lines are used to probe the details of molecular clouds. However they are weak and require the most sensitive equipment. Hence they are not among the list of most important radio-frequency spectral lines.

The 1665 and 1667 MHz lines of OH have been detected in nearby galaxies [Whiteoak and Gardner, 1973]. However, because they are so weak, these lines have not been exploited for extensive probing of the composition of these other galaxies.

3.2 *Techniques*

The individual 18 cm OH lines can usually be accommodated in a band covering ± 300 km/s from the rest frequency of the line. However, all four lines are often observed in the same study so the receiver must be readily tunable from 1612 to 1720 MHz.

The 18 cm OH lines are observed with single antenna interferometer and VLBI radio telescopes. VLBI is particularly applicable for study of the maser emission sources because they are very intense and point like.

Maser lines often have a high percentage of polarization; either linear or circular. Receivers are specially configured to study these polarization properties.

Most of the interest in OH centres on the 18 cm lines. The excited state and isotope lines are studied only with the most sensitive telescopes.

4. Formaldehyde (H_2CO)

4.1 *General*

Formaldehyde was first discovered in interstellar space in 1969 [Snyder *et al.*, 1969] through its transition at 4.83 GHz. Subsequent surveys of this line have proven that H_2CO is a common constituent of most types of molecular clouds. Other lines of H_2CO have been detected with rest frequencies at 14.488; 28.97; 48.28; 72.41; 140.84; 145.60; 150.498; 211.211; 225.698; and 281.523 GHz. In several cases the equivalent transitions of the $H_2{}^{13}CO$ and $H_2C^{18}O$ isotopes have also been observed. The 4.83 GHz line has been detected, in absorption, from external galaxies [Gardner and Whiteoak, 1974].

The H_2CO lines that are observed result from rotational energy level transitions. The formaldehyde molecule may exist in two states (ortho and para) and electric dipole transitions between these states are forbidden. The lowest energy state of ortho-formaldehyde will normally have a large population, and this explains the observed widespread distribution of the 4.83 GHz line. Two of the lines observed are para-formaldehyde (72.84 and 145.60 GHz).

The energy states of H_2CO are actually split into hyperfine components: the 4.83 GHz line is composed of 6 hyperfine components covering a frequency range of about 30 kHz [Tucker *et al.*, 1971]. In many cases Doppler broadening due to motions in the molecular gas is much greater than the hyperfine splitting. All of the component lines are then blended together, and the observed profile may be treated as one line.

Observations of lines of formaldehyde provide an excellent probe of the overall distribution of molecular clouds in our galaxy, and are used to study the full range from diffuse interstellar clouds to giant molecular clouds. Studies using H_2CO have the advantage of better angular resolution (because of the higher frequency) over equivalent studies using OH or HI. With lines available over a wide range of radio frequencies, the H_2CO molecule also provides a good probe of the detailed characteristics of individual molecular clouds. The various H_2CO lines originate in different parts of molecular clouds because of the different requirements for excitation, giving a method of examining a wide range of physical conditions. Molecular hydrogen densities of at least $10^5/cm^3$ are required to produce the observed H_2CO emission at millimetre wavelengths. Thus these high frequency lines originate in the densest parts of molecular clouds.

The oddity about observations of H_2CO is that the 4.83 GHz line is almost always in absorption, even when there is no discrete background continuum source. Therefore the molecule must be absorbing the 2.8 K cosmic background radiation. This is possible only if some excitation mechanism exists to invert the energy level populations to over-populate the lower energy state of the transition relative to the upper state. In only two H_2CO sources, the densities are apparently sufficiently high to inhibit this process, and the 4.83 GHz line is seen in emission.

4.2 *Techniques*

The observing techniques and instruments for H_2CO are similar to those used for OH. A velocity spread of $\pm$ 300 km/s will cover most of the H_2CO sources in our galaxy, although this range should be extended somewhat on the low frequency side of the rest frequency to accommodate extra-galactic observations.

A complete study of the H_2CO molecule would require facilities for observations over a wide frequency range, at least from 4 GHz to 300 GHz, and several of the transitions in that range are considered to be of equal importance to astrophysics. In intercomparing data collected on different transitions, there is an advantage in the interpretation if facilities can be found which provide comparable telescope beam sizes at all studied frequencies. In practice this can rarely be achieved.

Single antenna radio telescopes are commonly used for all types of H_2CO observations. Interferometers are sometimes used at 4.83 GHz to study the detailed structure of individual molecular clouds. VLBI telescopes are not used for H_2CO because the sources in our galaxy are fully resolved with the high angular resolution. Instrument sensitivity seems to be the only limitation on full scale observations of H_2CO in other galaxies.

5. Carbon monoxide (CO)

5.1 *General*

Carbon monoxide was first detected in interstellar space in 1970 [Wilson *et al.*, 1970] at 115 GHz, and it was detected from other galaxies in 1975 [Rickard *et al.*, 1975; Solomon and de Zafra, 1975]. The CO molecule is easily formed in interstellar space, and once formed it is stable. CO is second to molecular hydrogen (H_2) in abundance. Millimetre wavelength observations of CO have become the dominant method for determining the physical properties of dense interstellar clouds, and are used extensively for explaining the structure and kinematics of the galactic disk.

CO is used as an indirect tracer of H_2 within molecular clouds and of molecular clouds throughout the galaxy. This is based on two premises:

– the CO to H_2 abundance ratio is assumed to be relatively constant, and
– the excitation resulting in the CO line emission is due to collisions between H_2 and CO.

These premises link the CO line intensity directly to the H_2 abundance. CO is used to probe denser cloud material ($n_H > 10^3/\text{cm}^3$) in a way analogous to HI probing of the lesser dense clouds.

Observations of the ^{13}CO and $C^{18}O$ and $C^{17}O$ isotopes, and the wide range of frequencies make CO an excellent probe of the detailed characteristics of molecular clouds. $^{12}C^{16}O$ emission often has a large opacity which means that ^{13}CO and $C^{18}O$ observations are often needed to obtain an accurate quantitative interpretation of the data.

The CO molecule has a simple rotational spectrum, and the lines of astrophysical interest are due to transitions between rotational energy levels. The $J = 1 - 0$ line occurs at approximately 115 GHz and $J = 2 - 1$, $J = 3 - 2$, etc., lines occur at integral multiples higher in frequency. CO lines have been detected which have rest frequencies at 115.271, 230.538, 345.795, and 691.473 GHz. The ^{13}CO and $C^{17}O$ and $C^{18}O$ isotope equivalents of several of these transitions have also been detected. The CO and isotope lines which occur between 105 and 115 GHz are the most extensively studied, primarily because of availability of equipment.

5.2 *Techniques*

Like HI, CO observations of a given transition must cover relatively wide frequency bands to accommodate observations of lines from other galaxies. The percentage bandwidth required for CO is not yet as great as that for HI but only because of instrumental sensitivity limitations. The CO lines of interest to radio astronomers fall within the frequency range 100 GHz to 1000 GHz.

Most CO observations are performed with single antenna telescopes. Very small antennas (approximately 1 m diameter) are used for large scale surveying to achieve an angular resolution comparable to that achieved for HI (10-60 arc min) for direct comparisons. Single antennas with diameters of 25 to 45 m and interferometers are being built to probe the details of individual clouds with resolutions of less than 1 arc min. VLBI has not yet evolved to frequencies above 50 GHz. As instrumental sensitivity increases, the extra-galactic work will increase, leading to wider band requirements.

Atmospheric attenuation is a problem for many CO observations, particulary above 300 GHz. To avoid this, telescopes are placed atop high mountains or flown in aeroplanes.

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REPORT 699-2*

IONOSPHERIC LIMITATIONS TO GROUND-BASED RADIOASTRONOMY BELOW 20 MHz

(Question 5/2)

(1978-1982-1986)

1. Introduction

Although some of the first discoveries of galactic radio emission were made at decametre wavelengths, there has been a general progression in radio astronomy to measurements at shorter wavelengths. The high resolution attainable with paraboloidal antennas at the shorter wavelengths, the development of low noise pre-amplifiers and the succession of important discoveries at the higher frequencies have contributed to this trend.

There are, however, many phenomena of astrophysical interest which manifest themselves only at the longer radio wavelengths. "Free-free" absorption in ionized regions of the galaxy, self-absorption in extra-galactic radio sources, low-frequency emission mechanisms from tenuous plasmas in clusters of galaxies are some phenomena which require extensive investigation. To date (1985), extensive astronomical measurements below 20 MHz have been limited to a few source surveys [Bridle and Purton, 1968; Braude *et al.*, 1969, 1978, 1979] with resolutions of one-half degree to a few degrees; measurements of galactic background emission [Ellis and Hamilton, 1966; Reber, 1968; Caswell, 1976; Cane, 1979] with resolutions of several degrees; and observations of the strong decametric bursts from Jupiter [Ellis, 1975]. The angular resolution of radio telescopes which have been used or are in use below 100 MHz, is summarized in Fig. 1.

The lack of high resolution instruments below 20 MHz is evident. There are three main technical reasons which account for this:

- antennas of several kilometres extent are required for resolution better than 1°. Dotted lines in Fig. 1 illustrate the resolution attainable with apertures of 3, 10, and 30 km width;
- conditions in the Earth's ionosphere vary with time of day, time of year, and solar activity. Observation is possible only when the electron density in the F-region is sufficiently low and relatively free of irregularities on the kilometre scale;
- there are no exclusive frequency allocations for radioastronomy below 20 MHz. World radio communications make extensive use of these frequencies for propagation via ionospheric reflections. For this reason it is extremely difficult to find radioastronomy sites on the Earth isolated from interfering signals. It is significant that the few ground-based measurements made below 10 MHz have been made from Tasmania which, with regard to freedom from interference, is an advantageous location.

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* This Report should be brought to the attention of Study Group 6.

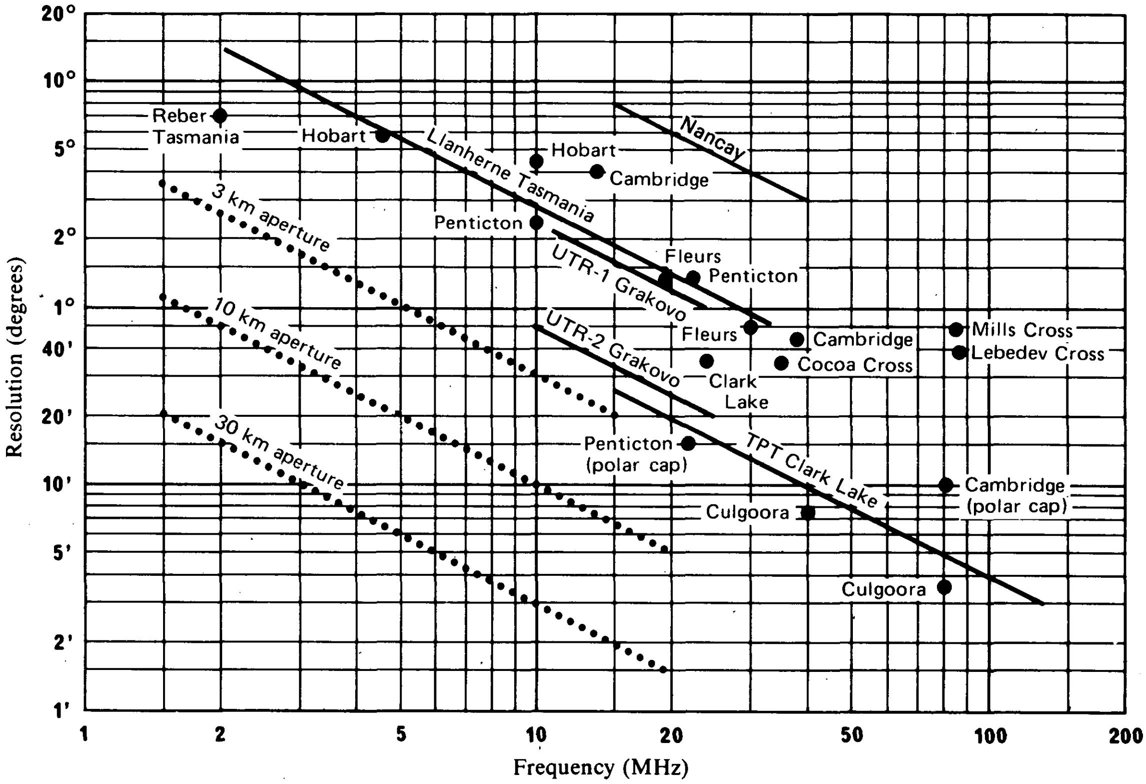

FIGURE 1 – *Resolution of fixed-frequency radio telescopes in current and past use*

(Dotted lines indicate attainable resolution)

● fixed frequency —— broadband

The telescopes are described in the following references:

Fixed frequency telescopes

Reber Tasmania:	REBER, G. [1968] *J. Franklin Inst.*, Vol. 285, **1**, 1-12.
Hobart 4.7 MHz:	ELLIS, G. R. A., GREEN, R.J. and HAMILTON, P. A. [1963] *Austral. J. Phys.*, **16**, 545.
Hobart 10 MHz:	HAMILTON, P. A. and HAYNES, R. F. [1968] *Austral. J. Phys.*, **21**, 895.
Penticton 10 MHz:	GALT, J. A., PURTON, C. R. and SCHEUER, P. A. G. [1967] Publ. Dominion Obs., XXV, **10**.
Cambridge 13 MHz:	ANDREW, B. H. [1969] *Monthly Notices Roy. Astron. Soc.*, Vol. 143, 17.
Fleurs 19.7 MHz:	SHAIN, C. A. [1958] *Proc. IRE*, Vol. 46, 85.
Penticton 22 MHz:	COSTAIN, C. H., LACEY, J. D. and ROGER, R. S. [1969] *IEEE Trans. Ant. Prop.*, Vol. AP-17, 162.
Penticton Polar Cap:	DEWDNEY, P. E. [1978] Ph. D Thesis, Univ. of British Columbia, Canada.
Clark Lake 26 MHz:	ERICKSON, W. C. [1965] *IEEE Trans. Ant. Prop.*, Vol. AP-13, 422.
Fleurs 30 MHz:	FINLAY, E. A. and JONES, B. B. [1972] *Proc. Astron. Soc. Australia*, **2**, 115.
Gauribidanur 34.5 MHz:	SASTRY, C. V. [1983] *Bull. Astron. Soc. India*, Vol. II, 167.
Cocoa Cross:	CRONYN, W. M. and SHAWHAM, S. D. [1975] University of Iowa Physics and Astronomy, 75-12.
Cambridge 38 MHz:	COSTAIN, C. H. and SMITH, F. G. [1960] *Monthly Notices Roy. Astron. Soc.*, Vol. 121, 405.
Culgoora 43 MHz:	SHERIDAN, K. V., LABRUM, N. R. and PAYTEN, W. J. [1973] *Proc. IEEE*, Vol. 61, 1312.
Cambridge Polar Cap:	BRANSON, N.J. B. A. [1967] *Monthly Notices Roy. Astron. Soc.*, Vol. 135, 149.
Mills Cross:	MILLS, B. Y., LITTLE, A. G., SHERIDAN, K. V. and SLEE, O. B. [1958] *Proc. IRE*, Vol. 46, 67.
Culgoora 80 MHz:	See Culgoora 43 MHz.
Lebedev Cross:	VITKEVICH, V. V. and KALACHEV, P. D. [1965] Radio Telescopes Trudy Fiz. Inst. Lebedeva 28.

Broadband telescopes

Llanherne Tasmania:	ELLIS, G. R. A. [1972] *Proc. Astron. Soc. Australia*, **2**, 135.
UTR-1 Grakovo:	BRAUDE, S. Ya., LEBEDEVA, O. M., MEGN, A. V., RYABOV, B. P. and ZHOUK, I. N. [1969] *Monthly Notices Roy. Astron. Soc.*, Vol. 143, 289.
UTR-2 Grakovo:	BRAUDE, S. Ya., MEGN, A. V., RASHKOVSKI, S. L., RYABOV, B. P., SHARYKIN, N. K., SOKOLOV, K. P., TKATCHENKO, A. P. and ZHOUK, I. N. [1978] *Astrophys. and Space Sci.*, Vol 54, 37.
Clark Lake TPT:	ERICKSON, W. C. and FISCHER, J. R. [1974] *Radio Sci.*, Vol. 9, **3**, 387.
Nancay Jupiter Array:	BOISCHOT A. *et al.* [1980] *Icarus*, Vol. 43, 339.

On the basis of measurements made between 1962 and 1964, Ellis and Hamilton [1966] suggest 1.5 MHz as a practical lower limit to ground-based measurements. The following sections contain an examination of the ionospheric factors which limit observations below 20 MHz and an assessment of the feasibility of observations both with and without interference from users of the allocated communication bands.

The ionosphere is a dynamic part of the atmosphere tied very closely to solar activity. Observations below 20 MHz made under disturbed ionospheric conditions cannot yield data of astronomical value. Hence, subsequent sections deal primarily with quiescent conditions such as usually prevail during the 4 to 5 years around sunspot minimum. From recent predictions of sunspot activity [Lamb and Andersen, 1980] the years 1984 to 1988 and 1995 to 1999 should be periods of relatively quiescent conditions. In addition, emphasis is placed on the night-time ionosphere (F layer only) when the electron density has dropped well below its daytime maximum. Observations are possible at other times but suitable conditions occur much less frequently.

2. Geographical limitations

The distribution of ionization at any time of year is strongly dependent upon latitude. This is due in part to the incident solar radiation at a given latitude, and in part to the Earth's geomagnetic field. Lines of constant geomagnetic latitude often form the boundaries between disturbed and quiet regions in the ionosphere (see Report 263). Both geographic and geomagnetic latitudes are important for a detailed consideration of the ionosphere above any site, but it is sufficient for the purposes of this Report to use the term latitude to refer to a rough mean of the two.

The ionosphere, both in the equatorial region (latitude < 30°) and in the polar-auroral zones (latitude > 60°) is known to be more subject to disturbed conditions than at mid-latitudes. A broad minimum in the F-region electron density of the night-time ionosphere near latitude 55° was detected many years ago [Reber and Ellis, 1956], and has been well documented with top-side sounding [Muldrew, 1965] and other techniques [Sharp, 1966; Liszka, 1967]. As we are primarily interested in optimum observation conditions at low frequencies, attention will be confined to the mid-latitude region. This is not to imply that useful radioastronomy cannot be pursued outside this range but simply that the probability at any time of encountering acceptable observing conditions is significantly higher at mid-latitudes.

3. Propagation through the ionosphere

Ground-based radioastronomical observations can be made only when propagation through the ionosphere is possible. The minimum frequency for which such transmission occurs is determined by the maximum value of the electron density. In a quiescent ionosphere this maximum usually occurs in the F region at a height of about 300 km.

Wavefronts impinging vertically on the ionosphere will penetrate if the index of refraction remains greater than zero along the path. Because of the Earth's magnetic field, two component parts of a wave, possessing elliptical polarizations of opposite sense, propagate with different refractive indices. The frequency at which the refractive index of each component (termed the ordinary and extraordinary modes) reaches zero at the height of maximum density, is its critical frequency, ν_c. Because the critical frequency of the ordinary mode is lower than that of the extraordinary mode (by an amount of the order of 1 MHz) there is an obvious advantage in constructing a radio telescope whose polarization is close to that of the ordinary wave.

For waves at frequency $\nu > \nu_c$, penetration of the ionosphere is possible for angles within a cone defined by the limiting zenith angle,

$$\varphi_c(\nu) \approx \text{arc cos}\left(\frac{\nu_c}{\nu}\right) \tag{1}$$

This relation follows Snell's Law and applies to a plane, stratified ionosphere; for the spherically stratified ionosphere this is a slight underestimation of the limiting cone angle. The limiting angle is one for which the ray path becomes almost tangential to the stratification near maximum density. The spherical stratification introduces a small net refraction for traversing rays with the sense that the apparent zenith angle is always less than the true zenith angle. The amount of this refraction depends on the zenith angle and the total integrated electron content [Chvojková, 1958]. For an observing cone extending 60° from the zenith the net refraction would not exceed several degrees.

Horizontal gradients of total electron content provide another source of refraction, first measured by [Smith, 1952]. To a first-order approximation a uniform gradient has the effect of skewing the axis of the observing cone away from the vertical in the direction of decreasing density. This component of refraction may amount to a few degrees when the critical frequency is less by a factor of two, than the observing frequency. However, with multibeam antennas such as would be used for low frequency observations, the pointing errors caused by both sources of refraction can be allowed for by monitoring the apparent positions of the calibration sources.

4. Interference via the ionosphere

For angles of reception greater than the limiting zenith angle, φ_c, the receiving antenna sees, in its sidelobes, a reflection of radiation from an annulus on the Earth's surface. The maximum radius of the annulus, corresponding to a zenith angle near 90° and to reflections from the F layer, is about 4000 km. This defines a limiting distance for interfering signals reaching a radioastronomy receiver after a single hop. However, given sufficient radiating power, interfering signals may reach a radioastronomy receiver, after multiple hops, from almost any point on the Earth's surface. In the lower portion of the frequency band considered in this Report, absorption in the sunlit ionosphere will limit the sources of interference to one-half of the Earth's surface at any one time.

The ratio of the critical frequency corresponding to vertical reflection to that needed to sustain a single reflection path length of 3000 to 4000 km, typically falls in the range 2.7 to 3.3. Since the electron density is proportional to the square of the critical frequency, a maximum electron density of at least one-tenth that required for vertical reflections is needed to sustain propagation paths of 3000 km. In support of this, it is the general experience of radioastronomers observing at 10 to 30 MHz that once the critical frequency falls below the observing frequency by a factor of 3 to 4, the band becomes quiet. Although the antenna may be designed for reception of the ordinary mode in the main beam, the sidelobes, which accept the interfering signal, will, in general, be equally sensitive to both modes. Since the extraordinary mode has the higher critical frequency the band becomes quiet only when its critical frequency falls sufficiently below the observing frequency.

5. Available observing time at mid-latitudes near sunspot minimum

Monthly median values of critical frequencies [Ionospheric Telecommunications Laboratory, 1965] for three stations at mid-latitudes have been used to estimate the average number of hours per day for which the ionosphere near sunspot minimum has a low enough density to allow observations at 3, 6 and 12 MHz.

In order to provide an observing cone extending to 45° from the zenith, the critical frequency must be less than 0.7 times the observing frequency. Table I lists the number of hours per day for which, on average, this is so for Hobart (latitude 42.9° S), Fort Monmouth (40.4° N) and Ottawa (45.4° N) for summer, winter, and equinox, 1965. In addition, listed in parentheses in Table 1 are the number of hours for which the ionosphere has a critical frequency "X-mode" which is less than 0.3 times the observing frequency and so is unlikely to support interfering communication signals.

Since the estimate for the number of hours is based on monthly medians, no account is taken of the days on which the densities are significantly lower than the median values. The tables indicate that at mid-latitudes near sunspot minimum, observations at all three frequencies are possible for several hours a day, except at 3 MHz near the summer solstice. However, one can, in general, expect interference from signals in communicaton bands during useful observing times except at 12 MHz during night-time.

6. Scintillation and the quality of observations

The major factor limiting the quality of observations at times of sufficiently low ionospheric density and no interference is the phenomenon of scintillation (see Report 263). Scintillation is caused by phase distortions imposed on the wavefront by electron density irregularities mainly in the F-region on a scale of 0.5 to 10 km. For antennas less than about 2 km in extent, the irregularities are in the far field of the antenna and r.m.s. phase deviations up to one radian can be tolerated. For larger antennas, the irregularities may be in the near field and will produce phase and amplitude variations which vary across the aperture. In this case irregularities of large horizontal scale with r.m.s. phase variations in excess of about one-quarter radian will distort the shape of the beam.

TABLE I – *Number of hours per day of available observing time (zenith angle < 45°) at three frequencies for 3 times of the year 1965*

Values in parentheses are estimates of the average number of hours per day for which interfering signals would not propagate by reflection.

Hobart, Tasmania	3 MHz	6 MHz	12 MHz
Winter Solstice	9 (0)	16 (0)	24 (13)
Equinox	3 (0)	15 (0)	24 (7)
Summer Solstice	0 (0)	6 (0)	24 (1)

Ottawa, Ontario	3 MHz	6 MHz	12 MHz
Winter Solstice	9 (0)	16 (0)	24 (13)
Equinox	6 (0)	11 (0)	24 (8)
Summer Solstice	2 (0)	10 (0)	24 (5)

Fort Monmouth, New Jersey	3 MHz	6 MHz	12 MHz
Winter Solstice	1 (0)	15 (0)	24 (12)
Equinox	0 (0)	10 (0)	24 (7)
Summer Solstice	0 (0)	8 (0)	24 (3)

Because of the transient nature of scintillations, it is important to make full use of the best conditions. This implies use of antennas with extensive multibeaming networks [Galt *et al.*, 1967] and possibly some provision for final beam formation "off-line" with adjustment of the large scale phase errors which cause beam distortion. Observations with virtually scintillation free conditions at 10 MHz do, on occasion, persist for periods of several weeks at a time. Since the r.m.s. phase fluctuations introduced by irregularities vary directly as to wavelength, one can be fairly confident of useful observations at such times down to 2 to 3 MHz.

7. Absorption at low frequencies

Most of the absorption experienced by low frequency radio waves occurs in the D-region of the ionosphere which is present only during the day-time. An on-site riometer operating at the same frequency as the radio telescope can be used to monitor the absorption and to provide corrections. This technique has been used successfully at 10 and 22 MHz [Bridle and Purton, 1968; Roger *et al.*, 1969].

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REPORT 224-6*

INTERFERENCE PROTECTION CRITERIA FOR THE RADIOASTRONOMY SERVICE

(Question 5/2 and Study Programme 5A/2)

(1963-1966-1970-1974-1978-1982-1986)

1. Introduction

The radiation measured in radioastronomy has a Gaussian probability distribution in amplitude, and qualitatively cannot be distinguished from the noise generated in the receivers or from thermal radiation from the Earth and its atmosphere. Furthermore, the level of cosmic radiation as received by an antenna is usually much lower than the system noise/power, often by 30 dB or more. A full recognition of these facts is the key to understanding the interference problems encountered by the radioastronomy service. The radio astronomers' signal-to-noise ratio is −30 dB or worse; in extreme cases a signal-to-noise ratio as low as −60 dB may yield useful data. In the following paragraphs the theoretical considerations leading to the sensitivity criteria in radioastronomy are described. The characteristics of the radioastronomy service are described in Report 852.

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* This Report should be brought to the attention of Study Groups 1, 3, 4, 8, 9, 10 and 11.

2. Classes of observations

2.1 Radioastronomy observations can be broadly divided into two classes:

2.1.1 *Class A observations* are those in which the sensitivity of the equipment is not a primary factor. They are often used in the study of those cosmic emissions which are of relatively high intensity. Many of the solar, Jupiter, riometer, and scintillation observations fall into this class; continuity is a primary factor for these observations.

2.1.2 *Class B observations* are of such nature that they can be made only with advanced low-noise receivers using the best available techniques; long integration times and wide receiver bandwidths are usually involved. The significance of these observations is critically dependent upon the sensitivity of the equipment used in making them.

2.2 The sensitivity of receivers used for Class B observations and the levels of harmful interference are discussed later in this Report. The simplest way to define the sensitivity of an observation in radioastronomy is to state the smallest power level change at the radiometer input which can, with high certainty, be detected and measured by the radiometer. In § 3 this quantity is defined, and typical values for it are derived. It is convenient to measure the smallest detectable change (ΔT_e) in the equivalent temperature at the output terminals of the antenna connected to the radiometer.

3. Sensitivity of radioastronomy systems

3.1 *Theoretical considerations*

The output of the radiometer detector is a function of the total power at the input of the receiver. (It is assumed that the gain and other parameters of the receiving system remain constant during the observation.) The total input power consists of the wanted signal power P_S and the unwanted noise power P_N (e.g. thermal and receiver noise). Both P_S and P_N are caused by random processes, and it is not possible to distinguish between them qualitatively. However, both have an average power level, and if these levels can be established with sufficient precision, the presence of the wanted signal can be detected. The statistical average of a stationary random variable such as noise power (P) can be found with a precision which is inversely proportional to the square root of the number of samples (N), and the standard deviation of this average is:

$$\Delta P \sim \frac{P}{\sqrt{N}} \tag{1}$$

The standard deviation (ΔP) is often called root mean square or r.m.s. By observing a sufficient number of samples (N), the measurement of the radio noise power can be made with any desired precision. By reducing the fluctuations ΔP to a value less than the wanted signal power, P_S, detection of very weak signals is possible. N can be made very large by using wide bandwidths and long observing times. Within a band Δf, approximately Δf samples per second are measured by the radiometer, and by extending the observing time (t), (also called integration time), N can be made very large.

Now,

$$N \approx \Delta f \cdot t \tag{2}$$

and if this relation is combined with (1),

$$\frac{\Delta P}{P} \sim \frac{1}{\sqrt{\Delta f \cdot t}} \tag{3}$$

which is the basic sensitivity relation in radioastronomy.

The proportionality factor which is needed to make (3) an equation is dependent on details of the equipment and the observing technique. Conditions making this factor $1/\sqrt{2}$ have been discussed by [Kraus, 1966]. With this value adopted, the sensitivity equation becomes:

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{\Delta f t}} \tag{4}$$

As used above, P and ΔP refer to noise powers, but equation (4) also holds if P and ΔP are power spectral densities. Thus ΔP, the noise fluctuation in power spectral density in the sensitivity equation (4), is related to the total system sensitivity (noise fluctuations) expressed in temperature units through the Boltzmann constant, k, as shown in equation (5):

$$\Delta P = k\Delta T; \qquad \text{also} \qquad P = kT \tag{5}$$

and we may express the sensitivity equation as:

$$\Delta T = \frac{T}{\sqrt{2\Delta f t}} \tag{6}$$

where:

$$T = T_A + T_R \tag{7}$$

and represents the sum of T_A, (the antenna noise temperature contribution from the cosmic background, the Earth's atmosphere and radiation from the Earth), and T_R, the receiver noise temperature.

3.2 *Sensitivity estimates*

Equations (4) or (6) can be used to estimate the sensitivities and harmful interference levels for radioastronomical observations. The results are listed in Tables I and II; an observing (or integration) time t of 2000 s is assumed. In Table I (continuum observations), Δf is assumed to be the bandwidth of the allocated radioastronomy bands. In Table II (spectral line observations) Δf is the channel bandwidth (corresponding to a velocity of 3 km/s) typical of a spectral line system.

The harmful interference levels given in Tables I and II are expressed as the interference level which introduces an error of 10% in the measurement of ΔP (or ΔT), i.e.:

$$\Delta P_H = 0.1\ \Delta P \Delta f \tag{8}$$

In summary, the appropriate columns in Tables I and II may be calculated using the following methods:

- ΔT, using equations (6) and (7),
- ΔP, using equation (5),
- ΔP_H, using equation (8).

Harmful interference can also be expressed in terms of the power flux-density incident at the antenna, either in the total bandwidth or as a spectral power flux-density S_H per 1 Hz of bandwidth *. For convenience, the values are given for an antenna having a gain, in the direction of arrival of the interference, equal to that of an isotropic antenna (which has an effective area of $c^2/4\pi f^2$, where c is the speed of light and f the frequency).

Consideration of the value of antenna gain to be used in different circumstances is presented in § 4. Values of $S_H\Delta f$, in dB(W/m²), are derived from ΔP_H by adding:

$$20 \log f - 38.6 \qquad \text{dB} \tag{9}$$

where f is in MHz. S_H is then derived by subtracting $10 \log \Delta f$ to allow for the bandwidth.

Figure 1 shows graphically the harmful interference levels for the radioastronomy service expressed in Tables I and II where S_H in dB(W/(m² · Hz)) is plotted as a function of frequency. The curves are not smooth because the different frequency bands have different bandwidths.

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* In radioastronomy, S_H is generally denoted by the term "flux density". In this Report the recommended CCIR terminology (Recommendation 574, Appendix I, § 1.4) is followed, in which "power flux-density" refers to quantities with units W/m² and "spectral power flux-density" refers to quantities like S_H with units W/(m² · Hz).

TABLE I – *Sensitivities and harmful interference levels for radioastronomy continuum observations with 2000 s integration time*

Centre frequency ([1]) f_c (MHz)	Assumed bandwidth Δf_A (MHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity (noise fluctuations)		Harmful interference levels		
				Temperature ΔT (mK)	Power spectral density ΔP (dB(W/Hz))	Input power ΔP_H (dBW)	Power flux-density $S_H \Delta f_A$ (dB(W/m²))	Spectral power flux-density S_H (dB(W/(m²·Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
13.385	0.05	60000	100	4250	−222	−185	−201	−248
25.610	0.120	20000	100	917	−229	−188	−199	−249
73.8	1.6	1000	100	14	−247	−195	−196	−258
151.525	2.95	200	100	2.76	−254	−199	−194	−259
325.3	6.6	40	100	0.86	−259	−201	−189	−258
408.05	3.9	25	100	1.00	−259	−203	−189	−255
611	6.0	15	100	0.74	−260	−202	−185	−253
1413.5	27	10	20	0.091	−269	−205	−180	−255
2695	10	10	20	0.15	−267	−207	−177	−247
4995	10	10	20	0.15	−267	−207	−171	−241
10650	100	12	20	0.05	−272	−202	−160	−240
15375	50	15	30	0.10	−269	−202	−156	−233
23800	400	15	50	0.051	−271	−195	−147	−233
31550	500	18	100	0.083	−269	−192	−141	−228
43000	1000	25	100	0.063	−271	−191	−137	−227
89000	6000	30	150	0.037	−273	−185	−125	−222
110500	11000	40	150	0.029	−274	−184	−121	−222
166000	4000	40	150	0.048	−272	−186	−120	−216
224000	14000	40	200	0.032	−274	−182	−114	−215
270000	10000	40	200	0.038	−273	−183	−113	−213

([1]) Calculation of harmful interference levels is based on the centre frequency shown in this column although not all regions have the same allocations.

Note. – If an integration time of 15 minutes, one hour, two hours, five hours or ten hours is used, the relevant values in the Table should be varied by +1.7, −1.3, −2.8, −4.8 or −6.3 dB respectively.

TABLE II – *Sensitivities and harmful interference levels for radioastronomy spectral line observations* with 2000 s integration*

Frequency f (MHz)	Assumed spectral line channel bandwidth Δf_c (kHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity (noise fluctuations): Temperature ΔT (mK)	System sensitivity (noise fluctuations): Power spectral density ΔP (dB(W/Hz))	Harmful interference levels: Input power ΔP_H (dBW)	Harmful interference levels: Power flux-density $S_H \Delta f_c$ (dB(W/m²))	Harmful interference levels: Spectral power flux-density S_H (dB(W/(m²·Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
327	10	40	100	22.1	– 245	– 215	– 204	– 244
1420	20	10	20	3.35	– 253	– 220	– 196	– 239
1665	20	10	20	3.35	– 253	– 220	– 194	– 237
4830	50	10	20	2.12	– 255	– 218	– 183	– 230
14500	150	15	30	1.84	– 256	– 214	– 169	– 221
22200	250	40	50	2.85	– 254	– 210	– 162	– 216
23700	250	40	50	2.85	– 254	– 210	– 161	– 215
43000	500	25	100	2.80	– 254	– 207	– 153	– 210
48000	500	30	100	2.91	– 254	– 207	– 152	– 209
88600	1000	30	150	2.85	– 254	– 204	– 144	– 204
98000	1000	40	150	3.00	– 254	– 204	– 143	– 203
115000	1000	50	150	3.16	– 254	– 204	– 141	– 201
140000	1500	40	150	2.45	– 255	– 203	– 139	– 200
178000	1500	40	150	2.45	– 255	– 203	– 136	– 198
220000	2500	40	200	2.40	– 255	– 201	– 133	– 197
265000	2500	40	200	2.40	– 255	– 201	– 131	– 195

* This Table is not intended to give a complete list of spectral-line bands, but only representative examples throughout the spectrum.

Note. – If an integration time of 15 minutes, one hour, two hours, five hours or ten hours is used, the relevant values in the Table should be changed by + 1.7, – 1.3, – 2.8, – 4.8 or – 6.3 dB, respectively.

COLUMN DESCRIPTIONS FOR TABLES I AND II

Column

(1) Centre frequency of the allocated radioastronomy band (Table I) or nominal spectral line frequency (Table II).

(2) Assumed or allocated bandwidth (Table I) or assumed typical channel widths used for spectral line observations (Table II).

(3) Minimum antenna noise temperature includes contributions from the ionosphere, the Earth's atmosphere and radiation from the Earth.

(4) Receiver noise temperature representative of a good radiometer system intended for use in high sensitivity radio-astronomy observations.

(5) Total system sensitivity in millikelvins as calculated from equation (4) using the combined antenna and receiver noise temperatures, the listed bandwidth and an integration time of 2000 s.

(6) Same as (5) above, but expressed in noise power spectral density using the equation $\Delta P = k\Delta T$, where $k = 1.38 \times 10^{-23}$ (J/K) (Boltzmann's constant). The actual numbers in the Table are the logarithmic expression of ΔP.

(7) Power level at the input of the receiver considered harmful to high sensitivity observations (ΔP_H). This is expressed as the interference level which introduces an error of not more than 10% in the measurement of ΔP; $\Delta P_H = 0.1\ \Delta P \Delta f$. The numbers in the Table are the logarithmic expression of ΔP_H.

(8) Power flux-density in a spectral line channel needed to produce a power level of ΔP_H in the receiving system with an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of $S_H\ \Delta f$.

(9) Spectral power flux-density in a spectral line channel needed to produce à power level ΔP_H in the receiving system with an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of S_H.

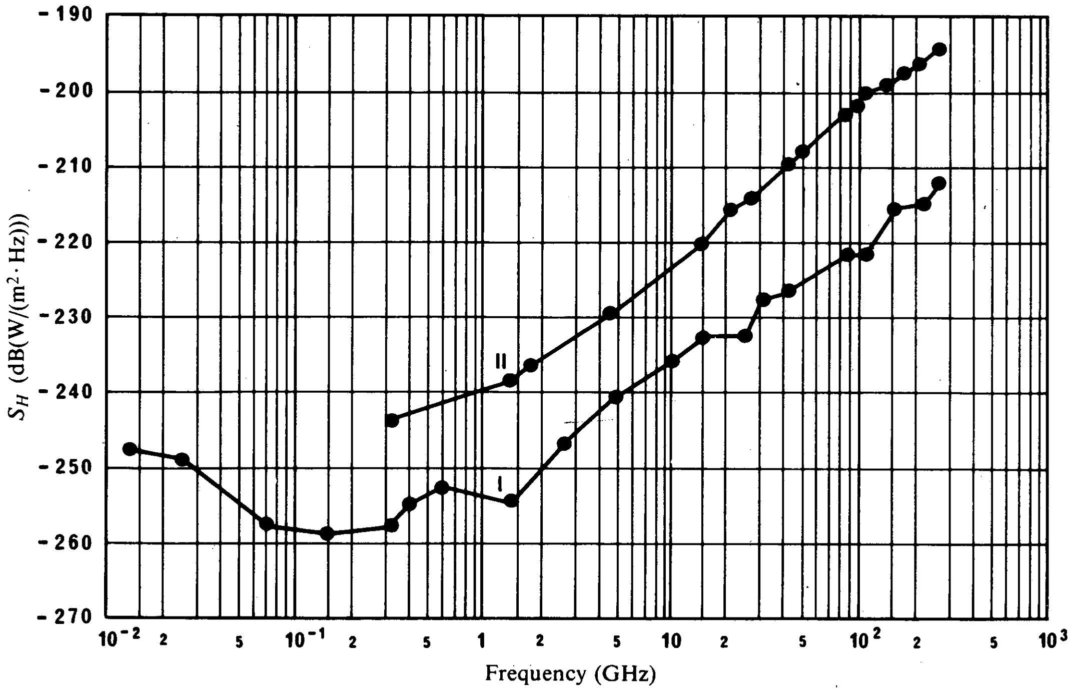

FIGURE 1 – *Harmful interference limits versus frequency as expressed in Tables I and II for t = 2000 s*

I: Continuum

II: Line

The calculated sensitivities and harmful interference levels presented in Tables I and II are based on assumed integration times of 2000 s. Integration times actually used in astronomical observations cover a wide range of values. Continuum observations made with telescopes operating singly (rather than in interferometric arrays) are reasonably well represented by the integration time of 2000 s. It is representative of good quality observations although there are many occasions when this time is exceeded by an order of magnitude. On the other hand 2000 s is less representative of spectral line observations. Improvements in receiver stability and the increased use of correlation spectrometers have resulted in the more frequent use of longer integration times. Spectral line observations lasting several hours are now quite common. A more representative value would be 10 hours with a consequent improvement in sensitivity of 6 dB over that now shown in Table II.

The sensitivity of a radioastronomy receiving system to wideband radiation improves when the bandwidth is increased (equations (4) and (6)). The reason for this is the following: the noise power increases with bandwidth, but, since the signal also is broadband noise, so does the signal. Actually the signal-to-noise power ratio remains constant, independent of the bandwidth. However, as the bandwidth increases, the precision of the determination of the power levels improves (by a factor of $\sqrt{\Delta f}$), and thus the sensitivity is correspondingly improved.

Equations (4) or (6) suggest that one may achieve any desired sensitivity by making the bandwidth and/or the observing time, large enough. In reality, however, factors other than the statistical ones described above, sooner or later put a practical limit on the sensitivity of a radioastronomy observation. Examples of such other effects are the stability of the receiver, fluctuations in the Earth's atmosphere and the patience and endurance of the observer. The sensitivity levels given in Tables I and II use values for the bandwidth and integration time for which these other factors usually are insignificant. However, one should bear in mind that these sensitivity levels are not fundamental limits and that they actually have been exceeded in cases where the utmost sensitivity was required for a successful experiment.

It should be recognized that astronomical sources of radiation exist which may interfere with highly sensitive observations; their spectral power flux-densities can exceed those given in Table I. The Sun is a powerful source of emission. Because of solar interference, certain investigations can only be conducted at night. Other experiments are possible during daytime except during periods of solar activity, especially for frequencies below about 200 MHz. The quiet Sun is of large angular diameter and constant in flux; it usually presents no difficulties. Below 38 MHz, radiation from Jupiter may also exceed the limits given in Table I. At such frequencies Jupiter is a sporadic radio source which emits strongly only a few per cent of the time at highly predictable periods. These periods of emission can be avoided.

Below 1 GHz, many other cosmic radio sources exceed the spectral power flux-densities given in Table I. These sources however, are generally at known positions and of known constant strength and vary only slowly in frequency. In principle and in practice the radioastronomer can make corrections for their effects. This is necessary when performing observations at the highest possible sensitivity. On the other hand, low level terrestrial interference normally has an unknown position, flux density and spectrum, and can be highly time variable, so corrections cannot be made for its effects.

3.2.1 *Observed sensitivities*

The sensitivities in Tables I and II are extremely high, several orders of magnitude higher than often considered practical, or even obtainable, in other radio services. It is of interest to examine actual high sensitivity observations which have been made at various radioastronomy observatories, and compare these results with the calculated values in Tables I and II.

Table III gives examples of very sensitive continuum and line observations appearing in published literature.

Table III shows that very sensitive observations are being made at various radioastronomy observatories. The system temperatures, bandwidths and integration times chosen for the calculations leading to harmful interference limits given in Tables I and II and in Fig. 1, represent practical values currently being used by the radioastronomy service throughout the world. Were interference to be encountered with intensities increasing above these limits, radioastronomy observations would become increasingly untrustworthy.

Changes in receiving systems can be expected to give improved performance in the future. It is safe to assume that within ten years, observations will be made routinely at sensitivity levels better than those shown in Tables I and II. Such improvements might result from changes in any one of the factors entering into equations (6) and (7). It appears unlikely however, that major improvements could result from changes in receiver noise temperature. At frequencies of 150 MHz and less, the receiver temperature is not a large contributor to the total system temperature. At the high frequency end of the spectrum now being used by radio astronomers, improvements in receiver technology are likely to have their largest effect. If receiver temperatures of 10 K can be achieved at frequencies in excess of 30 GHz then improvements in sensitivity of 6 dB will result in this millimetric region of the spectrum.

TABLE III – *Comparison of observational results with harmful interference limits given in Table I and II*

Frequency (GHz)	Line or continuum	Observed spectral power flux-density (dB(W/(m²·Hz)))	Harmful limit (dB(W/(m²·Hz)))	References
2.7	Continuum	– 283	– 247	Wade and Hjellming [1971]
5.0	Continuum	– 292	– 241	Weiler *et al.* [1981]
1.42	Line (neutral hydrogen)	– 283	– 239	Giovanelli *et al.* [1981]
10.5	Line (helium 85α)	– 279	– 223 (¹)	Higgs *et al.* [1979]

(¹) Value interpolated from Fig. 1.

4. The radioastronomy antenna

4.1 *Sensitivity within the main beam*

The typical radioastronomy antenna has high directivity in order to obtain the best possible angular resolution of the observed sources, and a large collecting area (high gain) for good sensitivity. In modern systems beamwidths of the order of minutes of arc to seconds of arc are used (100 millidegrees-10 millidegrees), corresponding to antenna gains of more than 70 dB. The high gain combined with the good sensitivity of a radioastronomy receiving system makes it possible for the radio astronomer to observe very faint power flux-densities indeed. For example at 1420 MHz, with a receiver sensitivity of 10^{-27} W/Hz (-270 dB(W/Hz)) and with an antenna of effective collecting area 4000 m² (61 dB gain), the detectable spectral power flux-density is:

$$S = \frac{10^{-27}}{4000} = 2.5 \times 10^{-31} \text{ W/(m}^2 \cdot \text{Hz)}$$

or:

$$-306 \text{ dB(W/(m}^2 \cdot \text{Hz)).}$$

Obviously a different antenna would yield a different sensitivity level.

4.2 *The effect of side lobes on the harmful interference levels*

To obtain an estimate of the interference problems which may be applied to all radio telescopes, large and small, the conditions where the telescope is pointed away from the interfering source should be considered. The harmful power flux-density and spectral power flux-density shown in Tables I and II are based on the isotropic case and should be regarded as the general interference criteria for high sensitivity radioastronomy observations, when the interference does not enter the near side lobes. The levels given in Tables I and II are applicable to terrestrial sources of interfering signals, and are valid for intentional as well as unwanted emissions.

The power level of an interfering signal at the receiver terminals depends upon the side-lobe level of the receiving antenna as well as upon the power flux-density of the interfering signal. A model of the typical side-lobe levels for large paraboloid antennas in the frequency range 2 to 10 GHz is given in Recommendation 509. In this model, the side-lobe level decreases with angular distance (degrees) from the main beam axis, and is equal to $(32 - 25 \log \varphi)$ dBi for $1° < \varphi < 48°$. A level of 0 dBi occurs at 19° from the main beam axis. A source of interference of power flux-density equal to the threshold values given in Table I would be harmful if such an antenna was pointed within 19° of it. Thus, in some situations, interference at the harmful thresholds in Table I can be a problem to radioastronomers.

4.3 *The special case of transmitters on geostationary satellites*

Interference from geostationary satellites is a case of particular importance. Because the power levels in Tables I and II were calculated assuming 0 dBi antenna gain, harmful interference will be encountered when a reference antenna, such as described in Recommendation 509, is pointed within 19° of a satellite radiating at levels in accordance with those listed in the tables. A series of similar transmitters located at intervals of 20° around the geostationary-satellite orbit would preclude radioastronomy observations with high sensitivity from a band of sky 38° wide and centred on the orbit. The loss of such a large area of sky would impose severe restrictions on radioastronomy observations.

In general, it would not be practical to suppress the unwanted emissions from satellites to below the harmful level when the main beam of a radio telescope is pointed directly towards the satellite. A workable solution is suggested in Fig. 2 of Report 697, which shows the projection of the geostationary-satellite orbit in celestial coordinates as viewed from the latitudes of a number of major radioastronomy observations. If it were possible to point a radio telescope to within 5° of the orbit without encountering harmful interference, then for that telescope a band of sky 10° wide would be unavailable for high sensitivity observations. For a given observatory this would be a serious loss. However, for a combination of radio telescopes located at northern and southern latitudes, operating at the same frequencies, the entire sky would be accessible. A value of 5° should therefore be regarded as the requirement for minimum angular spacing between the main beam of a radioastronomy antenna and the geostationary-satellite orbit.

In the model antenna response of Recommendation 509, the side-lobe level at an angle of 5° from the main beam is 15 dBi. Thus, to avoid harmful interference to a radio telescope pointed within 5° from the transmitter, the satellite emissions must be reduced 15 dB below the power flux-densities given in Tables I and II. When satellites are spaced at intervals of only a few degrees along the orbit, the emission levels associated with the individual transmitters must be even lower to meet the requirement that the sum of the powers of all the interfering signals received should be 15 dB below ΔP_H in Tables I and II. Report 713 reaches similar conclusions.

It is recognized that the emission limitations discussed above cannot, in practice, be achieved so as to enable sharing of the same frequency band between radioastronomy and down-link transmissions from satellites to take place. The limitations are, however, applicable to unwanted emission from the satellite transmitters which fall within the radioastronomy bands listed in Tables I and II. These emission limitations have implications for the space services responsible for the interference, which require careful evaluation. Furthermore, the design of new radioastronomy antennas should strive to minimize the level of side-lobe gain near the main beam as an important means of reducing interference from transmitters in the geostationary-satellite orbit.

5. Interference

5.1 *Types of interference*

It is convenient to divide harmful interference into three main categories:

Category 1: Strong interference that causes non-linear operation of the receiver, sometimes to the point of harming the sensitive input amplifier.

Fortunately, this type of interference is rare and unlikely to be caused by normal transmissions. However, radar transmitters in low flying aircraft are capable of physically damaging the electronics of a radioastronomy receiving system. Typically a power level at the radiometer input of 0.1 W would burn out the varactor in a parametric amplifier. This corresponds to a power flux-density of 10 W/m^2 (10 dB(W/m^2)) at 1400 MHz, if the interfering source is outside the main beam of the antenna. The corresponding spectral power flux-density, assuming a bandwidth of 27 MHz (1400 to 1427 MHz) would be 3.7×10^{-7} W/(m^2 · Hz) or -64 dB(W/(m^2 · Hz)). If the antenna is accidentally pointed at such a strong interference source, the power flux-density that could burn out the input varactor must be reduced by the gain of the antenna.

Category 2: Relatively strong interference which is easy to recognize.

Usually this is the case if the interference power is stronger than the noise power in the radiometer input. This type of interference is fatal to observations, and there is no doubt that it is interference. There is no choice but to discard the data. Typically, interference power flux-densities above -110 dB(W/m^2) belong to this category. With an assumed bandwidth of 27 MHz (the 1413.5 MHz band), the corresponding spectral power flux-density is -184 dB(W/(m$^2 \cdot$ Hz)).

Category 3: Very low-level interference with a very low interference to noise ratio (less than -20 dB) that cannot be recognized.

The long integration times required to bring the wanted signal out of the noise will mask the characteristic features of the interfering signal. It cannot be recognized as interference and erroneous data result; this type of low-level interference is therefore particularly harmful. Furthermore, because the radio astronomer cannot determine by examination of the data that he has encountered interference, there is no possibility of identifying the source.

5.2 *Interference reduction techniques*

A number of techniques designed to reduce the effects of interference can be tried by the radio astronomer. Some of these are obvious and straightforward, and some are clever, complicated and often time consuming. They all suffer from the problem of being of limited usefulness. In general, the employment of interference reduction techniques leads to the need for more observing time.

5.2.1 *Filtering techniques*

Unwanted signal energy outside the observed band is rejected in the radioastronomy receiver by using bandpass filters. Normally, when the interfering signals are of low intensity and do not cause non-linear operation anywhere in the system, limiting the observed passband by a filter in the IF channel is useful. Since the IF frequencies are relatively low, typically between 100 to 300 MHz, relatively steep skirt selectivity is possible. However, limiting the observing band decreases the sensitivity of the system which is proportional to $\sqrt{\Delta f}$. Filtering in the radiometer input is also used, particularly when the potentially-interfering signals are strong. Again decreased sensitivity is the result, both because of the narrower bandwidth and because of the insertion loss of the filter which, when inserted in the receiver input, adds to the loss and the noise temperature of the system. Since the filtering takes place at the observing frequency, adequate skirt selectivity may be a problem. Typically, about 75% of an allocated band remains available after reasonable IF filtering (see Report 697) which corresponds to a sensitivity loss of about 13%. If input filtering is needed, sensitivity reduction of a factor of 2 or more could be expected.

In order to obtain 100 dB reduction of the midband response at the band edge of the radioastronomy band, one needs three or more 8-section filters in the IF channel. Although such a filter system is feasible, there are important phase considerations to be taken into account when observing with an antenna array or interferometer. This makes it questionable whether filtering really is a viable general solution to the band edge interference problem. Bandpass filters do not, of course, alleviate the in-band interference problem.

5.2.2 *Observing techniques*

It is possible, and often necessary, to reduce the effect of interference by using special observing techniques. One possibility is to repeat the observation several times, with the assumption that the interference is present only occasionally. It is also useful to move the telescope on and off the source during an observing run, assuming that the interference is present all the time. Both methods are of limited usefulness, because of the assumptions one has to make of the behaviour of the celestial source as well as of the interference. They also increase the required observing time by a sizeable factor. Furthermore, the technique of repeating the observations is not very useful in the case of sources of variable intensity, as it is not possible to distinguish between variations in the interference and intrinsic variations in the source. The on/off technique is not useful for observations of extended astronomical objects, such as the cosmic background, since there is no region of the sky which can be considered off-source. An assumption that the intensity of the interference is constant must also be made. This is not generally true; often the interference varies in intensity with time and in a complicated way across the frequency band.

5.2.3 *Data processing techniques*

After-the-fact reduction of the effects of very low-level interference is of very limited usefulness in radioastronomy. One reason for this is that in order to detect power at a very low level, long integration times, which mask the identifying characteristics of the interfering signals, have to be used. The added power caused by the interference is then no longer distinguishable from the random noise one is looking for. It might be possible, in some special cases such as pulsed radar interference where the characteristics of the interfering signals are accurately known, to process the data in a way that might reduce the effect of the interference.

Continuum observations, which require a large bandwidth in order to achieve good sensitivity, can be made by a receiver covering the desired bandwidth with a number of contiguous channels (a spectral line receiver). The spectral information can then be used to identify a narrow interfering signal. However, for interference covering a bandwidth comparable to the continuum bandwidth observed, this technique is not useful.

In very special and rare cases, when the characteristics of the wanted signal are known this information can be used to separate the signal from the interference and noise. However, for the general case of radioastronomy observations, there seems to be no useful data processing technique that can be used to identify and reduce interference.

5.3 *Interference and long base-line interferometers*

High-resolution observations require the use of interferometers or arrays of antennas with wide spacings between their elements. Each antenna may be subject to different interference conditions. In the extreme case of very long base-line interferometers (VLBI), the interference may affect only one antenna of the system. This may reduce the effect of interference. On the other hand, it should be noted that VLBI experiments involve sophisticated data reduction and use of very distant antennas with consequent coordination problems. Interference affecting only one antenna may invalidate a whole observation. This leads to the need for world-wide protection of VLBI observations.

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RECOMMENDATION 314-6*

PROTECTION FOR FREQUENCIES USED FOR RADIOASTRONOMICAL MEASUREMENTS

(Question 5/2)

(1953-1956-1959-1966-1970-1974-1978-1982-1986)

The CCIR,

CONSIDERING

(a) that the development of radioastronomy has already led to major technological advances, particularly in receiving techniques, and to improved knowledge of fundamental radio-noise limitations of great importance to radiocommunication, and promises further important results;

(b) that protection from interference on certain frequencies is essential to the advancement of radioastronomy and the associated measurements;

* This Recommendation should be brought to the attention of Study Group 1, with particular reference to Question 45/1.

(c) that an updated list of spectral lines of particular importance was prepared at the General Assembly of the International Astronomical Union (IAU), 1982;

(d) that account should be taken of the Doppler shifts of the lines, resulting from the motion of the sources;

(e) that, for other types of radioastronomical observation, a certain number of frequency bands are in use, the exact positions of which in the spectrum are not of critical importance, but of which the centre frequencies should be approximately in the ratio of two to one;

(f) that propagation conditions at frequencies below about 40 MHz are such that a transmitter operating anywhere on the Earth might cause harmful interference to radioastronomy;

(g) that radioastronomers have demonstrated their ability to make useful astronomical observations from the Earth's surface at frequencies as low as 2 MHz;

(h) that the movement of the Moon produces occultations of radio sources, permitting unique radioastronomical observations of high resolution which are particularly important at metre wavelengths;

(j) that the sensitivity of radioastronomical receiving equipment, which is still steadily improving, greatly exceeds the sensitivity of communications and radar equipment;

(k) that harmful interference to radioastronomy can be caused by terrestrial transmissions reflected by the Moon, by aircraft, and possibly by artificial satellites;

(l) that some transmissions from spacecraft introduce problems of interference to radioastronomy and that these cannot be avoided by choice of site for an observatory or by local protection;

(m) that certain types of radioastronomical observation require long periods of uninterrupted recording, sometimes up to several days;

(n) that some types of high-resolution interferometric observations require simultaneous reception, at the same radio-frequency, by receiving systems located in different countries or on different continents;

(o) that some degree of protection can be achieved by appropriate frequency assignments on a national rather than an international basis;

(p) that the World Administrative Radio Conference, Geneva, 1979, made improved allocations for radioastronomy, but that protection in many bands, particularly below 20 GHz, will need careful planning of other radio services;

(q) that the technical criteria concerning harmful interference, referred to in Recommendation No. 61 of the World Administrative Radio Conference, Geneva, 1979, should in respect of the radioastronomy service be those set out in Tables I and II of Report 224 for transmitters operating outside the main beam of the radioastronomy antenna,

UNANIMOUSLY RECOMMENDS

1. that radioastronomers should be encouraged to choose sites as free as possible from interference;

2. that administrations should afford all practicable protection to the frequencies used by radioastronomers in their own and neighbouring countries;

3. that particular attention should be given to securing adequate protection for the frequency bands listed in Tables I and II, which contain rest and Doppler shifted frequencies of the most important spectral lines selected at the General Assembly of the International Astronomical Union (IAU), 1982;

4. that administrations should bear in mind the technical desirability of affording protection to radio astronomy at frequencies below 10 MHz while taking CONSIDERING *(e)* and *(g)* into account;

5. that consideration be given to securing improvement in the international protection of the series of frequency bands above 10 MHz, now available to the radioastronomy service, in accordance with the Radio Regulations as amended by the World Administrative Radio Conference, Geneva, 1979;

6. that administrations, in seeking to afford protection to particular radioastronomical observations, should take all practical steps to reduce to the absolute minimum amplitude, harmonic radiations and other spurious emissions falling within the band of the frequencies to be protected for radioastronomy, particularly those emissions from aircraft, spacecraft and balloons;

7. that it is very difficult for the radioastronomy service to share frequencies with any other service in which direct line-of-sight paths from the transmitters to the observatories are involved. Above about 40 MHz sharing may be practicable with services in which the transmitters are not in direct line-of-sight from the observatories, but coordination may be necessary, particularly if the transmitters are of high power.

TABLE I – *Radio-frequency lines of the greatest importance to radioastronomy at frequencies below 275 GHz*

Substance	Rest frequency	Suggested minimum band	Notes (1)
Deuterium (DI)	327.384 MHz	327.0- 327.7 MHz	
Hydrogen (HI)	1420.406 MHz	1370.0- 1427.0 MHz	(2) (3)
Hydroxyl radical (OH)	1612.231 MHz	1606.8- 1613.8 MHz	(3) (4)
Hydroxyl radical (OH)	1665.402 MHz	1659.8- 1667.1 MHz	(4)
Hydroxyl radical (OH)	1667.359 MHz	1661.8- 1669.0 MHz	(4)
Hydroxyl radical (OH)	1720.530 MHz	1714.8- 1722.2 MHz	(3) (4)
Methyladyne (CH)	3263.794 MHz	3252.9- 3267.1 MHz	(3) (4)
Methyladyne (CH)	3335.481 MHz	3324.4- 3338.8 MHz	(3) (4)
Methyladyne (CH)	3349.193 MHz	3338.0- 3352.5 MHz	(3) (4)
Formaldehyde (H_2CO)	4829.660 MHz	4813.6- 4834.5 MHz	(3) (4)
Formaldehyde (H_2CO)	14.488 GHz	14.439- 14.503 GHz	(3) (4)
Water vapour (H_2O)	22.235 GHz	22.16 - 22.26 GHz	(3) (4)
Ammonia (NH_3)	23.694 GHz	23.61 - 23.71 GHz	(4)
Ammonia (NH_3)	23.723 GHz	23.64 - 23.74 GHz	(4)
Ammonia (NH_3)	23.870 GHz	23.79 - 23.89 GHz	(4)
Silicon monoxide (SiO)	42.821 GHz	42.77 - 42.86 GHz	
Silicon monoxide (SiO)	43.122 GHz	43.07 - 43.17 GHz	
Carbon monosulphide (CS)	48.991 GHz	48.94 - 49.04 GHz	
Deuterated formylium (DCO^+)	72.039 GHz	71.96 - 72.11 GHz	(3)
Silicon monoxide (SiO)	86.243 GHz	86.16 - 86.33 GHz	
Formylium ($H^{13}CO^+$)	86.754 GHz	86.66 - 86.84 GHz	
Ethynyl radical (C_2H)	87.3 GHz	87.19 - 87.54 GHz	(5)
Hydrogen cyanide (HCN)	88.632 GHz	88.34 - 88.72 GHz	(4)
Formylium (HCO^+)	89.189 GHz	88.89 - 89.28 GHz	(4)
Hydrogen isocyanide (HNC)	90.664 GHz	90.57 - 90.76 GHz	
Diazenylium (N_2H^+)	93.17 GHz	93.07 - 93.27 GHz	
Carbon monosulphide (CS)	97.981 GHz	97.88 - 98.08 GHz	
Carbon monoxide ($C^{18}O$)	109.782 GHz	109.67 -109.89 GHz	
Carbon monoxide (^{13}CO)	110.201 GHz	110.09 -110.31 GHz	
Carbon monoxide (CO)	115.271 GHz	114.88 -115.39 GHz	(4)
Formaldehyde (H_2CO)	140.840 GHz	140.69 -140.98 GHz	
Carbon monosulphide (CS)	146.969 GHz	146.82 -147.12 GHz	
Formaldehyde (H_2CO)	150.498 GHz	150.34 -150.65 GHz	(3)
Water vapour (H_2O)	183.310 GHz	183.12 -183.50 GHz	
Carbon monosulphide (CS)	195.962 GHz	195.76 -196.16 GHz	(6)
Carbon monoxide ($C^{18}O$)	219.560 GHz	219.34 -219.78 GHz	
Carbon monoxide (^{13}CO)	220.399 GHz	220.17 -220.62 GHz	
Carbon monoxide (CO)	230.538 GHz	229.77 -230.77 GHz	(4)
Carbon monosulphide (CS)	244.953 GHz	244.71 -245.20 GHz	(6)
Hydrogen cyanide (HCN)	265.886 GHz	265.62 -266.15 GHz	
Formylium (HCO^+)	267.557 GHz	267.29 -267.83 GHz	
Hydrogen isocyanide (HNC)	271.981 GHz	271.71 -272.25 GHz	

(1) If Notes (4) or Note (2) are not listed, the band limits are the Doppler-shifted frequencies corresponding to radial velocities of ± 300 km/s (consistent with line radiation occurring in our galaxy).

(2) An extension to lower frequency of the allocation of 1400-1427 MHz is required to allow for the higher Doppler shifts for HI observed in distant galaxies.

(3) The current international allocation is not primary and/or does not meet bandwidth requirements. See the Radio Regulations for more detailed information.

(4) Because these line frequencies are also being used for observing other galaxies, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1000 km/s.

(5) There are six closely spaced lines associated with this molecule at this frequency. The listed band is wide enough to permit observations of all six lines.

(6) This line frequency is not mentioned in the Radio Regulations as being of astronomical interest.

TABLE II – *Radio-frequency lines of the greatest importance to radioastronomy at frequencies between 275 and 700 GHz (not allocated in the Radio Regulations)*

Substance	Rest frequency (GHz)	Suggested minimum band (GHz)
Diazenylium (N_2H^+)	279.511	279.23-279.79
Carbon monoxide ($C^{18}O$)	329.330	329.00-329.66
Carbon monoxide (^{13}CO)	330.587	330.25-330.92
Carbon monoxide (CO)	345.796	345.45-346.14
Hydrogen cyanide (HCN)	354.484	354.13-354.84
Formyl ion (HCO^+)	356.734	356.37-357.09
Diazenylium (N_2H^+)	372.672	372.30-373.05
Water vapour (H_2O)	380.197	379.81-380.58
Carbon monoxide ($C^{18}O$)	439.088	438.64-439.53
Carbon monoxide (^{13}CO)	440.765	440.32-441.21
Carbon monoxide (CO)	461.041	460.57-461.51
Carbon (CI)	492.162	491.66-492.66
Water vapour (H_2O)	556.936	556.37-557.50
Ammonia (NH_3)	572.498	571.92-573.07
Carbon monoxide (CO)	691.473	690.78-692.17

RECOMMENDATION 611 *

PROTECTION OF THE RADIOASTRONOMY SERVICE FROM SPURIOUS EMISSIONS

(Question 5/2 and Study Programme 5A/2)

(1986)

The CCIR,

CONSIDERING

(a) that radioastronomy continues to be in the forefront of the expansion of scientific knowledge;

(b) that the radioastronomy service requires frequency bands free of harmful interference in order that astronomical observations can be made;

(c) that the growing use of the radio spectrum, particularly in space, increases the possibility of harmful interference to radioastronomy from spurious emissions;

(d) that Appendix 8 to the Radio Regulations establishes the maximum permitted levels of spurious emissions from transmitters operating at frequencies below 17.7 GHz;

(e) that stations in the space services operating at frequencies above 960 MHz are excluded from the application of Appendix 8 to the Radio Regulations;

(f) that radioastronomy observations are conducted in frequency bands up to, and above, 275 GHz;

* This Recommendation should be brought to the attention of Study Groups 1, 4, 8, 9, 10 and 11.

(g) that the technical criteria concerning harmful interference, referred to in Recommendation No. 61 of the WARC-79, should, in respect of the radioastronomy service, be those set out in Tables I and II of Report 224 for transmitters operating outside the main beam of the radioastronomy antenna;

(h) that the technical criteria for the special case of harmful interference due to spurious emissions from transmitters in geostationary space stations should, in respect of the radioastronomy service, be those set out in Reports 224 and 697 enabling radioastronomy observations to be made at 5° or more of the geostationary-satellite orbit;

(j) that, as evidenced in Report 807, progress has been made in meeting the requirements of the radioastronomy service without detrimental effects on other services;

(k) that there are continuing improvements in antenna design,

UNANIMOUSLY RECOMMENDS

1. that the radioastronomy service continues to place observatories in locations which have good natural protection from harmful interference;

2. that the radioastronomy service not rely on protection from harmful interference due to the spurious emissions of geostationary satellites when observing within 5° of the geostationary-satellite orbit;

3. that the radioastronomy service should make all practicable efforts to minimize the side-lobe gains of radioastronomy antennas;

4. that, in bringing stations into operation in frequency bands not covered by the provisions of Appendix 8 to the Radio Regulations, administrations should take into account, to the maximum extent practicable, the special risk of interference to radioastronomy observations due to spurious emissions from high-powered terrestrial stations or from space stations;

5. that, for the special case of geostationary space stations, administrations should take into account, to the maximum extent practicable, the objective of the radioastronomy service to be free of harmful interference from spurious emissions when observing more than 5° from the geostationary-satellite orbit.

REPORT 696-1 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN RADIOASTRONOMY AND OTHER SERVICES

(Question 5/2 and Study Programme 5A/2)

(1978-1982)

1. Introduction

1.1 The characteristics of the radioastronomy service are described in Report 852. In Report 224 the harmful interference levels are derived. The material contained in these Reports is applied here to a consideration of sharing between radioastronomy and other services. Sharing is first discussed in general terms and some examples of sharing problems are described. This is followed by a quantitative examination of sharing, starting with a consideration of the protection criteria and continuing with the application of these criteria to geographical sharing. An analysis of interference received from a transmitter within line-of-sight of a radioastronomy observatory emphasizes the difficulty of sharing with a space service or with a terrestrial service involving airborne transmitters. Finally there is a case-by-case examination of sharing problems in each of the bands below 40 GHz where a radioastronomy interest is recognized in the Radio Regulations.

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* This Report is brought to the attention of Study Group 5 with a view to their comment on the propagation data set out herein. This Report is also brought to the attention of Study Group 9.

1.2 Before proceeding with a discussion of conditions which can produce harmful interference, it is useful to consider the question of whether any harmful interference can be tolerated by the radioastronomy service. The answer must be somewhat subjective. Many radioastronomers would reply that no interference above the levels specified in Report 224 can ever be tolerated. Yet many radioastronomers do excellent work in the intervals between bursts of strong interference. The best answer is probably that strong, recognizable interference can sometimes be tolerated if it occurs in short bursts for a small fraction of the total time; but that an insidious danger to the radioastronomy service lies in interference which is just below the power level at which it can be recognized and is present for large fractions of the total time. In this case there may be no means of detecting that interference has occurred, even in subsequent examination of the data, and erroneous results may be deduced.

1.3 Interference to radioastronomy from spurious radiations of transmitters in other bands, and problems of adjacent band interference, are important factors which can reduce the efficient use of the radio spectrum. These matters are not discussed in detail in this Report although there are some brief references to the problem. A detailed discussion will be found in Report 697.

2. General remarks on sharing

2.1 Radioastronomy observatories are usually located at sites specially chosen to minimize interference from other services. The sites are usually at a considerable distance from the major terrestrial sources of interference and frequently are screened by nearby high ground. With this protection for the observatory and the protection afforded by the curvature of the Earth, sharing with terrestrial transmitters is possible when the transmitted power is low and there is sufficient geographical separation. However, with the very sensitive systems used by radioastronomers, large separations are usually necessary. Signals propagated via the mechanism of tropospheric scatter can lead to harmful interference levels at great distances and for a large fraction of the time. In meteorological conditions leading to anomalous tropospheric propagation, the distance from which interference can be caused by ground transmitters is likely to be increased by several hundred kilometres but these conditions will occur only infrequently in most parts of the world.

2.2 Transmitters carried in aircraft, spacecraft or balloons can remain within line-of-sight of an observatory to very great distances. The advantages associated with a carefully selected observatory site and the attenuation around the curvature of the Earth are both lost. As an example of the sharing problem, the data in § 7.13.2 show that a 30 mW transmitter with an omnidirectional antenna on a geostationary satellite (36 000 km altitude) and sharing a frequency near 2.7 GHz with a radioastronomy receiver could interfere when its signal is received through the 0 dB side lobes of the radioastronomy antenna. Furthermore, it is likely that a satellite, because of its high angle of elevation, may appear in the near side-lobe region of the antenna. In that case, an e.i.r.p. from the satellite of 3 μW could cause harmful interference. A satellite, whether geostationary or in low orbit, illuminates a large segment of the Earth's surface and a few satellites could prevent useful observations from being made anywhere on Earth at the satellite frequency. In general the radioastronomy observatory will be interfered with even if it lies well outside the service area of the satellite antenna.

2.3 At HF any interference received is almost invariably propagated via the ionosphere. In this case too the selection of the observatory site and the curvature of the Earth do not provide protection. If the operating frequency is less than about 4 times the critical frequency of the F-layer, interference can be experienced from a transmitter located anywhere on the Earth. The special problems associated with interference at frequencies less than 20 MHz are outlined in Repot 699. Some detail is also included in § 7.3 of this Report.

2.4 Reflections from aircraft are likely causes of harmful interference in a shared band even when the terrestrial transmitter is distant, and the possibility of interference by reflections from low-orbit satellites also exists. A single reflecting body will be effective for only a short time and the interference problem will depend on the density of the air or space traffic. As a result of space activities there are a large number of metallic objects in orbit around the Earth.

As an illustration we may take 100 m^2 as the scattering cross-section of a large aircraft, and assume that the aircraft is equidistant from the transmitter and radioastronomy observatory. With the aircraft flying at a height of 12 km, the horizon distance is 450 km and one may ask under what conditions can harmful interference be propagated to the horizon. At 408 MHz, for example, if it is assumed that the gain of the side-lobes of the receiving antenna is 0 dBi, the minimum e.i.r.p. power to cause harmful interference is 6 kW. The range at which aircraft reflected interference can be harmful is thus limited primarily by the horizon distance; i.e. 450 km for an aircraft at a height of 12 km. This can mean that interference from a high-power transmitter, as far away as 900 km from the radioastronomy observatory, could be harmful.

One must also consider scattering from artificial satellites. Here the horizon distance is greatly increased and the satellite will be within simultaneous line-of-sight of a vast area of the Earth. The scattering cross-section is perhaps a factor of 100 below that of an aircraft, but this will be more than counterbalanced if, because of the high angle of elevation of the satellite, it appears in the near side-lobes of the radioastronomy antenna, where gains may be greater than 30 dB. However, the scattered power density on the telescope would be significant only for satellites with orbits below 1000 km. Such satellites have a high angular velocity and would appear in the near side-lobe region of the radioastronomy antenna for only a very short time and, as in other interference problems, this would need to be taken into account in determining the severity of the interference.

2.5 For certain types of radioastronomical measurement in shared bands, reflections of terrestrial transmissions by the Moon can cause serious interference. The Moon is of great importance to radioastronomy for two main reasons. The first, and most important, is that because both the shape and the motion of the Moon are known, the observation of lunar occultations of radio sources provides an accurate method for determining their angular positions and, in some instances, their sizes. Occultation of a particular radio source by the Moon occurs very infrequently and it is important that there should be no harmful interference at these times. The second use of the Moon is as a calibration source, because its effective temperature over a range of frequencies is accurately known.

In both applications the main beam of the radio telescope is directed at the Moon and the observations are, therefore, particularly susceptible to interference by signals reflected from the lunar surface. Illumination of the Moon by terrestrial transmitters, either intentionally or otherwise, in frequency bands used by the radioastronomy service, can thus cause harmful interference; occultation measurements have already been prevented on many occasions by radar pulses reflected from the Moon.

2.6 In addition to those listed above a number of other propagation mechanisms can result in severe interference to the radioastronomy service. These include reflections from sporadic-E ionization and from meteor trails and scattering from free electrons in the ionosphere. These mechanisms are effective at metre wavelengths. The first two can result in severe interference but the frequency of occurrence is not high. The ionospheric scattering mechanism would require high-power transmissions to produce harmful interference levels. All of these mechanisms are effective over large distances. At centimetric and millimetric wavelengths scatter from heavy rain can produce interference at large separations between transmitter and observatory. In most climates such rain does not occur frequently enough to be a major concern.

3. Protection criteria for the radioastronomy service

3.1 An important protection criterion for radioastronomy is the power level of the interference considered harmful. Values are given in Table I of Report 224 for continuum observations and in Table II for spectral line observations. In each case these levels are presented for frequency bands for which there is some measure of protection for radioastronomy in the Radio Regulations. The specification of harmful interference as the input power to the receiver in dBW, presented in column 8 of Table I and column 7 of Table II of Report 224 is adopted in this Report.

3.2 A second criterion affecting the protection of the radioastronomy service relates to the fraction of the total sky for which radioastronomy observations are to be protected. To provide protection over the entire sky would require that the harmful interference level not be exceeded when the main beam of the radioastronomy antenna is directed towards the interfering transmitter, or towards the horizon in the direction of the interfering transmitter when the latter is beyond the horizon of the telescope. In fact radio astronomers are usually prepared to accept some restriction of their sky coverage. Based on the generalized radiation pattern for space research earth station antennas (Recommendation 509) the antenna gain falls to 0 dB at 19° from the main beam and to −10 dB at 47°. For interfering transmitters beyond the horizon the use of −10 dB for the radioastronomy antenna gain restricts observations to elevation angles greater than 47° and is unacceptable. The value of 0 dB for the gain of the radioastronomy antenna when calculating interference power into the receiver input has been adopted in this Report and means that observations are restricted to elevation angles greater than 19°. It should be noted that if observations were required down to the horizon the level of interference considered harmful would be 50 dB to 80 dB less, depending upon the frequency.

3.3 A third criterion which must be considered is the percentage of time that a harmful interference level may be exceeded without serious damage to the operation of the service. This factor is not considered in Report 224 or in any other CCIR document pertaining to radioastronomy. In this Report a single percentage value has been chosen for all cases although it is clear that some observations are more susceptible to brief periods of interference than others. There is an improvement in the efficient use of the radio spectrum if protection criteria are no more rigorous than necessary. Consequently it has been accepted in this Report that the harmful interference levels of

Report 224 may be exceeded 10% of the time. This is sufficiently infrequent that observations affected by interference stand out from those not affected and at the same time does not exact an exorbitant penalty if observations can be repeated. During periods of interference from signals propagated by tropospheric scatter, observations 10 dB or 15 dB less sensitive stand a good chance of being successful. Strong interference occurring only 10% of the time because transmissions are limited to that period of time, would not be acceptable. Less sensitive observations would not be possible during the interference period. It should be noted that the detailed characteristics of the interference and their relation to the type of radioastronomical observation being made will need to be taken into account.

3.4 It must be emphasized that for some types of observation a 10% failure rate due to interference imposes severe restrictions on the radioastronomer. For some observations a high probability of success is desirable because of the difficulty or impossibility of repeating them. An example is an observation of a lunar occultation. It might be necessary to wait up to 19 years before the Moon returns to the same position in the sky so that the observation can be repeated. Some other types of observation require simultaneous measurements at a number of sites, at each of which success must be obtained if the experiment as a whole is to be successful. Very long base-line interferometry (VLBI) provides an example; observations are made simultaneously at a number of observatories hundreds or thousands of kilometres apart. The experiment may be severely damaged if observations at any one of the observatories are ruined due to interference. An observatory having difficulties of this type will require special national arrangements at certain frequencies at certain times.

3.5 The three protection criteria so far considered, the power threshold of harmful interference, the percentage of sky which is to be protected and the fraction of observing time which is to be protected, all relate directly to geographical sharing; that is, the geographical spacing of two services which permit both to work at the same frequency at the same time. In sharing between some services additional protection may be obtained by the use of orthogonal polarizations. This is not a useful technique for protecting radioastronomy since different polarizations must be used for some observations and at the 0 dB gain level of an antenna the cross polarization may be large.

3.6 It should be noted that except in rare cases sharing with the radioastronomy service is possible only with considerable geographical separation. Bands allocated to radioastronomy are too narrow to permit assignment of different parts of a shared band to the different services. Any reduction in bandwidth decreases the sensitivity of the observations. Time sharing is usually not feasible because parts of the otherwise observable sky will rise and set during the period used by the other service. This is especially important for synthesis interferometers because the radioastronomical sources usually need to be observed during the entire period that they are above the horizon. Limited time sharing to permit special observations at a radioastronomy site may be possible, and may indeed be necessary on occasion, as mentioned for lunar occultation observations in an earlier paragraph.

3.7 Only geographical sharing is considered in the remainder of this Report.

4. Basic relations for calculating geographical separation needed for sharing

4.1 If geographical sharing is to be successful the interfering transmitter and the interfered-with receiver must be separated by a distance at which interference is not considered harmful. Using the criteria developed in the previous section the attenuation over this distance must be sufficient to reduce the received signal below the appropriate level of Table I or II of Report 224 for all but 10% of the time. Report 382 defines a basic transmission loss $L_b(p)$ as:

$$L_b(p) = P_t + G_t + G_r - P_r(p) \tag{1}$$

where:

- $L_b(p)$: minimum permissible basic transmission loss (in dB) for p% of the time; this value must be exceeded by the actual transmission loss for all but p% of the time;
- P_t : transmitting power level (in dBW) in the reference bandwidth at the input to the antenna;
- G_t : gain (in dB relative to isotropic) of the transmitting antenna;
- G_r : gain (in dB relative to isotropic) of the receiving antenna in the direction of the transmitter;
- $P_r(p)$: maximum permissible interference power (in dBW) in the reference bandwidth to be exceeded for no more than p% of time at the receiver input.

Using the protection criteria of the previous section $G_r = 0$ dB, $p = 10\%$, and equation (1) assumes the form:

$$L_b(10) = P_t + G_t - P_r(10) \tag{2}$$

where P_r is to be taken from column 8 of Table I or column 7 of Table II of Report 224.

For the special case of line-of-sight transmission, L_b has a simple analytical form and equation (2) may be written as:

$$20 \log (4\pi d) - 20 \log (\lambda) = P_t + G_t - P_r \tag{3}$$

where:

d: distance in metres between transmitter and receiver,

λ: wavelength in metres.

This particular case is considered in § 5. It should be noted that the free-space signal is not variable and the percentage of time criterion is not pertinent.

5. Sharing within line-of-sight

5.1 It is rarely possible for radioastronomy to share successfully with any other service whose transmitters are within line-of-sight of the observatory. Figure 1 exhibits this fact. Using equation (3) the maximum e.i.r.p. which would not result in harmful interference to the radioastronomy service has been calculated for two distances using the frequencies and harmful interference levels of Table I of Report 224. One distance is representative of the maximum distance which is possible for a terrestrial station within line-of-sight. It is the horizon distance for an airborne transmitter at a height of 20 000 metres. The other is based on the distance of the geostationary orbit and is consequently representative of the maximum distance of most spaceborne transmitters not on deep-space missions. Atmospheric absorption has not been taken into account. The curves are applicable for a clear dry atmosphere. Above 10 GHz some additional protection would be accorded by a humid atmosphere or by precipitation. The frequency range most affected by absorption, 50-70 GHz, has been blanked out since ground-based radioastronomical observations are impossible throughout most of this band.

5.2 It is clear from Fig. 1 that sharing with a terrestrial transmitter within line-of-sight is not likely to be possible at frequencies below 10 GHz because of the severe restriction sharing would impose on the transmitter e.i.r.p. Even for frequencies up to 50 GHz either the transmitter power must be measured in milliwatts or the transmitting antenna must discriminate strongly against the direction of the observatory, if sharing is to be possible. For transmitters in space with typical power in excess of 1 W, sharing will not be possible even outside the coverage area of the spaceborne antenna for frequencies up to about 10 GHz. Between 10 GHz and 50 GHz sharing is not likely to be possible within the coverage area of the spaceborne antenna. When sharing with a geostationary space transmitter, there will also be an additional restriction on the radio-astronomy service. Equation (3) and consequently Fig. 1 are based on the assumption of 0 dB gain of the radioastronomy antenna. To avoid having a higher gain in the direction of the satellite, the radioastronomer would be required to take no observations within a 38° band centred on the geostationary satellite orbit.

6. Sharing with terrestrial services beyond the horizon

6.1 In § 7 there is a brief discussion of the sharing situation facing radioastronomy in each of the frequency bands below 40 GHz where the Radio Regulations recognize a radioastronomy interest. In many of these bands a calculation has been made to determine a separation distance necessary to protect radioastronomy from interference from a hypothetical active system operating in the band. The calculation is based on equation (2) where $P_r(10)$ is the maximum permissible interference power in dBW and is taken from column 8 of Table I of Report 224 for continuum observations or column 7 of Table II for spectral line observations. P_t and G_t are derived from the choice of the hypothetical system with which radioastronomy must share. An attempt has been made to choose an active system representative of the most likely source of interference in a particular band. However in some bands the variety of systems used in different parts of the world means that there is no single representative system. G_t, the transmitting antenna gain in the direction of the observatory is usually taken as G_T, the maximum gain of the transmitting antenna. In some cases the transmitting antenna beam is deliberately directed away from the observatory and $G_t = 0$ dBW is more appropriate. P_t is the power transmitted by the active service within the bandwidth B_r of the radioastronomy receiver. If the transmitter power P_T is distributed over a bandwidth B_t where $B_t > B_r$ then:

$$P_t\,(\text{dBW}) = P_T\,(\text{dBW}) - 10 \log (B_t/B_r) \qquad \text{for } B_t > B_r \tag{4}$$

on the assumption that the transmitter power has a uniform spectral density. When the bandwidth of a single transmitter is less than that of the radioastronomy receiver then a number of transmitting channels within the receiver bandwidth may be occupied. It is unlikely that all such channels are operating simultaneously and at the same distance and an arbitrary decision has been made to cut the bandwidth ratio term in half.

$$P_t\,(\text{dBW}) = P_T\,(\text{dBW}) + \tfrac{1}{2}\,[10 \log (B_r/B_t)] \qquad \text{for } B_t < B_r \tag{5}$$

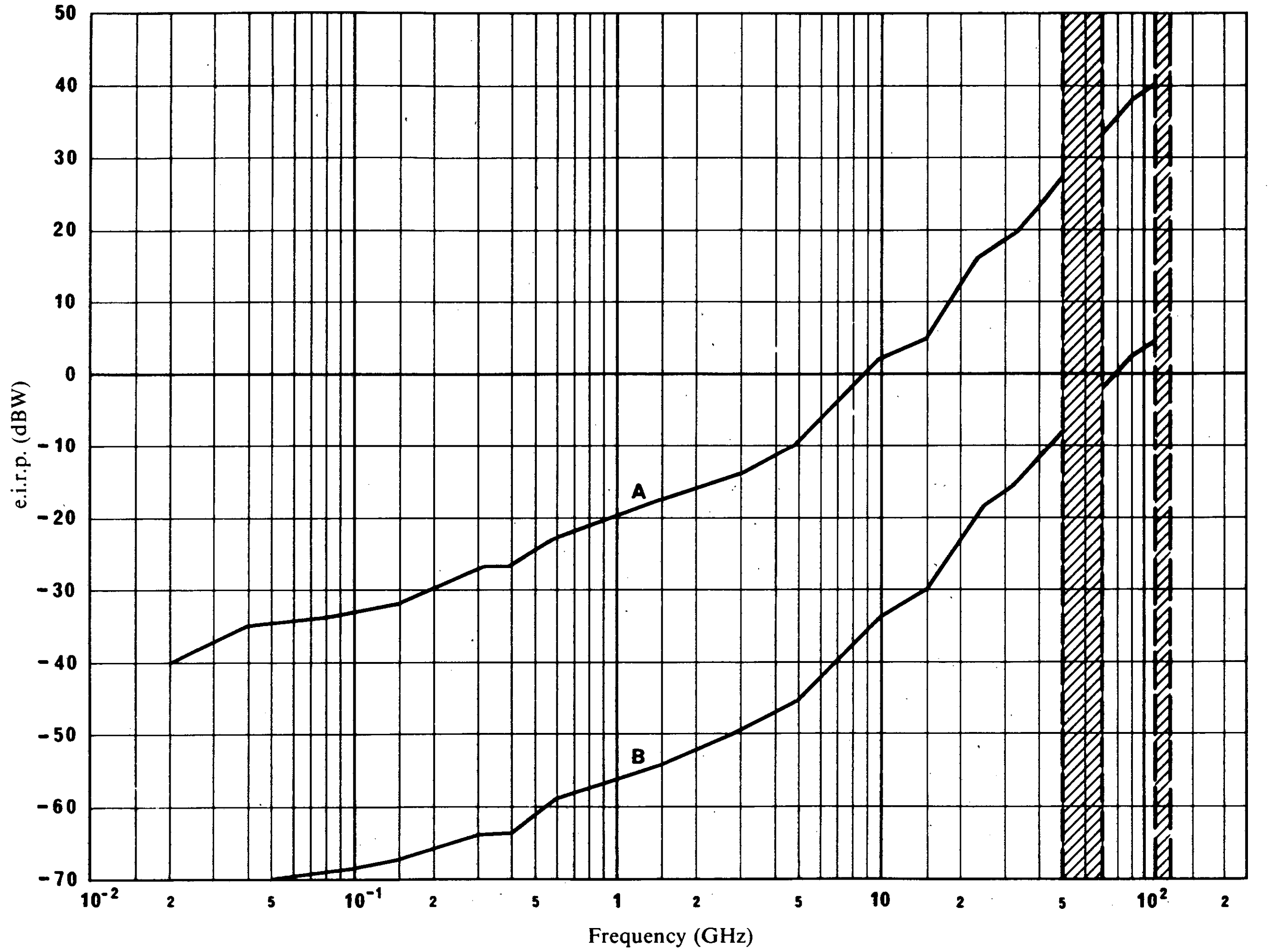

FIGURE 1 – *Maximum allowable e.i.r.p. for sharing transmitters within line-of-sight * of a radioastronomy observatory*

Curves A: geostationary space transmitter
B: terrestrial transmitter at 600 km

Regions of high atmospheric attenuation

* Ducting may cause an interference problem at distances greater than normal line-of-sight, depending upon climatic and topographic factors (see Report 718).

6.2 Following a choice of P_t and G_t and with $P_r(10)$ selected from Report 224, the required value of $L_b(10)$ is calculated from equation (2). For most of the bands allocated to radioastronomy the propagation mechanism primarily responsible for interfering signals at the 10% level is tropospheric scatter. For frequencies up to 3 GHz the calculation of L_b as a function of distance is based on Report 238. With that Report the basic transmission loss can be calculated for a number of different climatological regions. Although the calculations were in fact performed for a number of climates, only the results from one (climate 6) are included in this Report. The over-water climates were eliminated because most existing radioastronomy observatories are distant from major bodies of water and of those close to water few are likely to suffer interference from the seaward side. There are five climates dealing with propagation over land. Of these climates, Types 2, 6 and 7a (continental sub-tropical, continental temperate and maritime temperature overland) give almost identical results for the 10% of time considered in this Report. The other two land climates (Types 1 and 4, equatorial and desert) give smaller separation distances, as much as 200 km smaller. The use of the single climate Type 6 results in a considerable simplification and provides a realistic "worst case". Sharing may be appreciably easier in some areas of the world and should be more difficult only where interfering signals may reach an observatory over a water path.

6.3 Report 238 is intended for propagation calculations below 1 GHz although it is being used above that frequency in this Report. When this Report was prepared Study Group 5 documentation did not contain an appropriate Report for use above 1 GHz. Of necessity, use was made of propagation material contained in the CCIR Report of the Special Joint Meeting, Geneva, 1971. Tropospheric scatter is the dominant propagation mode at the 10% of time required, and the SJM Report presents a simple method of calculation. Annex 10-1 of the SJM Report contains a series of graphs from which the basic transmission loss, including atmospheric attenuation, may be obtained as a function of distance. The Report of the SJM presents results for three climates, only one of which involves overland propagation. This climate (Type A) agrees well with Type 6 of Report 238 at 3 GHz where a comparison of the two methods shows an agreement to about 3 dB. Revisions to documents made at the 1981 Final Meetings of Study Group 5 would now permit the calculations to be made with up-to-date propagation material. It is believed that the use of Report 238, and Report 569, would result in little change to the results presented in this Report. However, a definite statement must await the recalculation of the propagation problems using these new Reports.

6.4 Some additional assumptions must be made about the nature of the radioastronomy site. In each case it is assumed that the radioastronomy antenna is at a height of 25 m. The result is not strongly dependent on this assumption. Because most radioastronomy sites are chosen with the aim of reducing interference problems, it is appropriate to assume that the local horizon is above the horizontal. The results of two calculations are presented: one for a site which is moderately well protected with a horizon angle of 1° and the other for a well-protected site with a horizon angle of 4°.

7. Sharing considerations for all radioastronomy bands below 40 GHz

7.1 In the following paragraphs a brief description is given of the sharing situation in each of the radioastronomy bands below 40 GHz. For most bands a separation distance necessary for sharing between a hypothetical reference circuit and radioastronomy has been calculated as described in the previous sections. Table I lists the details of the system and the results of the propagation calculations. Column 1 lists the frequency for which the calculations have been made. Columns 2, 3 and 4 list the power (P_t), antenna gain (G_t) and e.i.r.p. of the interfering transmitter. Column 5 lists the bandwidth (B_t) over which the transmitted power is assumed to be distributed with uniform power spectral density. P_r in column 6 is the harmful interference level (from Report 224). A footnote indicates that a spectral line observation is being considered and the harmful interference level is taken from Table II of Report 224. Column 7 is the receiver bandwidth (B_r) which is also taken from Report 224. Column 8 is for the basic transmission loss (L_b) calculated from equation (2). Columns 9 and 10 list the separation distances (d) for radioastronomy sites with moderate shielding (horizon angle = 1°) and good shielding (horizon angle = 4°).

7.2 It should be emphasized that the calculated geographical separation is based on particular protection criteria and particular models of the interfering service and propagation path. The protection criteria (§ 3) include harmful interference levels from Report 224, radioastronomy antenna gain of 0 dB in the direction of the interfering transmitter and 10% as the percentage of time that the harmful interference level is exceeded. Specific choices of transmitter power, e.i.r.p. and bandwidth are assumed. The transmitted power spectral density is assumed to be uniform and the transmitting antenna height is in the range of 10 m to 20 m above ground. The propagation path is generalized and the chosen climate is a "worst case" for over land paths. Site protection at the radioastronomy observatory has been simplified to the consideration of two angles of the horizon above the horizontal. It is believed that the chosen parameters represent many of the sharing situations. However in any particular case the actual parameters may be different and may result in the separation distance requirement being significantly different.

TABLE I – *Summary of sharing calculations*

(For explanation of column headings see § 7.1)

Frequency	Assumed interfering transmitter				Assumed radioastronomy receiver		Propagation path parameters		
(MHz)	P_t (dBW)	G_t (dB)	*e.i.r.p.* (dBW)	B_t (MHz)	P_r (dBW)	B_r (MHz)	L_b (dB)	d(1°) (km)	d(4°) (km)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
13			10	0.01	– 178	0.05		> 4000 (2)	> 4000 (2)
25			10	0.01	– 188	0.12			
38	13	3	16	0.02	– 190	0.50	213	1000	790
80	15	10	25	0.03	– 195	1.6	223	1000	775
408	14	4	18	0.025	– 203	3.9	232	860	660
608			40	6.0	– 202	6.0	242	950	765
			50		– 202		252	1090	915
			60		– 202		262	1220	1055
1400	27	0	27	0.50	– 220 (1)	0.02	233	590	410
1665	7	38	45	3.5	– 220 (1)	0.02	242	700	500
	7	0	7		– 220		204	260	175
4975	10	44	54	40	– 207	10	255	715	600
	10	0	10		– 207		211	200	120
10650	7	44	52	100	– 205	100	257	625	510
	7	0	7		– 205		212	150	115
22235	0	0	0	20	– 210 (1)	0.25	191	100	< 100
	0	50	50		– 210 (1)		241	340	230

(1) Spectral line observation.

(2) See text: signals are propagated to very large distances by ionospheric propagation.

7.3 *Sharing in band 7, 13.36-13.41 MHz and 25.55-25.67 MHz*

7.3.1 The Radio Regulations show two allocations for radioastronomy in band 7. The band 13 360-13 410 kHz is shared with the fixed service. The band 25 550-25 670 kHz is to become an exclusive radioastronomy band but fixed stations will continue to operate during an extended transition period.

7.3.2 Radio communications in these bands rely principally upon reflections from the F region of the ionosphere for long-distance propagation. Radioastronomical observations from the Earth are possible only when the electron density is sufficiently low and relatively free of irregularities on the kilometre scale (Report 699).

7.3.3 Conditions in the ionosphere affecting both radioastronomical observations on the one hand, and reflection propagation on the other, vary with time of day, time of year and solar activity as well as with the latitude of the observatory. Three situations relating to band sharing can be distinguished depending on the relative values of the observing frequency ν_o and the critical frequency of the F-region ν_c:

(a) $\nu_o < \nu_c$: ground-based observations are not possible due to the total reflectivity of the ionosphere. Reflection propagation is possible.

(b) $\nu_c < \nu_o < 4\ \nu_c$: observations can be made within a zenith cone angle. $\varphi = \arccos \nu_c/\nu_o$ (Report 699): reflection propagation is possible. Radioastronomical observations will be susceptible to interference received at zenith angles greater than φ. A system radiating 10 W from an antenna of low directivity at 4000 km distance will produce interference more than 100 dB in excess of the harmful levels.

(c) $\nu_o > 4\ \nu_c$: reflection propagation is not generally possible. Observations are susceptible only to directly propagated interference.

7.3.4 For the allocation near 13 MHz, it is apparent from Table I, Report 699 that, even in years near sunspot minimum, situation *(b)* will apply for at least 50% of the time at mid-latitude sites, and sharing is not realistic. Situation *(a)* may prevail for a few hours near midday at times of maximum sunspot activity.

7.3.5 For the allocation near 25 MHz, situation *(c)* may prevail for about 80 to 90% of the time at mid-latitudes for a few years around minimum sunspot activity. However, averaged over a typical sunspot cycle, situation *(b)* will prevail for more than 20% of the time. Hence sharing is undesirable in this band as well.

7.4 *37.50-38.25 MHz*

7.4.1 In the band at 38 MHz, radioastronomy has a world-wide secondary allocation and there is a footnote urging administrations to take all practicable steps to protect the service from harmful interference. The fixed and mobile services have primary status in the band. Although the systems operating within these services, in this band, display a wide range of characteristics, radiated power of 20 W or 30 W from an antenna of low directivity is representative of many systems. An e.i.r.p. of 16 dBW has been chosen for the standard system used in interference calculations. Bandwidths are typically of the order of 20 kHz to 30 kHz and there are 15 to 25 channels within the 0.75 MHz band allocated to radioastronomy.

7.4.2 It is arbitrarily assumed that five transmitters are potentially harmful to radioastronomy observations. Table I lists the details and the results.

7.4.3 The large separation distances, large even for a well-shielded site, make sharing difficult. In addition, propagation via reflections from sporadic-E layers in the ionosphere needs to be taken into account. Recommendation 534 provides the data. Basic transmission loss over paths of 1000 km to 2500 km will be less than 213 dB for more than 10% of the time during summer months in much of the world. This propagation mode will be much less important during winter months and sharing considerations will be dominated by the tropospheric scatter field.

7.5 *73-74.6 MHz and 79.75-80.25 MHz*

7.5.1 There are different regional allocations to radioastronomy in this part of the spectrum. The bands are 73 MHz to 74.6 MHz and 79.75 MHz to 80.25 MHz and the sharing is with the fixed, mobile, aeronautical radionavigation and broadcasting services. With this variety of services and different regional allocations there is no one system which characterizes the general usage. However a reference system with a 30 W transmitter feeding an antenna of 10 dB gain has been chosen as representative of the fixed service. The antenna height is taken to be 10 m and seven similar transmitters are assumed to be operating in the band at approximately the same distance from the observatory. Table I shows the results of the calculation of basic transmission loss and required separation distances.

7.5.2 With a separation distance as large as 775 km for a well-shielded site, sharing with radioastronomy is difficult. An additional difficulty may be the affect of propagation via the sporadic-E layer although Recommendation 534 indicates that this mechanism is more likely to be important at the 1% level rather than 10%.

7.6 *150.05-153 MHz*

The fixed and mobile services have primary allocations in all three regions. Radioastronomy has a primary allocation in Region 1 but is given no recognition in either of the other two regions except for an additional primary allocation, by footnote, to radioastronomy in Australia and India. No calculation of a separation distance has been made. The intensity of the troposphere scatter signal will certainly be less than at 75 MHz and ionospheric propagation will not be a factor but the separation distance required for protection of the radioastronomy service will still be large.

7.7 *322-328.6 MHz*

At the WARC-79, radioastronomy in this band was elevated from a footnote requesting administrations to bear in mind the radioastronomy interests to a shared (with fixed and mobile) primary allocation. In addition a footnote permitting space emissions in the mobile-satellite service was deleted. Protection for radioastronomy has been improved but the required separation distance from a transmitter on the ground has not been calculated. In some locations the most likely source of interference could be airborne transmitters. Figure 1 shows that an e.i.r.p. of less than 1 μW could cause interference at a distance of 600 km if within line-of-sight.

7.8 *406.1-410 MHz*

7.8.1 In the band 406.1-410 MHz, radioastronomy shares primary status with the fixed and mobile, except aeronautical mobile, services. A typical system in the land mobile service has a transmitter power of 25 W into an antenna of low gain at a height of 10 m. With a bandwidth of 25 kHz there is in excess of 150 possible channels within the 3.9 MHz bandwidth. It is assumed that just 12 are operating at the same time and within a narrow interference range. A total basic transmission loss of 232 dB is required.

7.8.2 The required separation distances are 860 km for a moderately well-protected site and 660 km for a site with good shielding.

7.9 *608-614 MHz*

7.9.1 Radioastronomy has different levels of protection in the three Regions in this television band near 610 MHz. Since high power television stations may be located in the adjacent channels, adjacent-channel interference can be a problem. This is considered in Report 697. Here only the possibility of co-channel interference from a sharing television transmitter is considered.

7.9.2 As an example, separation distances for sharing with three different classes of television stations are shown in Table I. These three classes are:

Class A:	10 kW e.i.r.p.	antenna height = 100 m
Class B:	100 kW e.i.r.p.	antenna height = 150 m
Class C:	1000 kW e.i.r.p.	antenna height = 300 m

7.9.3 The bandwidths of the radioastronomy receiver and television transmitter are assumed to be equal. With −202 dBW as the harmful interference level, the required basic transmission losses are 242 dB, 252 dB and 262 dB for Classes A, B and C respectively.

7.9.4 The separation distance required to reduce interference to an acceptable level is very large even for the lowest power television transmitter listed above. The problem is complicated by the possibility of additional interference from adjacent channels as described in Report 697.

7.10 *1330-1400 MHz*

7.10.1 The region of the frequency spectrum in the vicinity of the 21 cm wavelength spectral line of hydrogen is of very great importance to radioastronomy. This importance has been recognized by the world-wide allocation to radioastronomy, in the exclusively passive band 1400 MHz to 1427 MHz for both line and continuum observations. In recent years, observations of the same hydrogen spectral line, Doppler-shifted to lower frequencies, have grown in importance. This shift to lower frequencies is the result of the large velocities at which distant galaxies are moving away from the galaxy in which the Sun is located. The importance of these observations of the redshifted hydrogen line was recognized in a footnote which gives some protection to radioastronomy in a band below 1400 MHz. In this band radiolocation has primary status in Regions 2 and 3 and shares primary status with the fixed and mobile services in Region 1.

7.10.2 A typical radiolocation system used for aeronautical purposes in this band is a ground-based radar with 500 kW peak pulse power and an antenna gain of 34 dB. If the dynamic range of the radioastronomy receiver is sufficient to accommodate the radar peak power, the important parameter, with respect to interference, is the average power into the radioastronomy receiver during its integration period. For a radar scanning 360°, the average power transmitted in the direction of the radioastronomy observatory is of the order of the average power from the transmitter. The actual power so transmitted is a function of the radar antenna pattern and of the nature of the scan. With the assumption that the radar has a duty cycle of 0.001, the average power is 500 W. For a spectral line observation, Table II of Report 224 is used, and the harmful interference level is −220 dBW in a 20 kHz band. The radar output power of 500 W is assumed to be distributed uniformly over 0.5 MHz (a 2 μs pulse). This reduces the power into a single channel of the radioastronomy receiver by 10 log (500/20) = 14 dB. The required basic transmission loss is then 233 dB. A basic transmission loss of 233 dB is realized at a distance of 590 km from a radioastronomy site with moderate shielding and at 410 km from a site with good shielding.

7.10.3 It must be noted that the peak power into the receiver input is −142 dBW when the average interference is just at the harmful level. This is about 15 dB above the receiver noise power in a 0.5 MHz band and, particularly if more than one radar signal is in the passband of the receiver front end, non-linear effects may invalidate the analysis in terms of average power.

7.11 *1400-1427 MHz*

7.11.1 This is an exclusively passive band and there is consequently no interference to radioastronomy from shared services. The possible sources of interference are transmitters in adjacent bands and spurious emissions from other out-of-band transmitters. This topic is dealt with in Report 697.

7.12 *1610.6-1613.8 MHz, 1660-1670 MHz and 1718.8-1722.2 MHz*

7.12.1 These three bands are designed for observations of spectral lines of the hydroxyl radical. The wider bandwidth of the middle allocation permits Doppler-shifted observations of lines from extra-galactic sources. Although the observing requirements are similar, the sharing problems are very dissimilar.

7.12.2 In the band 1610.6-1613.8 MHz, radioastronomy has a secondary allocation and the primary table allocation is aeronautical radionavigation. The band is reserved for airborne electronic aids to air navigation (footnote 732) and line-of-sight transmissions from these airborne systems must count as the most likely mechanism for interference.

7.12.3 The band 1660-1670 MHz consists of three sub-bands. In each sub-band radioastronomy has a primary allocation but the sharing services are different. In the most important sub-band, 1660.5-1668.4 MHz, the fixed and mobile, except aeronautical mobile, services are listed in the Table as secondary services although (footnote 737) lists forty administrations in which these services have primary status until 1990. There are a variety of fixed systems in this region of the spectrum. A reasonable representative is a low capacity system with 3.5 MHz bandwidth transmitting 5 W through an antenna of 38 dB gain. Table II of Report 224 lists the harmful interference level as −220 dB into a 20 kHz wide channel of a spectral line receiver. Separation distances are large if the fixed-service antenna is directed at the observatory. However where the routes can be chosen to avoid pointing at the observatory a separation distance of 175 km is sufficient for a well protected observatory site and 260 km for a site with moderate protection.

7.12.4 In the band 1718.8-1722.2 MHz, the fixed service has a world-wide primary allocation and the mobile service is primary in Regions 2 and 3 and secondary in Region 1. Radioastronomy has a secondary allocation. The requirements for separation distances to protect radioastronomy from fixed-service operations would be very similar to those set for the 1660-1670 MHz band in § 7.12.3.

7.13 *2655-2700 MHz*

7.13.1 In the upper 10 MHz of this band, radioastronomy has a primary allocation and an attempt has been made to create a purely passive band. However, a large number of administrations have additional allocations by footnote to the fixed and mobile except aeronautical mobile services.

7.13.2 In the 2655-2690 MHz band, radioastronomy has a secondary allocation and the primary services are the fixed and mobile and broadcasting satellite. The fixed-satellite service is also present in the Table for Regions 2 and 3. Clearly the development of this band by the broadcasting-satellite service would make the band unusable for radioastronomy. Figure 1 shows that a geostationary transmitter radiating 30 mW from the far side lobes of a satellite antenna (0 dB gain) can result in harmful interference to radioastronomy observations being conducted in directions far from the satellite position.

7.14 *3260-3267 MHz, 3332-3339 MHz, 3345.8-3352.5 MHz*

In footnote 778 of the Radio Regulations administrations are urged to take all practical steps to protect spectral line observations in the three bands mentioned above. The radical CH is responsible for all three lines. The primary table allocation is to the radiolocation service. Calculations to determine the separation distance required to protect radioastronomy have not been made. However, for sharing with ground-based radars the situation will be similar to that described in § 7.10 for the 1330-1400 MHz band but the basic transmission loss will be some 10 dB larger at the higher frequency. A more difficult sharing problem exists if the radars are airborne and are within line-of-sight of the observatory to a distance of perhaps 600 km.

7.15 *4800-5000 MHz*

7.15.1 In the 4800-4990 MHz band, radioastronomy has a secondary allocation in the Table. Fixed and mobile are the primary services. However, footnotes single out the bands 4825-4835 MHz and 4950-4990 MHz for special treatment. The first of these bands is for the observation of formaldehyde in interstellar space; one footnote excludes the use of aeronautical mobile and another urges administrations to take all practicable steps to protect radioastronomy. The use of aeronautical mobile is also excluded from the band 4950-4990 MHz. With the exclusion of the aeronautical service the sharing situation is similar to that described in the next paragraph.

7.15.2 Radioastronomy is on an equal primary basis with the fixed and mobile except aeronautical mobile services in the band 4990-5000 MHz. Fixed-service usage in this band may be either low power radio-relay systems or tropospheric scatter systems. Because of the very high average power used in the latter system, sharing with radioastronomy is very difficult. The radio-relay systems with perhaps 10 W transmitter power, 40 MHz RF bandwidth and 44 dB antenna gain presents an easier sharing problem. The separation required for sharing is, if the radio-relay system antenna is directed at the radioastronomy observatory, 715 km for moderate shielding and 600 km for a well-shielded site. If, however, the radio-relay antenna may be assumed to have 0 dB gain in the direction of the observatory, the separation distances are 200 km and 120 km for the two sites.

7.15.3 Thus to share with radio-relay systems requires that, to distances which may be as great as 800 km from the radioastronomy observatory, care be taken that the radio-relay antennas are not pointed at the observatory. However if such care is taken, the system may operate within 120 km of a well-shielded observatory.

7.16 *10.6-10.7 GHz*

7.16.1 Radioastronomy has an allocation in the passive band 10.68-10.70 GHz and shares primary status with the fixed and mobile services, except aeronautical mobile, between 10.60 GHz and 10.68 GHz. Generally, the systems in use are low-powered in both the fixed and mobile services. Except that tropospheric scatter is not used at this frequency, the situation is very similar to that at 5000 MHz. A reference system with 5 W into an antenna of 44 dB gain has been chosen. For the same distances the basic transmission loss at 10 GHz is 8 to 9 dB greater than at 5 GHz. The harmful interference level from Report 224 is 2 dB higher. If high gain antennas in the fixed service are not directed at the observatory, the system can work within 115 km of a well-shielded observatory. Within 510 km, care would be required to avoid directing an antenna at the same observatory.

7.17 *14.47-14.50 GHz*

7.17.1 Radioastronomy has a secondary allocation in the Table for the observation of a spectral line from formaldehyde. The primary services are fixed and mobile, except aeronautical mobile and the fixed-satellite service (Earth-to-space). Sharing with the fixed and mobile (except aeronautical mobile) services presents much the same problem as in the band 10.6-10.7 GHz discussed in the preceding paragraph. No calculations have been made concerning sharing with earth stations in the fixed-satellite service. The orientation of the earth station antenna with respect to the observatory is an important factor. If its discrimination in the direction of the telescope is large, sharing should normally be feasible.

7.18 *15.35-15.40 GHz*

This is a passive band and all emissions are prohibited except for an additional allocation on a secondary basis to the fixed and mobile services of 15 administrations.

7.19 *22.01-22.21 GHz, 22.21-22.5 GHz*

7.19.1 In the first of these two bands, administrations are urged to protect radioastronomy observations but in the second, radioastronomy has a primary shared allocation. Fixed and mobile, except aeronautical mobile, are primary services in both bands. The total bandwidth is wide enough for continuum measurements but there is also an important spectral line of water at 22.235 GHz and it is sharing with spectral line observations which is considered here.

7.19.2 There is no operational use of this band in the fixed and mobile services. An extension of some available fixed systems at 15 GHz suggests a hypothetical system at 22 GHz may be digital with 1W RF power in a 20 MHz bandwidth. Antenna gains of about 50 dB may be common. The required basic transmission loss is 241 dB if the full antenna gain is directed at the observatory and 191 dB if the interference is received through a 0 dB side lobe. A reduction in interference potential of 19 dB results from the ratio of the fixed system bandwidth and the bandwidth of a channel of the radioastronomy spectral line receiver.

7.19.3 With the fixed-system antenna directed at the observatory, separations of 340 km and 230 km are required for moderately well and well-shielded sites respectively. With care in the orientation of the antenna, the system could work within 100 km of either type of site. At this range the basic transmission loss becomes more dependent on the details of the path profile and on the antenna heights. For this reason separation distances less than 100 km are just listed in Table I as upper limits.

7.20 *22.81-22.86 GHz, 23.07-23.12 GHz*

There is an ammonia line observable in space in each of these two bands. The use by radioastronomy of the bands is notified by a footnote. In addition to the fixed and mobile services the inter-satellite service is in both bands on a primary basis. The broadcasting-satellite service has a primary allocation in the lower of the two bands in Regions 2 and 3. The active services in these bands are not sufficiently developed to present any difficulties to radioastronomy observations at this time. The operation of broadcasting-satellites could present problems in the future but it appears from Fig. 1 that the inter-satellite service is unlikely to cause harmful interference to radioastronomy unless the space antenna is directed at the observatory.

7.21 *23.6-24 GHz*

7.21.1 This is a passive band and radioastronomy does not have a sharing problem. The most likely cause of interference would be emissions of the second harmonic from broadcasting satellites or fixed satellites (space-to-Earth) in bands near 12 GHz.

7.22 *31.2-31.3 GHz, 31.3-31.5 GHz, 31.5-31.8 GHz*

7.22.1 The middle band, 31.3-31.5 GHz, is for passive services only. In the band 31.5-31.8 GHz, the passive services are primary but the fixed and mobile, except aeronautical services, have secondary status in Regions 1 and 3. In comparison the lowest band 31.2-31.3 GHz is not of great value to radioastronomy since it is covered by only a notification-of-use footnote and fixed and mobile services have primary status and space research and standard frequency and time signal satellite (space-to-Earth) services are secondary.

7.22.2 No calculations of the sharing requirements between radioastronomy and the fixed and mobile services have been made. However, if a reference system similar to that described for 22 GHz is § 7.19.2, is appropriate to this frequency then, provided the active service antennas are not directed at the observatory, the separation distance should be small enough to make sharing simple.

7.23 *36.43-36.50 GHz*

7.23.1 A footnote in this band urges administrations to take all practicable steps to protect spectral line observations from interference. The spectral line referred to is a recombination line of hydrogen. Sharing with the primary fixed and mobile services is not a problem at this time and will not be a problem until operational use of the band by active services develops.

7.24 *Above 40 GHz*

7.24.1 There are a number of allocations for the radioastronomy service above 40 GHz for both continuum and spectral line observations. Some of these are allocations to passive services only but many are shared allocations with a variety of active services.

7.24.2 There are very few active systems operating above 40 GHz and consequently there are few problems of interference to radioastronomy at this time. Certainly the choice of reference systems must await the development of active systems in this region of the spectrum.

7.24.3 No calculations have been made of separation distances required for sharing. Apart from the lack of suitable reference systems there is a lack of propagation information.

7.24.4 Sharing in the future will continue to be easier above than below 40 GHz. The sensitivity of receivers available to radioastronomers will probably continue to be poorer at the higher frequencies. The power available to a potentially interfering transmitter will probably continue to be lower at the higher frequencies. Although there is a paucity of propagation data, the basic transmission loss at a given distance is higher above 40 GHz than below. The troposphere scatter signal decreases monotonically with increasing frequency and also the atmospheric attenuation is higher and at some frequencies above 40 GHz it is very high.

8. Some conclusions on the possibilities of frequency sharing

8.1 Because of the nature of the phenomena observed in radioastronomy, only under special conditions will it be feasible to devise time-sharing programmes between radioastronomy and other services.

8.2 It is very difficult for the radioastronomy service to share frequencies with stations from which line-of-sight paths to the observatories are involved.

8.3 For frequencies at which interfering signals can be transmitted via the ionosphere over long distances (below about 30 MHz, depending on ionospheric conditions) it is extremely difficult for radioastronomy to share with other services using transmitters anywhere on the Earth.

8.4 Sharing with other services may be feasible if transmitters in the radioastronomy bands are on the ground, of low power, and at an adequate distance from the observatory; and also, if account is taken of any site-shielding, the occasional occurrence of abnormally good propagation and the possibility of reflections from aircraft. Typically, separations of several hundred kilometres may be involved at frequencies below 1 GHz, but shorter separations might be acceptable at much higher frequencies.

8.5 If frequencies are shared, special precautions might be needed to avoid the irradiation of the Moon by transmitter beams when the Moon is being used for occultation experiments or for calibration purposes.

8.6 To improve the chances of successful frequency sharing, radio-astronomy observatories should be sited as far as possible from urban areas and transmitters with interfering potential, and should be shielded to the greatest extent possible by surrounding terrain. These precautions are, however, likely to affect only the sharing possibilities discussed above. At frequencies above 10 GHz and particularly above 20 GHz, the need to site observatories at high altitudes to minimize atmospheric absorption may limit the extent to which site-shielding is practicable.

REPORT 697-2*

INTERFERENCE TO THE RADIOASTRONOMY SERVICE FROM TRANSMITTERS IN OTHER BANDS

(Question 5/2 and Study Programme 5A/2)

(1978–1982–1986)

1. Introduction

The sensitivity limit of most radioastronomy observations is at a flux density level far below that used for reception of radio communication signals. Reports 696 and 224 discuss harmful interference and protection criteria for frequency sharing between radioastronomy and other services; in Tables I and II of the latter the sensitivity limits are listed for different frequencies. However, as a consequence of the sensitivity of radioastronomy observations, interference can occur from transmitters which do not share the same band. This may be classified as band-edge interference and interference from harmonic and intermodulation signals.

1.1 Band-edge interference, resulting from a transmitter in an adjacent band, can arise by three mechanisms of interaction. It can occur if the response of the radioastronomy receiver to signals outside the radioastronomy band is not sufficiently low; this may be due to the practical limitations on the fall-off of receiver gain at the band edges. Secondly, non-linear effects in the receiver may, in the presence of two or more signals near the edge of the passband, give rise to intermodulation products falling within the passband of the receiver. Thirdly, interference may result from low-level signals from a transmitter (modulation sidebands etc.) which fall within the radioastronomy band. In dealing with band-edge interference, the problem common to both transmitting and receiving services is the design of filters which will adequately suppress the unwanted energy without introducing unacceptable modifications, e.g. attenuation or phase distortion, into the wanted signals.

1.2 Interference from harmonic radiation or by the intermodulation of two or more signals may be caused by transmitters well separated in frequency from the radioastronomy band. The problems are generally less severe than those of band-edge interference firstly because filter requirements are less demanding and secondly because the transmitting antennas are likely to be considerably less efficient radiators at frequencies remote from those for which they are designed.

2. The role of the transmitter in the production of interference

Some of the mechanisms of interaction depend strongly upon the characteristics of the transmitter involved, and therefore should be examined separately for different services. UHF television and services using satellite transmissions are examples of services which have been found to be troublesome to radioastronomy. In particular, transmitters on satellites or aircraft present a problem because when there are line-of-sight paths to observatories, interference cannot always be avoided. To make matters worse, the requirements for radioastronomy instruments such as extensive arrays or millimetre-wavelength telescopes do not always allow observatory sites to be chosen primarily for their freedom from man-made interference.

2.1 *Interference from terrestrial UHF television transmissions*

Although interference to a radioastronomy receiver may result from a transmitter operating in any service in another band, it is more likely to occur with services using high-power transmitters. Such a service is television broadcasting, which occupies a substantial fraction of the UHF band. Because radioastronomy measurements are required at octave or smaller intervals in frequency, in some parts of the radio-frequency spectrum the two services have been allocated frequency bands in close proximity to each other. Band-edge interference may then occur. The normal spectrum of the television transmission extends outside its nominal band and additional filtering may be needed to reduce the radiated energy in the radioastronomy band to an acceptable level. Normal filtering is accomplished largely in the low-power stages of the transmitter, but additional undesirable components may be generated as a result of non-linear operation of the power amplifier and these would need to be removed by filters operating at high power levels. However, two problems may arise in connection with such filters. Firstly, the passband attenuation in the region of the vision carrier-frequency may be significant, and this may necessitate a transmitting power or an antenna gain greater than would otherwise be required. Secondly, phase distortion may be appreciable and affect the quality of the television picture. Although phase correction at low-power levels is possible, the waveform to be handled by the transmitter will then contain overshoots, and this could require a

* This Report should be brought to the attention of Study Groups 1, 4, 8, 9, 10 and 11.

further increase in the power rating of the transmitter if distortion is to be avoided. There is therefore a preference for phase-corrected filters. Unless the radioastronomy station is remotely situated from the transmitter there must clearly be a "guard band" to allow for the finite slope of the attenuation characteristics of the high-power filters at the transmitter. The width of this guard band depends upon the degree of attenuation required and upon the complexity which is envisaged for the high-power filters but guard bands of the order of 2 MHz would seem reasonable. The potential for interference is increased when two or more transmitters are operated with the same antenna, since intermodulation may then be produced.

It is not easy to predict the strength of the band-edge interference. Because the interference would be caused by sideband components of the picture transmission as well as by discrete components derived from the sound sub-carrier and sound signals, the level of interference depends upon the bandwidth of the radioastronomy receiver and cannot be uniquely specified as with a single spectral component. The level also depends upon the picture content and, if integration techniques are adopted at the receiver, upon the duration of a particular picture. As a reasonable guide, the interference can be deduced assuming a 1 MHz receiver bandwidth and those pictures which occur fairly frequently and which are most likely to cause interference.

Suppression of the out-of-band radiation from a television transmitter to the low levels required for radioastronomy is justified only if the radioastronomy receiver can reject the energy in the adjacent television band to a comparable level. A typical parametric amplifier may start to overload at an input level of 1 μW, but it is considered that avoidance of overload is not the main problem. The more difficult problem in general is to reduce the interference by the shaping of the intermediate-frequency passband, since some 110 dB of rejection below the 1 μW input level is required to achieve the measurement sensitivity which is possible in the absence of interference, as indicated in this Report.

In general, band-edge interference introduces more serious technical problems than does harmonic or intermodulation interference. Special filtering may be needed but in the latter cases the design problems will be less difficult. The protection of radioastronomy stations in highly developed areas may call for the addition of filters, capable of handling the full transmitter output, at several television broadcasting stations. This means that, apart from technical feasibility and cost, the question of organizing checks of the degree of suppression will need consideration.

2.1.1 *Band-edge interference from UHF television transmissions in the 608-614 MHz radioastronomy bands*

As an example, band-edge interference presents a severe problem to transmission on European Channel 39 (or a US Channel 38) because, with the vision carrier frequency of 615.25 MHz, the fully-transmitted portion of the lower (vestigial) sideband extends downwards by 0.75 MHz, or by as much as 1.25 MHz with CCIR Standards I and L, thus reaching 614 MHz. Below this frequency, the lower sideband is attenuated, but the residual level constitutes a potential source of interference with the nominal radioastronomy band. If it is assumed that a high degree of band-edge suppression has been applied to the modulated signal before the final stage in the transmitter, the signals in the radioastronomy band generated in the final stage (assuming no output filter) will then extend to just below 610 MHz at a level typically about −55 dB relative to the vision carrier, when the measurement is made in a 1 MHz bandwidth. In addition there will be a narrow-band signal at about 611 MHz with a colour transmission, and this may reach a level of −42 dB under the worst picture conditions. An intermodulation product at 609.25 MHz produced as the result of power from the sound transmitter reaching the vision transmitter via the combining unit or diplexer will be at a level of −55 dB. Otherwise the signals over most of the lower half of the Channel will be at a level of −80 dB or lower. Since the signal will reach −42 dB only occasionally during the worst picture conditions, and since transmitters often include a simple notch filter at the output to reduce the regenerated colour sideband it seems realistic to take a round figure of −50 dB as a likely relative signal in a typical receiver bandwidth of 4 MHz when no special filtering is used. If high-power filters with group-delay correction were added in the outgoing feeders handling the Channel transmission, then because of the sharp rate of cut-off of these filters, one or two decibels of loss may be unavoidable. In such a case, higher power transmitter would be required. It is probably technically feasible, though expensive, to reduce the out-of-band signal in the radioastronomy band to −100 dB, but greater suppression would probably be impracticable.

Other cases of possible band-edge interference are listed in Table I.

TABLE I – *Services in adjacent bands which could cause harmful interference to the radioastronomy service* *

Band allocated to radioastronomy on world-wide primary basis	Adjacent band	Adjacent-band services (1)
13.36-13.41 MHz	13.26-13.36 MHz	AERONAUTICAL MOBILE (R)
25.55-25.67 MHz	25.67-26.10 MHz	BROADCASTING
322-328.6 MHz	273-322 MHz	MOBILE, including satellite
	328.6-335.4 MHz	AERONAUTICAL RADIONAVIGATION
1400-1427 MHz	1350-1400 MHz	RADIOLOCATION
	1429-1525 MHz	MOBILE (Region 1) Broadcasting satellite (2)
1660-1670 MHz	1646.5-1660 MHz	AERONAUTICAL MOBILE-SATELLITE (3)
	1670-1690 MHz	METEOROLOGICAL AIDS METEOROLOGICAL-SATELLITE (space-to-Earth)
2690-2700 MHz	2655-2690 MHz	BROADCASTING-SATELLITE (space-to-Earth) FIXED-SATELLITE (Region 2)
	2700-2900 MHz	AERONAUTICAL RADIONAVIGATION Radiolocation
4990-5000 MHz	4800-4990 MHz	MOBILE
	5000-5250 MHz	AERONAUTICAL RADIONAVIGATION
10.6-10.7 GHz	10.55-10.6 GHz	Radiolocation
	10.7-11.7 GHz	FIXED-SATELLITE (space-to-Earth)
15.35-15.4 GHz	14.8-15.35 GHz	MOBILE Space research
	15.4-15.7 GHz	AERONAUTICAL RADIONAVIGATION
22.21-22.5 GHz	22.5-22.55 GHz	MOBILE BROADCASTING-SATELLITE (Regions 2 and 3)
23.6-24 GHz	23.55-23.6 GHz	MOBILE
	24-24.05 GHz	AMATEUR AMATEUR-SATELLITE ISM (4)
31.3-31.8 GHz	31-31.3 GHz	MOBILE Standard signals-Satellite (space-to-Earth) Space research
	31.8-32 GHz	RADIONAVIGATION Space research

* Fixed and mobile except aeronautical mobile services are not included (see § 2.3).

(1) The category of service of these allocations is shown in conformity with the provision of Nos. 413-418 of the Radio Regulations.

(2) Under study (see Resolution No. 505 of the WARC-79).

(3) See § 2.2.

(4) ISM: industrial, scientific and medical.

TABLE I *(continued)*

Band allocated to radioastronomy on world-wide primary basis	Adjacent band	Adjacent-band services ([1])
42.5-43.5 GHz	40.5-42.5 GHz	BROADCASTING-SATELLITE BROADCASTING Mobile
	43.5-47 GHz	MOBILE MOBILE-SATELLITE RADIONAVIGATION RADIONAVIGATION-SATELLITE
86-92 GHz	84-86 GHz	MOBILE BROADCASTING BROADCASTING-SATELLITE
	92-95 GHz	MOBILE RADIOLOCATION
105-116 GHz	102-105 GHz	FIXED-SATELLITE (space-to-Earth) MOBILE
	116-126 GHz	INTER-SATELLITE MOBILE
164-168 GHz	151-164 GHz	FIXED-SATELLITE (space-to-Earth) MOBILE
	168-170 GHz	MOBILE
182-185 GHz	176.5-182 GHz	INTER-SATELLITE MOBILE
	185-190 GHz	INTER-SATELLITE MOBILE
217-231 GHz	202-217 GHz	MOBILE
	231-235 GHz	FIXED-SATELLITE (space-to-Earth) MOBILE Radiolocation
265-275 GHz	252-265 GHz	MOBILE MOBILE-SATELLITE RADIONAVIGATION RADIONAVIGATION-SATELLITE

([1]) The category of service of these allocations is shown in conformity with the provision of Nos. 413-418 of the Radio Regulations.

2.1.2 *Harmonic and intermodulation interference*

This type of interference can occur in any band, and is generated mainly in the output stages of the transmitters. The usual type of output valve for a high-power transmitter is the klystron. Figure 1 shows a typical arrangement of combining filters when four programmes (each involving a vision carrier, f_v and a sound carrier, f_s) are combined and fed into a common antenna. At some stations the equipment shown in Fig. 1 is duplicated, as a precaution against breakdown, and the two duplicated combined outputs may be split and fed by two feeders to two halves of the antenna.

The second and third harmonics of the carrier frequency may occur at a fairly high level at the klystron output, but transmitters are normally provided with filters (tuned or low-pass) which attenuate all harmonics at the output of the transmitter to at least 60 dB below peak (sync.) power. Carrier intermodulation will also occur when a proportion of the signal from one transmitter breaks through the combining filters to the output circuit of another transmitter. The levels of these terms cannot be predicted accurately but, assuming 30 dB cross-insertion loss between the outputs of all transmitters, it is likely that second or third order products involving two vision transmitters will be generated at about -60 dB, those involving two sound transmitters at about −80 dB, and those involving three sound or vision transmitters at about −100 dB relative to peak (sync.) power. Higher-order products in each category would be somewhat lower in level. Many stations may have two separate two-channel antennas rather than a single four-channel antenna but coupling will still occur between transmitters because of the mutual coupling between the antennas. In this case, it is reasonable to assume a cross-insertion loss of 40 dB and thus to reduce by 10 dB the levels given above if the intermodulation term involves transmitters connected to the different antennas. Relatively simple additional filters would attenuate these unwanted products, assuming they are not too close in frequency to that of the transmitter. It is current practice in some transmitters to employ harmonic filters of the low-pass type in which case intermodulation products whose frequencies lie above the cut-off frequency will already be suppressed to levels lower than those given above.

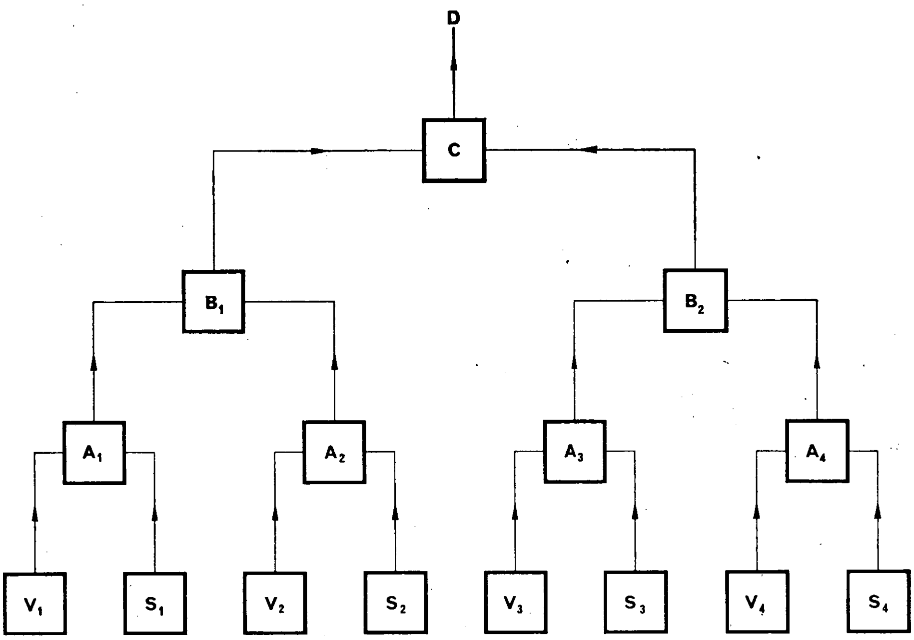

FIGURE 1 – *Typical arrangement of combining filters for feeding four programmes to a common antenna*

V_1, V_2, V_3, V_4:	vision transmitters
S_1, S_2, S_3, S_4:	sound transmitters
A_1, A_2, A_3, A_4: B_1, B_2: C:	combining filters
D:	output to antenna array

The levels discussed in the previous paragraph apply to interference generated in the klystrons. In addition, harmonics and intermodulation products may be generated by non-linearity in the feeders and antennas. Experience in the United Kingdom, when implementing the Band II service, showed that intermodulation products could not be reliably suppressed below about −100 dB relative to the level of the transmitted signals because of this type of non-linearity. Since the results of measurements at multi-programme UHF transmitters are not yet available, it is unwise at the present stage to assume that a great degree of suppression is feasible in the main antenna feeder at a UHF station. Therefore the addition of further filters at transmitters may only achieve an improvement up to the point where the level of any particular product in the feeders reaches −100 dB relative to peak (sync.) power. Improvement thereafter may not be economically practicable.

In any practical antenna, the gain in horizontal or near-horizontal directions, at frequencies far removed from the design frequency, may be anything from a few decibels to 50 dB below that at the design frequency. It will vary with frequency in a largely unpredictable manner, depending upon detailed aspects of the antenna design. Whilst it may later be found that the radiation characteristics of the antenna give a useful reduction of the interference at the majority of stations, it would be rash to rely on this reduction in every case.

Specific examples of harmonic and intermodulation products falling in radioastronomy bands may be mentioned, for the transmitters of the United Kingdom using CCIR Standard I. For a Channel 50 transmitter (carrier frequencies f_v = 703.25 MHz vision, and f_s = 709.25 MHz sound), $2f_v$, $f_v + f_s$ and $2f_s$ are in the 1400 to 1427 MHz hydrogen-line band. With a group of channels such as 21, 24, 27 and 31 radiated from the same site, third order intermodulation products of the $f_1 + f_2 - f_3$ type may fall in the 406 to 410 and 606 to 614 MHz bands. The third harmonic of Channel 21 is in the hydrogen band. Other examples are listed in Table II.

TABLE II – *Services which could cause harmonic interference to the radioastronomy service* *

Band allocated to radioastronomy on world-wide primary basis	Interfering service	Harmonic of allocated frequency
13.36-13.41 MHz	Aeronautical mobile	2
25.55-25.67 MHz	Maritime mobile	2, 3
322-328.6 MHz	Mobile (Regions 2 and 3)	2
	Broadcasting	3
	Aeronautical radionavigation	3
1400-1427 MHz	Broadcasting	2, 3
	Mobile	2 (Regions 2, 3), 3
	Meteorological-satellite (space-to-Earth)	3 (1)
1660-1670 MHz	Broadcasting	2, 3
	Mobile (Regions 2 and 3)	2, 3 (Region 3)
	Radionavigation (Region 3)	3
2690-2700 MHz	Aeronautical radionavigation	2
	Radiolocation	2 (1), 3 (1)
	Broadcasting (Regions 1 and 3)	3
	Mobile (Region 3)	3
4990-5000 MHz	Mobile	2
	Radiolocation	2
	ISM (2)	2
10.6-10.7 GHz	Radiolocation	2, 3 (1)
	Mobile (Region 1)	3 (1)
	Fixed-satellite (space-to-Earth)	3
15.35-15.4 GHz	Fixed-satellite (space-to-Earth)	2
	Aeronautical radionavigation	3
22.21-22.5 GHz	Fixed-satellite (space-to-Earth)	2, 3
23.6-24 GHz	Broadcasting (Regions 1 and 3)	2
	Broadcasting-satellite (Regions 1 and 3)	2
	Fixed-satellite (Region 2)	2
	Mobile	3

* Fixed and mobile except aeronautical mobile services are not included (see § 2.3).

(1) Secondary allocation.

(2) ISM: industrial, scientific and medical.

TABLE II *(continued)*

Band allocated to radioastronomy on world-wide primary basis	Interfering service	Harmonic of allocated frequency
31.3-31.8 GHz	Aeronautical radionavigation	2
	Radiolocation	2, 3
	Mobile	3
	Amateur	3 (1)
	Amateur-satellite	3 (1)
42.5-43.5 GHz	Mobile	2
	Radionavigation	3
	Radionavigation-satellite	3 (1)
	Space research	3 (1)
86-92 GHz	Mobile	2, 3
	Mobile-satellite	2
	Radionavigation	2
	Radionavigation-satellite	2
	Standard signals-satellite (space-to-Earth)	3 (1)
105-116 GHz	Inter-satellite	2
	Mobile	2, 3
	Space research	3 (1)
	Meteorological aids	3
	Radiolocation	3
	Fixed-satellite (space-to-Earth)	3
164-168 GHz	Fixed-satellite (space-to-Earth)	2
	Mobile	2, 3
	Mobile-satellite (space-to-Earth)	2
	Inter-satellite	3
182-185 GHz	Mobile	2, 3
	Radiolocation	2, 3
	Inter-satellite	3
	ISM (2)	3
217-231 GHz	Mobile	3
	Amateur	3
	Amateur-satellite	3
	Radiolocation	3
265-275 GHz	Inter-satellite	2
	Mobile	2
	Mobile-satellite	2
	Radionavigation	2
	Radionavigation-satellite	2
	Radiolocation	2

2.1.3. *Absolute levels of interference from UHF transmitters*

The levels of unwanted components have so far been considered relative to the peak signal of the vision transmitter. As a guide to the absolute levels of interference as a function of distance from the transmitter, we may estimate the field-strength of the television emission and assume that the interference will be propagated similarly, so that the field strength of the interference remains at the same level relative to the television signal.

Normally a television service is discussed in terms of the field strength at 10 m above ground level. For example, it has been estimated from CCIR propagation data that a 1000 kW (e.r.p.) transmitter with an antenna 300 m high will produce fields exceeding 80 dB above 1 μV/m at 50 km for 1% of the time. If it were possible to suppress the out-of-band part of the signal to a relative level of -100 dB (i.e. about 50 dB additional suppression at high-power level) the resulting field would be 20 dB below 1 μV/m. The importance of this field would depend on how near to the direction of the transmitter the radioastronomy antenna beam was intended to be used, but even if the gain in the transmitter direction never exceeded

0 dB, relative to an isotropic antenna, the interference level would be up to 20 dB above the values shown in Table I of Report 224 for continuum measurements for a small percentage of the time. It should be noted, moreover, that the mean heights of some large radioastronomy antennas are considerably greater than 10 m and correspondingly larger interfering fields may be expected. Depending on the topography, parts of such an antenna could be in a field equal to, or even greater than, that in free space, which at 50 km would be about 25 dB stronger than the field assumed for the 10 m height. It is evident that the possibility of interference needs to be estimated for each path, taking into account the path profile, and the size of, and the requirements for, the radioastronomy antenna.

In the 606 to 614 MHz band a field of 80 dB above 1 μV/m corresponds to a power at the receiving antenna of −82 dBW if the gain is 0 dB. This is well below the overload point of the preamplifier so the main receiver problem is to reduce the received power from the television band by about 100 dB, by a combination of filtering at radio-frequency and intermediate-frequency, to achieve the CCIR limits. This degree of suppression is technically feasible, though probably near the limits of what can be done without introducing other undesirable effects such as phase distortion.

Finally, a similar example can be used to study the effects of harmonic radiation. Assuming that the same field of 80 dB above 1 μV/m is produced by a Channel 50 transmitter at 50 km, having its second harmonic in the hydrogen band, this harmonic might, in normal circumstances, be 60 dB below the fundamental in the transmitter itself. Additional attenuation of about 60 dB would be required to achieve the limits of Report 224 with a 0 dB gain receiving antenna. Some of this additional attenuation will be derived from the reduced radiation efficiency of the transmitter antenna, and extra filtering should not be difficult with the wide frequency separations involved. Intermodulation products occurring at frequencies well removed from the nominal transmitter frequencies should in general be less of a problem than harmonics.

2.2 *Interference from satellite transmissions*

Satellite transmissions, in particular those associated with television and sound broadcasting, may cause severe interference to radioastronomy. By the nature of a satellite broadcasting system, large areas of the Earth will be illuminated and line-of-sight conditions will exist. Terrestrial interfering sources are normally in the far side-lobe region of a radio telescope, whereas a satellite transmission is likely to be received also in the main beam and near side lobes, with considerably higher gain. For example, as far as 5° from the main beam, the gain may be 25 dB higher than in the far side-lobe region (see Recommendation 509).

Geostationary satellites which are above the horizon at any observatory could be particularly troublesome. The radius of the geostationary-satellite orbit is approximately 6.6 times the radius of the Earth. The position of the orbit in celestial coordinates as seen from the latitudes of a number of major radioastronomy observatories is shown in Fig. 2. Plans for the development of some active services call for a large number of closely spaced geostationary satellites. Such a series of potential sources of interference which may be viewed in the near side-lobes of a telescope present an interference problem not otherwise faced by radioastronomers. In § 2.2.1 this problem is examined geometrically for two levels of interference but without considering the source or nature of the interference. Then in § 2.2.2 and 2.2.3 band edge and harmonic interference are examined for a number of specific services.

The very special concern for the interference which might result from the high levels of radiated power of the proposed satellite power system is treated separately in Report 853.

2.2.1 *Regions of the sky denied to radioastronomy by emissions from geostationary satellites*

Harmful thresholds for interference to radioastronomy are given in Report 224. Listed there is the level, in each radioastronomy band, of the power into the receiver which is just sufficient to cause harmful interference. Also listed are the power flux-densities (dB(W/m^2)) causing harmful interference which are calculated with the assumption that the gain of the radio telescope is 0 dB in the direction of the interfering source. Such a gain is appropriate for consideration of terrestrial sources of interference confined to the neighbourhood of the horizon. The very different result for geostationary sources is demonstrated in the first case below. In the second case, it is assumed that the power flux-density of the interfering signal is 30 dB less. A harmful interference level from a single interfering source is experienced when the radio telescope gain is 30 dB at an angular distance of 1.2° from the source.

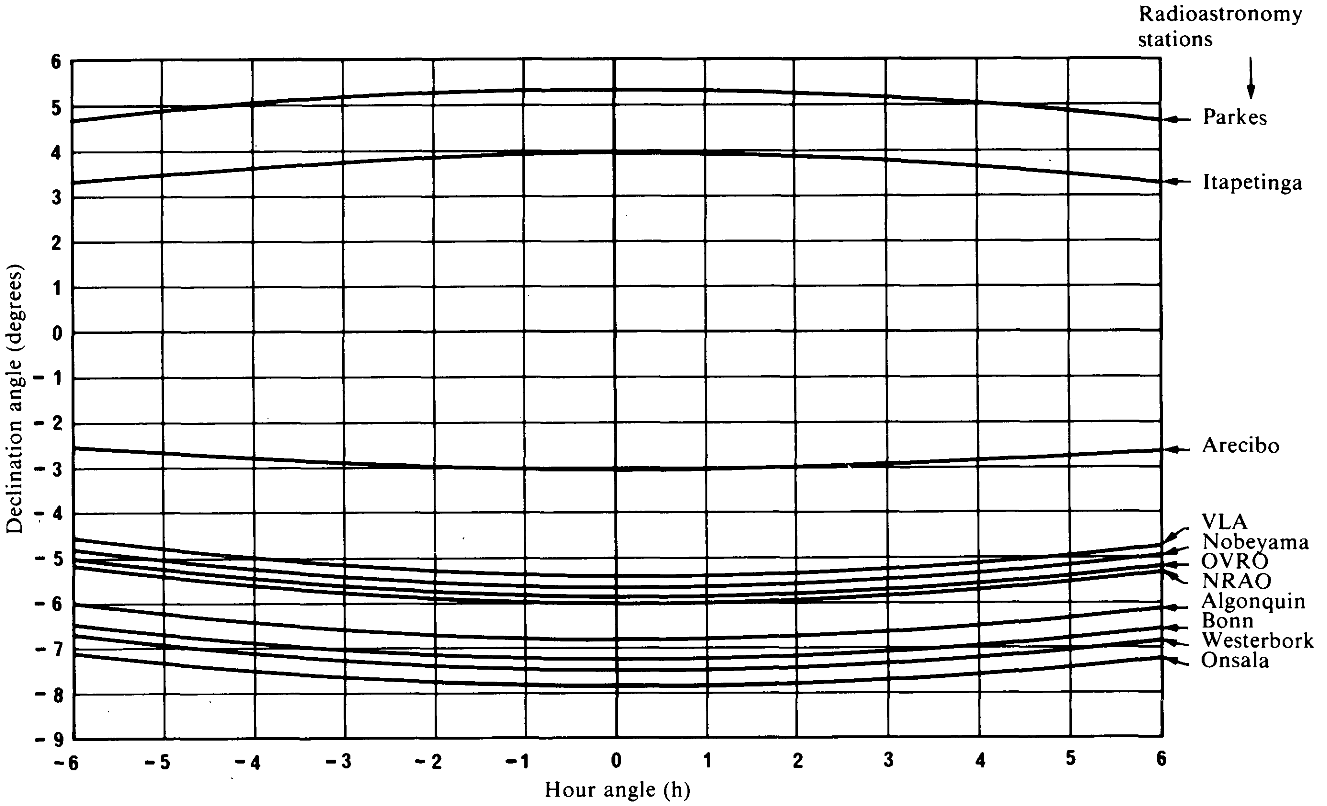

FIGURE 2 – *Projection of geostationary-satellite orbit on to the celestial sphere*

2.2.1.1 *Interference at the interference threshold levels given in Report 224*

If we assume that the radioastronomy antenna has the side-lobe characteristics assumed in Recommendation 509, the side-lobe gain would fall to 0 dBi at 19° from the axis of the main beam. For such an antenna the harmful interference level will be exceeded if the main beam is pointed within 19° of a satellite that produces within the radioastronomy bandwidth a power flux-density at the radio observatory equal to the harmful threshold in Report 224. A series of satellites spaced at intervals of about 30° along the geostationary-satellite orbit radiating interference at this level would result in a zone of width approximately 38° centred on the orbit in which radioastronomy observation free from harmful interference would be precluded. The width of this precluded zone would increase with the number of interfering satellites in the orbit, and could in principle cover the whole sky. The effective number of interfering satellites will depend upon whether the interfering signals are beamed by the satellites' transmitting antennas or are more widely radiated. Out-of-band emission that is not widely separated from the satellite's transmitter frequency is likely to be beamed by a satellite antenna. Interference that is widely separated in frequency, such as harmonics, may be radiated more widely, but is also likely to be less difficult to suppress.

2.2.1.2 *Interference 30 dB below the interference threshold levels of Report 224*

A more detailed, but arbitrary, examination has been undertaken for the situation where the geostationary satellites are assumed to be emitting unwanted interference at a level 30 dB below the harmful values in Report 224. In this case the interference to be expected at Nobeyama Radio Observatory in Japan is examined for a series of satellites distributed in orbit (see also § 7.5.3.1 of [CCIR, 1978-82]). The calculations were performed for the sample plans worked out for a number of fixed-satellite bands. The results are shown in Fig. 3 for the 6/4 GHz and 30/20 GHz bands. In each case the directivity of the satellite antenna is assumed to be the same at the interfering frequency as at the fixed-satellite frequency. The plan calls for 55 geostationary satellites using the 6/4 GHz band in a 120° arc of the orbit over Region 3, and 224 satellites in the same arc using the 30/20 GHz band. The cross-hatched areas in Fig. 3 show the areas of the sky where harmful interference would be experienced at the Nobeyama Observatory. At the lower frequency there are isolated areas surrounding the satellites, the largest area being centred on a satellite for which the observatory falls within the main beam response. At the higher frequency the satellites are sufficiently close together that they create a continuous zone of interference about 3° wide. With the interference levels assumed in this case, interference at the harmful threshold is experienced when the radioastronomy antenna is pointed at a distance of 1.2° from a single satellite for which the main beam of the transmitting antenna illuminates the observatory. In this situation the other satellites contribute a negligible amount to the total interference received in the 6/4 and 11/14 GHz band, and less than half in the higher frequency bands, where the number of satellites is greater.

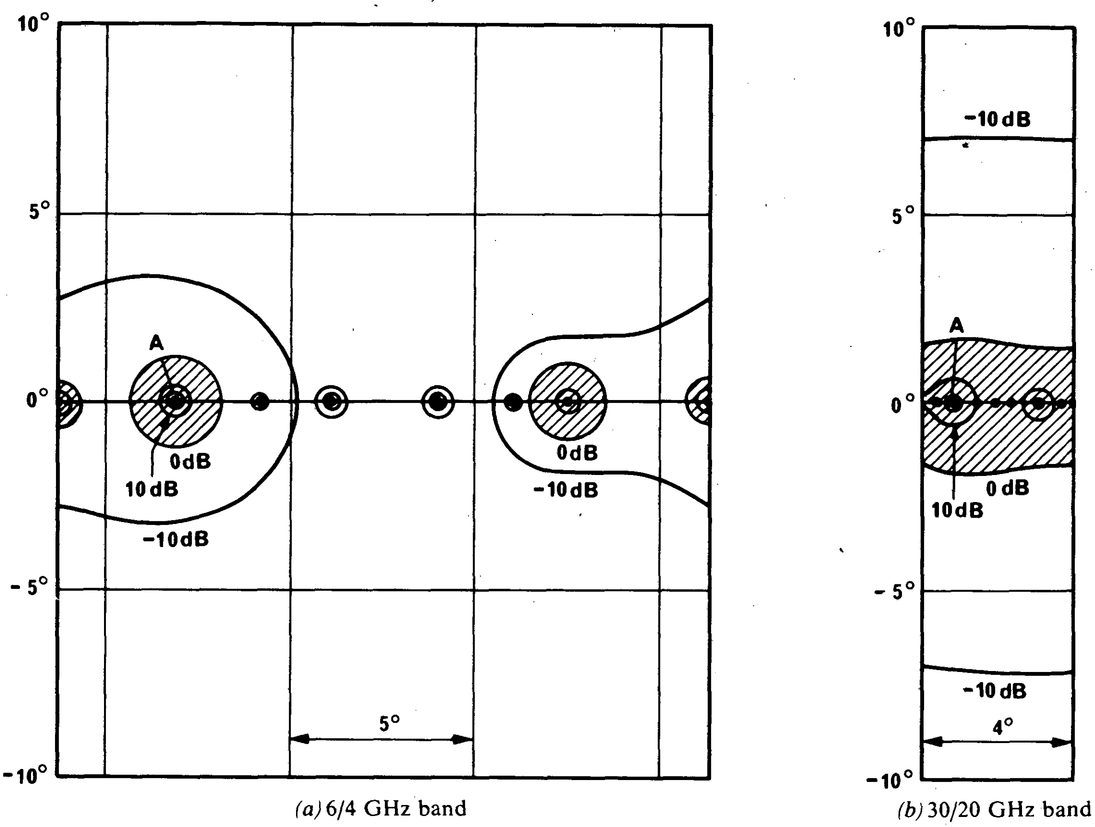

FIGURE 3 – *Examples of the spurious emission level from eight geostationary satellites in the 6/4 GHz band (a) and 30/20 GHz band (b). In the calculations, satellites in these configurations are assumed to be repeated periodically along the 120° arc. The letter A indicates a satellite for which the main beam is directed towards the Nobeyama Observatory.*

2.2.1.3 *Some additional considerations*

A severe problem of interference to radioastronomy observations could result as large numbers of geostationary satellites are put into service. A solution to this problem clearly involves a compromise between the area of sky lost to radioastronomy observations and the difficulty of suppressing unwanted emissions from the satellites. Such a solution may involve conditions intermediate between the two cases above. It is useful to examine such an intermediate case in detail. In considering the area of sky lost to radioastronomy, it should be noted that Fig. 2 indicates that if observations can be made to within a distance of about 5° from the geostationary-satellite orbit, each position in the sky can be observed from at least one existing observatory provided that it is suitably equipped. It should also be noted that not all types of radio telescopes are as sensitive to interference as the single-antenna telescopes to which Report 224 applies. Interferometers and synthesis arrays have higher thresholds for harmful interference [Thompson, 1982]. However, these instruments are useful mainly for studying sources with very small angular structure, while single-antenna telescopes fulfil an important role in astronomy in observing extended sources in space.

2.2.2 *Band-edge interference*

In discussing the possibilities of interference, the situation in and near the radioastronomy band 2690 to 2700 MHz may be taken as an example, in respect of potential interference from proposed broadcasting satellites in the band 2550 to 2690 MHz; other examples are listed in Table I. Maximum power flux-densities have been specified in the Radio Regulations, to protect the terrestrial fixed service with which the broadcasting-satellite service shares the band. The appropriate criterion is that the power flux-density should not exceed -137 dB(W/m^2) in any 4 kHz band when the angle of elevation of the satellite exceeds 25° (see No. 2562 of the Radio Regulations).

The spectral density of the broadcasting-satellite transmission should decrease towards the band-edge and into the radioastronomy band. On the assumptions of a square cut-off for the transmitter spectrum and typical receiver cut-off characteristics, then as a broad indication the energy in the upper 1 MHz of a broadcasting-satellite signal producing the full permitted power flux-density is likely to interfere with a radioastronomical observation if there is a separation less than 4 MHz between the nominal band edges. Whether this separation would be sufficient to prevent sidebands from the broadcast transmission extending harmfully into the radioastronomy band is not yet known. Furthermore, the radioastronomy observations will be less susceptible if the observatory is well outside the service area of the satellite, but again to an unknown extend. A reduction of 30 dB in the e.i.r.p. of the satellite in the observatory direction would enable the separation to be reduced to the order of 1 MHz provided that this was sufficient to exclude harmful satellite sideband signals from the radioastronomy band.

Careful control of the radiated spectrum can alleviate the problem of band-edge interference. Annex I describes some results of measurements of interference in the radioastronomy band 2690 to 2700 MHz, showing the benefits of filtering satellite transmissions. Annex II shows how the use of a carefully designed band-rejection filter on the geostationary meteorological satellite of Japan has been effective in reducing interference in the radioastronomy band 1660 to 1670 MHz. In Annex I the results of the measurements are compared with the harmful interference levels of Report 224. However, in Annex II the results show that the interference level is well below that given in Report 224 and is indeed below the level used in § 2.2.1.2 above.

2.2.3 *Harmonic interference*

A possible mode of interference to radioastronomy is second-harmonic radiation from broadcasting satellites in the band 11.7 to 12.5 GHz (see Report 807). The harmonic range 23.4 to 25.0 GHz includes the exclusive passive band 23.6 to 24.0 GHz. For Regions 1 and 3, Annex 8 of Appendix 30 to the Radio Regulations lists for individual reception a minimum power flux-density in the 11.7-12.5 GHz band of -103 dB(W/m^2) at the edge of the coverage area, and the power flux-density in the centre of the coverage area would normally be -100 dB(W/m^2). These values of power flux-density are applicable to each channel of the broadcasting-satellite service. The second harmonic of channels 5-15 falls within the radioastronomy band and of these a total of 8 channels may illuminate an observatory. The total power flux-density within the band 11.8-12.0 GHz may reach a value of -91 dB(W/m^2). According to Table I of Report 224, radioastronomy would be affected by interfering signals greater than -147 dB(W/m^2) in a bandwidth of 400 MHz at 24 GHz, with a side-lobe gain of 0 dB. The radio-telescope antenna may, for example, have a gain of about 70 dB and signals of -217 dB(W/m^2) from a single satellite would therefore cause interference if the antenna were directed towards the satellite. The required suppression of the second harmonic referred to the fundamental of the broadcasting signal would therefore be 126 dB and special precautions would need to be taken in the design of the transmitter to avoid interference through the main beam of the radio-telescope. If, instead, a radioastronomy gain of 0 dB is considered, the required harmonic suppression would be 56 dB, and for a 30 dB gain the required suppression would be 86 dB. These are the antenna gain values used in § 2.2.1.1 and 2.2.1.2. However, these sections deal with a more detailed distribution of satellites and a similar treatment in this section might lead to somewhat different values of required suppression than those listed above. If observations could be made to within 5° of the geostationary-satellite orbit, it was indicated in § 2.2.1.3 that with the use of existing major observatories all the sky would be accessible. The gain of the reference antenna of Recommendation 509 at 5° from its axis is 15 dBi. Therefore a harmonic suppression of 71 dB would be required, which can be achieved with established design techniques.

A corresponding possibility exists of harmonic interference to radioastronomy in the water vapour band at 22.2 GHz from transmissions in the fixed-satellite service in the band 10.95 to 11.2 GHz, but the permitted power flux-densities at the Earth from transmitters in the fixed-satellite service are lower than in the broadcasting-satellite service, and the interference problems will be correspondingly less. This also applies to the passive bands at 15.35-15.4 GHz and 164-168 GHz, which also contain second harmonics of frequencies allocated to space-to-Earth transmissions. Further examples are listed in Table II.

Some meteorological satellites collect data from platforms on or near the surface of the Earth and relay the information to data collection centres. The systems include the interrogation of the platforms by means of transmissions from the satellites in the band 460 to 470 MHz. For example, Annex I of Report 395 mentions the use of 468.825 MHz with powers up to 40 W. Because the third harmonic of this transmission (1406.475 MHz) falls in the passive band 1400 to 1427 MHz, the possibility of interference needs to be studied. Proposals for the future use of the band 460 to 470 MHz for interrogation appear, at present, to be restricted to geostationary satellites. Although the gain of the satellite antenna is said to be 7.4 dB at the fundamental frequency, its performance at a harmonic frequency is unknown, and its gain in the direction of any particular radioastronomy observatory is unlikely to be known. For the purposes of this initial discussion, therefore, harmonic radiation will be assumed to be isotropic. The power flux-density at the surface of the Earth, in the region of the sub-satellite point, is then -146 dB(W/m^2) from a 40 W transmitter at the fundamental frequency. According to Report 224 in the band 1400 to 1427 MHz the power flux-density of interfering signals should not exceed -180 dB(W/m^2) if the gain of the radio-telescope is 0 dB relative to isotropic. In these circumstances it is unlikely that the harmonic radiation will be sufficient to cause interference. On the other hand, if a radio-telescope with a gain of 60 dB were directed towards the satellite, then the power flux-density which would cause interference would be -240 dB(W/m^2) and so 94 dB of harmonic suppression would be necessary. Special precautions might be necessary to achieve this suppression. If an antenna gain of 30 dBi is assumed, as was done in § 2.2.1.2, the harmonic suppression required would be 64 dB.

2.3 *Interference from other services*

Signal levels encountered in adjacent bands vary widely with the nature of the service. In addition, designations of services are of a very general nature and each one covers many different types of transmitting systems. The highest peak signal levels are likely to be found in the bands designated for radiolocation and aeronautical radionavigation since these include high-powered radars in aircraft. Mean power flux-densities of such signals at relatively isolated observatory sites commonly exceed -100 dB(W/m^2), and may even exceed -50 dB(W/m^2). Observations in one of the most important bands to radioastronomy, 1400-1427 MHz, may suffer from band-edge interference from radiolocation allocated to the adjacent band 1350-1400 MHz. The radioastronomy band 4990-5000 MHz is adjacent to an aeronautical radionavigation band at 5000-5250 MHz which will be used by the new International Civil Aviation Organization microwave landing system (MLS). This will operate ground-based transmitters in the band 5030.85-5090.85 MHz. A peak effective radiated power of approximately 20-25 dBW can be expected on-channel within the scanning beam. The interference specifications for the system require that the mean power flux-density measured in a 150 kHz bandwidth centred 840 kHz or more from the nominal channel frequency shall not exceed -100.5 dB(W/m^2) for angle guidance transmissions and -95.5 dB(W/m^2) for data transmissions at heights above 600 m. The signal level at 5030 MHz does not exceed a spectral power flux-density of -147 dB(W/(m$^2 \cdot$ Hz)).

The Earth-to-space transmissions of the aeronautical mobile-satellite service may be troublesome to radioastronomy because the transmitters on aircraft may be in the line-of-sight of an observatory.

Services designated as fixed and mobile use various transmission techniques. Typical high spectral power flux-densities likely to be encountered at an observatory are -127 dB(W/(m$^2 \cdot$ Hz)) – this corresponds to a transmitter with an e.i.r.p. of 100 W over a bandwidth of 10 kHz at a distance of 60 km. Fixed and mobile (except aeronautical mobile) services are generally expected to have a short-range nature, and should not present too many band-edge interference problems; several frequency bands are in fact allocated to the fixed, mobile (except aeronautical mobile) and radioastronomy services.

2.3.1 *Unwanted emissions from broadband modulation*

In certain types of transmissions, often associated with data in digital form, spectral sidebands are generated over a much broader frequency band than is used in the reception of such signals. In particular, the biphase phase-shift keying (2-PSK) modulation technique produces a power spectrum of the form $(\sin x/x)^2$ with recurring subsidiary maxima outside the wanted bandwidth which decrease only slowly with frequency. If unfiltered, the sidebands which occur at about ten bandwidths 3 dB from the carrier frequency are reduced in power spectral density only about 36 dB below the power level at the band centre. If, in addition, the keying frequency of this 2-PSK transmission is 10-20 MHz, then these ten bandwidths encompass several hundred megahertz from the assigned frequency. For example, assume a simple 2-PSK transmitter with a keying frequency of 10 MHz centred on 1615 MHz with 40 W of power and an isotropic transmitting antenna mounted on an aircraft at a line-of-sight distance of 400 km, which is the distance of the horizon at an aircraft flying at an altitude of about 10 000 m. Unwanted emissions from this transmitter would result in a power flux-density level even in the band 1400-1427 MHz at the receiver site which is 40 dB above the harmful interference threshold given in Table I of Report 224; emission in the band 1660-1670 MHz, also allocated to radioastronomy, would, of course, be at a significantly higher level. Transmitters of this type located on spacecraft could be even more troublesome sources of interference to radioastronomy. It is important that care be taken in the design of these types of transmitters to ensure adequate suppression of the unwanted emissions.

2-PSK with a keying frequency of several megahertz is used in some types of spread-spectrum modulation. A characteristic of common spread-spectrum techniques is a wideband signal with low power density which resembles random noise. This characteristic usually reduces the possibility of these spread-spectrum systems causing interference to conventional, narrow-band communication systems, but not to the radioastronomy service. In radioastronomy, the cosmic signals have the form of random noise, and wide bandwidths are often used. At the low signal levels with which radioastronomers are concerned, there is usually no practical way to distinguish between spread-spectrum signals and cosmic signals. The harmful thresholds of power flux-density for man-made signals falling within a radioastronomy band, which are given in Report 224, apply to unwanted, as well as intentional, emissions and to all types of modulation, including that discussed above.

2.4 *Services which may cause interference to the radioastronomy service*

Table I lists the services that could present adjacent-band problems to the radioastronomy service. Table II lists the services that could cause harmonic interference; only the second and third harmonic frequencies have been considered.

3. Band-edge interference and the radioastronomy receiver

3.1 *The overall response*

To calculate the effective input signal power P received in a radiometer from adjacent-band signals, consider a band edge at frequency f_0 beyond which a uniform spectral power flux-density S (W/(m^2 · Hz)) is encountered (Fig. 4). Let A be the telescope collecting-area in the corresponding direction, $-a_0$ (dB) be the level to which the gain of the radiometer has been reduced at the band edge, and $-k$ (dB/Hz) be the slope of the radiometer response beyond the band edge. Since most of the signal is picked up within an effective bandwidth of $4.35/k$ which is typically 0.5 MHz, the upper limit of infinity in the integral is justified if the frequency range beyond the radioastronomy band edge is fully utilized over a few megahertz. Then we have

$$P = AS \int_{f_0}^{\infty} 10^{-\{a_0 + k\,(f-f_0)\}/10} \, \mathrm{d}f = 4.45 \times 10^{-a_0/10} \, AS/k \tag{1}$$

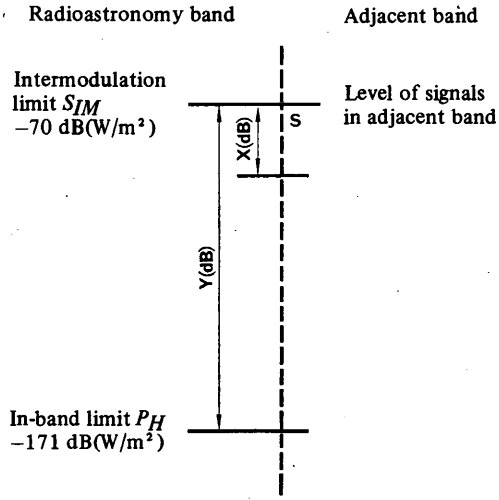

FIGURE 4 – *Signal levels in the vicinity of the band edge (Numerical values refer to the 5 GHz radioastronomy band)*

X dB : attenuation required at signal frequency at the band edge

Y dB : overall attenuation required at the band edge

The maximum tolerable power levels for radioastronomy operation given in Table I of Report 224 are in the range 10^{-17} to 10^{-21} W for typical bandwidths at frequencies greater than 1 GHz. For a continuous signal with $S = 2 \times 10^{-13}$ W/(m^2 · Hz), the level 10^{-21} W will not be exceeded if, for example, the response at the band edge, a_0, is 102 dB and the slope, k, is 50 dB/MHz, assuming a value of A of 10^{-3} m^2 (isotropic gain at approximately 3 GHz). The value of k is much less critical than a_0, and for $k = 10$ dB/MHz the same power level is received with $a_0 = 109$ dB. Some examples of required response characteristics are summarized in Table III in which isotropic response of the radio telescope is assumed.

For pulsed radar signals, assuming the same collecting area and a response at least 100 dB down, the peak power received will not exceed 10^{-21} W for power flux-density levels below 10^{-8} W/m^2. The effect of pulsed interference of low duty cycle in a radioastronomy system depends upon the type of observation being made, and may sometimes be no greater than that of a continuous signal at the same mean power level. In such cases, the −100 dB band edge response may allow operation in the presence of strong radar signals. On the other hand, the effects of overloading during the pulse could be important and lead to intermodulation effects as described below.

TABLE III – *Examples of the required response characteristics of radioastronomy receivers*

Service	Assumed distance of transmitter (km)	Typical mean signal levels at observatory	Required band-edge response of receiver (dB)
(1)	(2)	(3)	(4)
Broadcasting satellite (maximum allowable flux)	36000	5×10^{-18} W/(m^2 · Hz)	− 56 to − 63
Typical radio-relay transmitter	60	2×10^{-13} W/(m^2 · Hz)	− 102 to − 109
Airborne radar (10 W mean power)	10 300	10^{-8} W/m^2 10^{-11} W/m^2	− 100 − 70

3.2 *Non-linear effects within the receiver*

Two or more signals, present simultaneously at the receiver input but each falling outside the receiver passband, can, due to non-linearity or overloading within the receiver, give rise to a signal within the receiver passband. The most important effect is likely to be third-order intermodulation in which signals at frequencies f_1 and f_2, near one edge of the passband, regenerate components $(2f_1 - f_2)$ or $(2f_2 - f_1)$ within the band.

The intermodulation performance of a given amplifier is conveniently described in terms of an intermodulation intercept point [McVay, 1967], typical values of which range from about -55 dBW for a parametric amplifier to about -40 dBW for a transistor amplifier, both values being referred to the amplifier input.

An effective interfering signal of ΔP_H (dBW) could result from intermodulation of out-of-band signals of equal amplitude. S_{IM}, given by:

$$S_{IM} = \frac{1}{3}(2IP + \Delta P_H) \qquad \text{dBW} \tag{2}$$

where IP (dBW) is the input level to which the intercept point corresponds. Adopting the values of ΔP_H given in Report 224 and assuming an isotropic antenna, the corresponding power flux-density limits can be derived. Values appropriate to the primary radioastronomy bands are given in Table IV, using the values of IP quoted above. If the power flux-density of signals in the vicinity of the radioastronomy bands exceeds these levels, additional attenuation by means of passive filters at the input of the receiver would be needed.

The overall design requirements are summarized in Fig. 4; the values apply to a parametric amplifier operating in the 5.0 GHz band and assume an isotropic antenna response. Taken in conjunction with the data of Table III it appears that the response of a radiometer should be -100 to -110 dB down at the band-edge for frequencies in the GHz range, and correspondingly greater if the out-of-band source lies in a direction in which the telescope response is greater than isotropic. For radar or other signals having a peak power flux-density greater than about 10^{-7} W/m^2 filtering at the input stages would also be necessary.

TABLE IV – *Typical values of power flux-density of signals of equal strength which might cause interference by intermodulation*

Examples of bands allocated to radioastronomy	Mean power flux-density (dB(W/m^2))	
	Parametric amplifier	Transistor amplifier
25.55-25.67 MHz	– 112	– 102
1400-1427 MHz	– 80	– 70
2690-2700 MHz	– 76	– 66
10.68-10.7 GHz	– 63	–
15.35-15.4 GHz	– 58	–
23.6-24.0 GHz	– 52	–
31.3-31.5 GHz	– 50	–
86-92 GHz	– 40	–
105-116 GHz	– 36	–
217-231 GHz	– 25	–

3.3 *The attainable performance of practical receivers*

The precise design of any receiving system is likely to be influenced by the practical limitations of complexity and cost and also by the application for which the receiver is required, for example, as between continuum and line measurements or between single antenna and interferometer applications. The figures quoted here are intended to represent the best which can be achieved using current techniques without a disproportionate expenditure. In some cases, a slightly better performance might, in principle, be possible; in others, for example, where interferometric and, more particularly, interferometric spectral line measurements are involved, owing to the additional requirements of phase matching and stability and uniform passband response, a lower limit to the achievable rejection of adjacent-channel signals may be appropriate.

3.3.1 *Intermediate-frequency filtering*

For reasons of sensitivity, it is desirable that the effective (−3 dB) bandwidth of the receiver be as large as practicable. Since, for a given design of filter, the ratio of the −3 dB bandwidth to, say, the −100 dB bandwidth is a constant, it follows that the percentage of the radioastronomy band effectively available will be independent of the actual allocated bandwidth. The relative rate of cut-off provided by different filter designs depends on the filter type and on the number of filter sections employed.

Catalogue specifications of filter manufacturers indicate that a single filter of twelve sections, or three filters each of six sections placed in different parts of the receiver, could provide a −3 dB bandwidth of 60% of the −100 dB bandwidth. Filters having a total of more than about twenty sections are likely to introduce severe problems of alignment and stability and the use of the three eight section filters, providing a −3 dB bandwidth of 75% of the −100 dB bandwidth is likely to represent the limit of practicability. The overall receiver response provided by the latter filter arrangement is shown in Fig. 5. For interferometers, however, use of three eight section filters is likely to be prohibited by the phase requirements of the system.

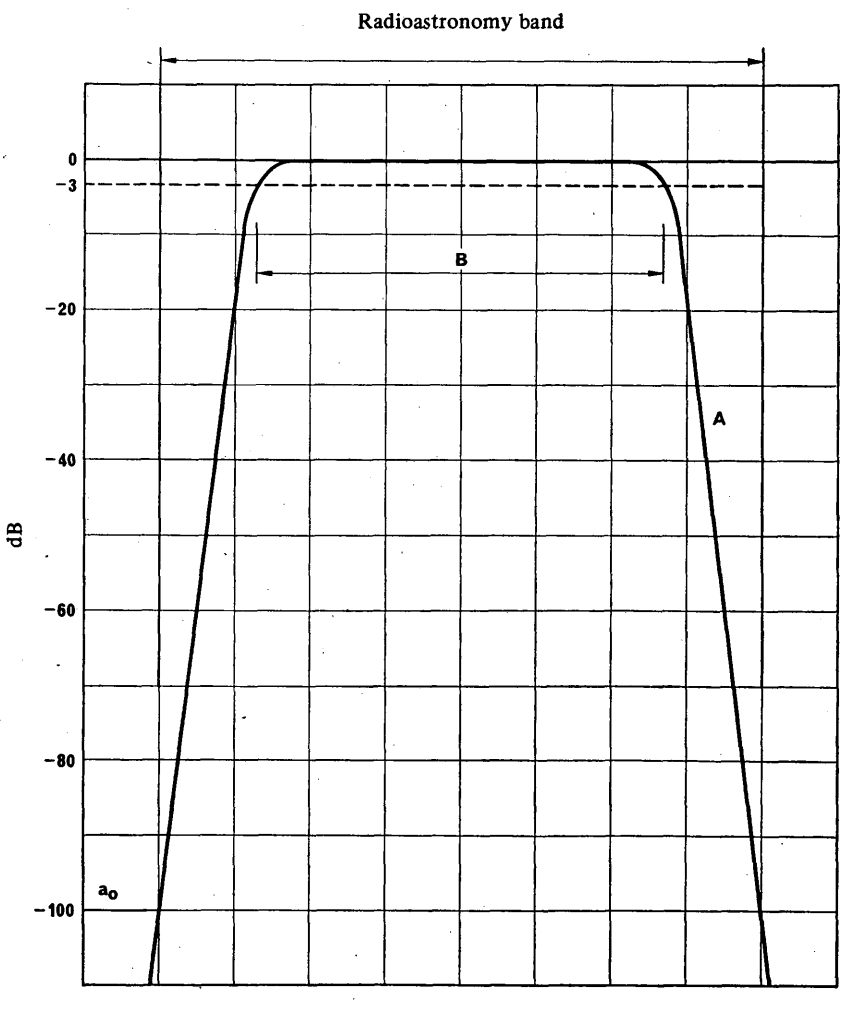

FIGURE 5 – *Relationship between a radioastronomy band and the required receiver characteristic*

A: Slope $-k$ dB/MHz

B: Half-power bandwidth

3.3.2 *Signal frequency filtering*

Severe restrictions are placed on the design of any input filter due to the requirement for very low loss in the passband. Overall system input noise temperatures of less than 100 K are readily obtainable in the 1 to 10 GHz range by the use of uncooled parametric amplifiers and an input filter having an in-band attenuation of only 0.15 dB is then sufficient to degrade the performance of the system by over 10%. In cases where the filter can be incorporated in a cooling system already in use by the amplifier, this difficulty can be largely overcome, but the addition of cooling to an otherwise uncooled system would result in a considerable increase in cost and operational complexity.

The development [Atia and Williams, 1971] of wave-guide cavity filters may also have application to radioastronomy receivers, but it would appear that signals having levels near the upper limit of those listed in Table III could, if situated within about 5 MHz of the band edge, present severe problems of receiver design.

4. Conclusions

An examination of the problem of interference to the radioastronomy service from transmitters in other bands has yielded a number of conclusions.

- Transmitters operating in bands adjacent to radioastronomy bands, particularly if high powered, may require output filters and close attention to good design to reduce out-of-band radiation to acceptable levels.
- Satellite transmissions are a particular hazard to radioastronomy observations in adjacent channels.
- Harmonics and intermodulation products from high-powered terrestrial transmitters or from satellites pose a problem to radioastronomical observations. Such transmitters may require filters but the design problem is not a difficult one.
- In general, allocating bands which are adjacent to radioastronomy bands, to services using high-powered terrestrial transmitters or transmissions from satellites, may lead to difficult, and expensive, technical problems. In addition the need for guard bands may lead to an inefficient use of the radio spectrum.
- Radioastronomy receivers may need to be equipped with very carefully designed IF filters to discriminate against radiation in adjacent bands. In spite of the best design procedures 25% to 50% of the radioastronomy band may need to be sacrificed to achieve the necessary discrimination.

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ANNEX I

EMISSION MEASUREMENTS OF THE ATS-6 SATELLITE IN THE 2690-2700 MHz RADIOASTRONOMY BAND

1. Introduction

The band 2500 to 2690 MHz is allocated to the broadcasting-satellite service, in addition to other space and terrestrial services. Adjacent to this band is the 2690 to 2700 MHz band which is allocated to the radioastronomy service. The first opportunity to make measurements of the potential interference to radioastronomy from a broadcasting satellite in orbit occurred after the launching of the United States of America's Application Technology Satellite (ATS-6) which was launched into the geostationary-satellite orbit on 30 May 1974, and positioned at 94° W longitude. This Annex provides the results of the measurements made by the Pennsylvania State University Radio Astronomy Observatory (PSURAO), during the periods June 1974 and April 1975 [Hagen and Swanson, 1975; Hagen *et al.*,1975]. A more detailed account of these measurements and of the operation of the satellite is given in Report 698 (Kyoto, 1978).

2. ATS-6 2670 MHz system characteristics

A major ATS-6 experiment during the first year of operations was the Health, Education, and Telecommunications Experiment (HET). HET featured daily transmissions in the 2600 MHz band of quality colour television in wideband FM format to small receiving systems located at schools, hospitals, and other institutions in Alaska, the Rocky Mountain States, and Appalachia [Whalen, 1975]. The TV-FM signals from earth stations were received in the 6 GHz band on the Earth Coverage Horn (ECH) of the satellite. The signals were then amplified, down-converted to IF where they were further amplified, filtered and limited. The signals were then converted to the 2560 or 2670 MHz band for final high power amplification and fed to the 9.1 m paraboloid antenna from its prime focus. A diplexer which coupled the output in the 2670 MHz band to the transmitting antenna was specifically designed to reduce the ATS-6 emissions in the 2690 to 2700 MHz band. This diplexer provided a minimum of 17 dB attenuation at 2690 MHz while maintaining an acceptable insertion loss in the 2655 to 2685 MHz band. The diplexer design criterion was to reduce the spectral power flux-density in the radioastronomy band below -247 dB(W/(m^2 · Hz)). This criterion of -247 dB(W/(m^2 · Hz)) is given in Report 224.

3. The PSURAO radiometer

The radiometer used for these tests was normally used for solar observations and thus did not have the high sensitivity upon which the CCIR interference criterion was based (Report 224). The radiometer receiving antenna was pointed directly at ATS-6 for all tests and the results were later referred to the isotropic gain condition for comparison with the CCIR criteria. The radiometer used conventional crystal mixing, a 30 MHz IF, and diode Dicke switching against a 300 K load. An 8-pole filter was inserted between the 1st and 2nd IF amplifiers to sharpen the passband. A signal generator and frequency counter replaced the normal 2725 MHz local oscillator. This permitted the radiometer passband to be accurately centred about different frequencies. The radiometer bandwidth, determined primarily by the filter, was 7 MHz at -3 dB, 12 MHz at -10 dB and 15 MHz at -40 dB.

The r.m.s. fluctuation temperature was approximately 0.5 K for a one second integration time. With the receiving antenna used, this corresponds to a spectral power flux-density of -241 dB(W/(m^2 · Hz)), or 6 dB above the CCIR interference criterion. The receiving antenna was a fully steerable 9.1 m diameter paraboloid fed with a linearly polarized horn. The half-power beamwidth was approximately 1° in the horizontal plane.

4. June 1974 test programme

During this period the following 3 radiometric measurements were made:

- centred at 2670 MHz; to determine the mean incident flux-density of the main in-band TV signal;
- centred at 2695 MHz; to determine the mean incident flux-density of the out-of-band signal appearing in the radioastronomy band;
- centred at a succession of frequencies across both bands to determine the power spectral density in the region of the edge of the band.

These results, shown in Fig. 6, were observed at the satellite footprint -4.5 dB contour and at a point where the incremental spreading loss relative to nadir was approximately 0.5 dB. Thus, they are not the maximum flux-density produced on the surface of the Earth; they must be increased by 5 dB when referenced to beam centre at nadir. Curve B in Fig. 6 shows the satellite spectrum near the edge of the radioastronomy band and was obtained from curve A by a deconvolution process to correct for the effect of the radiometer frequency response.

While most of the interference observed with the radiometer tuned to 2695 MHz (signal level $-240\pm\frac{1}{2}$ dB(W/(m^2 · Hz)) was due to the response of the radiometer to the main broadcast in-band signal (that is below 2690 MHz), a significant amount was due to the radiation of the satellite within the radioastronomy band (dashed curve in Fig. 6). The measured flux would have been greater if the 8-pole IF filter had not been used to improve the selectivity of the radiometer, and had the low pass filter on the transmitter output not been used.

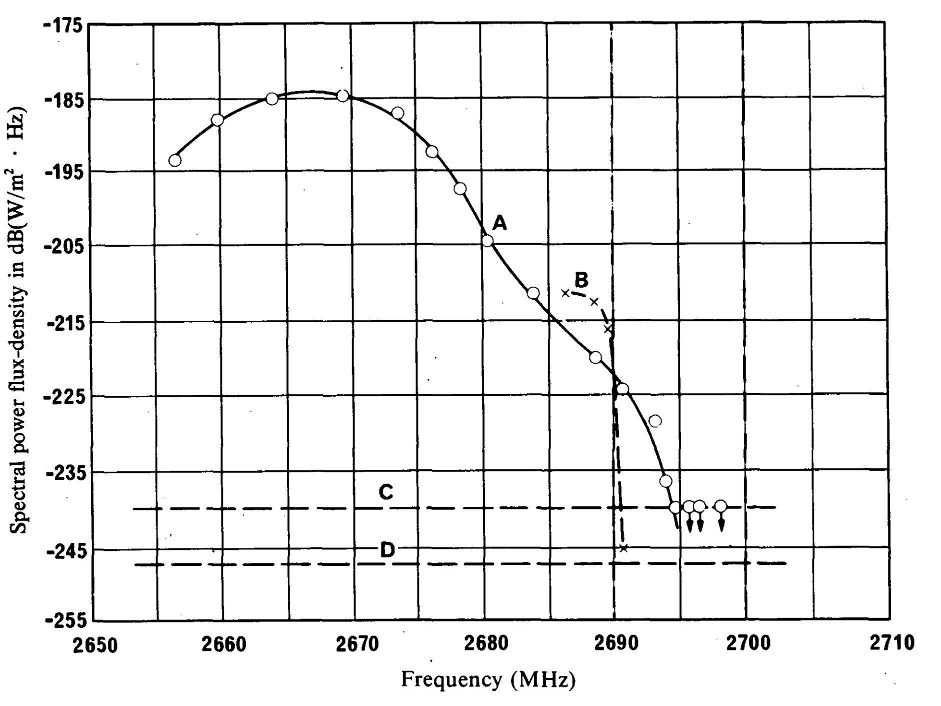

FIGURE 6 – *Radiometer output and ATS-6 flux density*

A : radiometer output
B : ATS-6 flux-density derived from curve A
C : PSURAO minimum fluctuation level
D : CCIR criterion

From Fig. 6, it is seen that the interference contained in the radioastronomy band (2690-2700 MHz) is almost all contained within one megahertz of the edge of the band. It is -223 dB(W/(m^2 · Hz)) at band edge and falls off at approximately 25 dB/MHz. The interference would have been well below the CCIR limit (-247 dB(W/(m^2 · Hz))) (see Recommendation 314) had the carrier frequency of the transmitter been 2 or 3 MHz lower than that used.

5. The April 1975 test programme

The purpose of this test was to characterize the out-of-band emissions as a function of the carrier modulation, the up-link signal strength and the spacecraft received carrier-to-noise ratio. Analysis and pre-launch test data indicated that under normal satellite operating conditions the principal source of ATS-6 emissions in the radioastronomy band was re-radiated satellite receiver noise and therefore dependent upon the satellite received signal strength. The results showed an inverse relationship between the strength of the up-link signal and the power flux spectral density in the radioastronomy band, in rough agreement with the expected result. Further details can be found in Report 698 (Kyoto, 1978).

6. Conclusions

The series of ATS-6 measurements have demonstrated that if mutual precautions are taken, there can be reasonable assurance that radioastronomy observations will not suffer harmful interference from satellites with the characteristics of ATS-6. As illustrated in Fig. 6, not only must the output of the satellite-borne transmitter be filtered to sharply reduce the amount of spurious emission in the neighbouring band, but the radiometers must exhibit sharp adjacent band rejection to minimize the effects of the large power spectral density associated with broadcasting satellites. With the best available filters, the CCIR limits can be achieved without excessive loss in bandwidth by the transmitter and without incurring severe penalties in system design or operation.

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ANNEX II

SUPPRESSION OF INTERFERENCE TO THE RADIOASTRONOMY SERVICE FROM OUT-OF-BAND RADIATION FROM A JAPANESE METEOROLOGICAL SATELLITE

A band-rejection filter was inserted in the output of the band 9 (1681.6 MHz) transmitter of the geostationary meteorological satellite (GMS) of Japan (see Report 395) which was launched in July 1977 and which is used to transmit data from a visible and infra-red spin-scan radiometer (VISSR) to an earth station. In Fig. 7, two curves are shown: one shows the estimated spectral power flux-density in the radioastronomy band from GMS before insertion of the band rejection filter (pfd_0) and the other after insertion of the filter (pfd_1); both are based on the actual output power measurement of the satellite transmitter. The insertion loss of the filter at the centre frequency of 1681.6 MHz is a small fraction of 1 dB and the effect on the error ratio of the VISSR signal (with the filter inserted) received at the earth station is negligible. The interference to the radioastronomy service due to other signals transmitted by the GMS is expected to be less than that of the VISSR. In Fig. 7, the results of actual measurements are also shown. The measurements were made at the radioastronomical observatory at Parkes, Australia, after the GMS launch. It can be seen that the results shown are in general agreement with the calculations discussed above.

Report 224 lists the harmful interference level in the band 1660 to 1670 MHz as -237 dB(W/(m$^2 \cdot$ Hz)), if the gain of the radioastronomy antenna is 0 dB in the direction of the satellite. When equipped with the band-rejection filter the signal from the GMS is much below this level at all frequencies within the radioastronomy band. In fact, over most of the band the margin is about 60 dB for the estimated level and about 50 dB for the measured level. Thus harmful interference will be caused only when the radioastronomy antenna is observing so that its gain in the direction of the satellite is close to the latter value. Observations at any observatory should be unaffected except within a few beamwidths of the satellite.

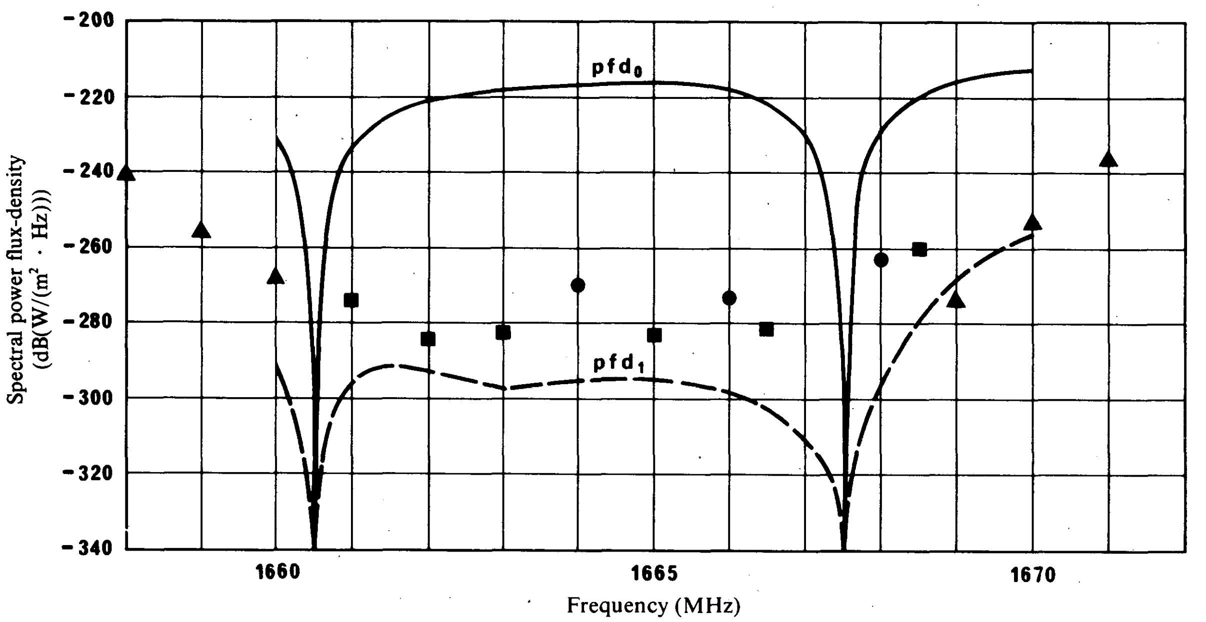

FIGURE 7 – *Estimated and measured spectral power flux-densities at the surface of the Earth in the radioastronomy band emitted by GMS*

pfd_0 : estimated spectral power flux-density before insertion of band-rejection filter

pfd_1 : estimated spectral power flux-density after insertion of band-rejection filter

● February, 1979 measurements with 4 MHz bandwidth

▲ June, 1979 measurements with 1.8 MHz bandwidth

■ June, 1979 measurements with 4 MHz bandwidth

RECOMMENDATION 517-1 *

PROTECTION OF THE RADIOASTRONOMY SERVICE FROM TRANSMITTERS IN ADJACENT BANDS

(1978-1982)

The CCIR,

CONSIDERING

(a) the value of the scientific results achieved by the radioastronomy service through the exploration of the Universe;

(b) the need for interference-free bands at intervals throughout the radio spectrum in order that radio-astronomy measurements can be made;

(c) the levels of interference that the CCIR consider to be harmful to the radioastronomy service, as given in Report 224;

(d) the desire on the part of both active and passive users of the radio-frequency spectrum to operate in harmony without mutual interference as evidenced by the provisions of Article 6, Nos. 339 to 343 of the Radio Regulations;

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* This Recommendation should be brought to the attention of Study Groups 4, 7, 8, 9, 10 and 11.

(e) that No. 344 of the Radio Regulations in many cases does not unambiguously provide needed protection for radioastronomy from transmitters operating in frequency bands adjacent to a band allocated to the radioastronomy service;

(f) the difficulties currently being experienced by radio services in the design and utilization of transmitters to operate in frequency bands adjacent to a band allocated to the radioastronomy service, in such a manner as to afford adequate protection from harmful interference to the radioastronomy service;

(g) the possible future increase in the level of usage of frequency bands adjacent to bands allocated to the radioastronomy service, particularly by airborne and satellite transmitters;

(h) that it is incumbent on both active and passive radio services to find means to minimize harmful interference, acting both separately and in cooperation with each other, with due consideration for the efficient use of the radio-frequency spectrum,

UNANIMOUSLY RECOMMENDS

1. that all practical, technical means, for example, the use of filters, be adopted both in radioastronomy receivers and in adjacent band transmitters to the maximum practicable extent, in order to reduce interference to the radioastronomy service;

2. that when frequencies are assigned to a station in a service operating in a band adjacent to one allocated on a primary basis to radioastronomy, attempts should be made to limit the edge of the necessary band adjacent to the radioastronomy band, so that the power radiated within this band should produce no harmful interference to a station of that service;

3. that when future frequency assignments are made by administrations in bands adjacent to those allocated to radioastronomy, on an exclusive or primary basis, account should be taken, to the maximum extent practicable, of the special risk of interference to radioastronomy observations from space-to-Earth and airborne transmissions, within the adjacent bands;

4. that taking into account § 1, 2 and 3 above, practical solutions to the band-edge interference problem be sought by administrations individually and if necessary in cooperation, and that proposals for solutions to the problem be considered at the next competent World Administrative Radio Conference.

REPORT 853-1

THE EFFECT OF A POWER SATELLITE SYSTEM UPON GROUND-BASED RADIOASTRONOMY AND RADAR ASTRONOMY

(Question 5/2 and Study Programme 5A/2)

(1982–1986)

This Report is a condensed and edited version of Report 853 (Geneva, 1982) which assesses the probable effects upon radioastronomy and radar astronomy of a satellite power system, as defined for study purposes by the United States Department of Energy and the National Aeronautics and Space Administration [Reference System Report, 1978]. The system includes 60 satellites which would be spaced at 1° intervals along the geostationary-satellite orbit, each with a photovoltaic array of dimensions 10.4 km × 5.2 km to enable 6.7 GW of solar power to be collected and transmitted to Earth at 2.45 GHz. The transmitting antenna would have a diameter of 1 km to allow 77% of the radiated power to be collected and converted to useful d.c. power by a receiving and rectifying antenna array (rectenna) on the Earth of dimensions 10 × 13 km. Interference to radioastronomy and radar astronomy could occur in the following ways.

The power signal at 2.45 GHz would have a typical flux-density of 0.01 W/m^2 at an observatory no closer than 100 km to the nearest rectenna. This level, received in the side lobes of a radio telescope, could cause overloading of a parametric or FET amplifier, or loss of sensitivity resulting from the insertion loss of the necessary filtering. Harmonics of the power signal could cause overloading when antennas are pointed close to the satellites, and when observing in the radioastronomy band close to the second harmonic.

Noise generated by the transmitting tubes, which might be klystrons or magnetrons, could be spread over many mehagertz in frequency, and would not be beamed towards the rectenna but radiated widely.

Thermal noise from solar cell arrays could exceed the harmful limits of flux density for radioastronomy given in Report 224.

Unwanted signals associated with failures of transmitting tubes, failure of phase-lock circuits, and warm-up and switching transients would require careful study. For example, with 70 kW klystrons a total of over 5×10^6 tubes would be required in orbit. With a mean time to failure of 25 years per tube, the failure rate would be over 20 per hour.

Noise and intermodulation products with other signals would be generated at the rectenna.

The effects upon radio and radar astronomy should be interpreted in terms of the discussion of harmful interference levels in Report 224. In particular, the band of sky centred upon the geostationary-satellite orbit within which observations would be precluded presents a serious problem. Interference from the satellites would be most serious in bands close to the fundamental frequency and its harmonics. Natural shielding between observatories and rectenna sites would be important.

For further details of the system and its predicted interference effects, see Report 679 and the Bibliography below.

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REPORT 854-1 *

INTERFERENCE TO RADIOASTRONOMY FROM MICROWAVE OVENS OPERATING IN THE 2450 MHz ISM BAND

(Question 5/2)

(1982-1986)

1. Introduction

The band 2450 ± 50 MHz is designated for Industrial, Scientific and Medical (ISM) equipment and is widely used for domestic microwave ovens. Although not a radio service, the power levels involved (0.5 to 2 kW) are such that out-of-band spurious or harmonic radiation can represent a potential problem for these services and, in particular, the radioastronomy service, since energy is not entirely confined within the oven. This Report considers the possible levels of interference at radioastronomy observatories from such equipment.

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* This Report should be brought to the attention of Study Group 1 and the CISPR.

2. Characteristics of the radiation

Microwave ovens typically use a magnetron which is operated from rectified (but unsmoothed) AC power. To avoid dominant standing-wave patterns, the oven cavity often incorporates a rotating paddle. The resulting fundamental radiation comprises a number of frequencies, covering a range of some 10 to 30 MHz around the nominal frequency, pulsed at 100 Hz and swept in frequency over a few MHz by the rotation of the paddle. In addition to this primary radiation, intermodulation products exist over a frequency range from some tens of MHz up to 7 to 8 GHz. Of these, the components above about 1 GHz are the more likely to be important for radioastronomy.

The results of measurements in the United Kingdom on three ovens are shown in Fig. 1 comprising one commercial and two domestic examples [Anderson *et al.*, 1979]. The values refer to the measured peak field strength in a 30 kHz band (normalized to a distance of 30 m) from a measurement distance of 3 m from the front of the oven. The radiation showed no preferred polarization. These data essentially corroborate earlier measurements by the United Kingdom Post Office. Outside the allocated band, peak field strengths are typically 30 dB(μV/m) with values some 20 dB higher in the vicinity of the radioastronomy bands near 2700 MHz and the second harmonic frequency of the ovens (4900 ± 100 MHz). Mean values in a 10 MHz band are some 15-20 dB lower.

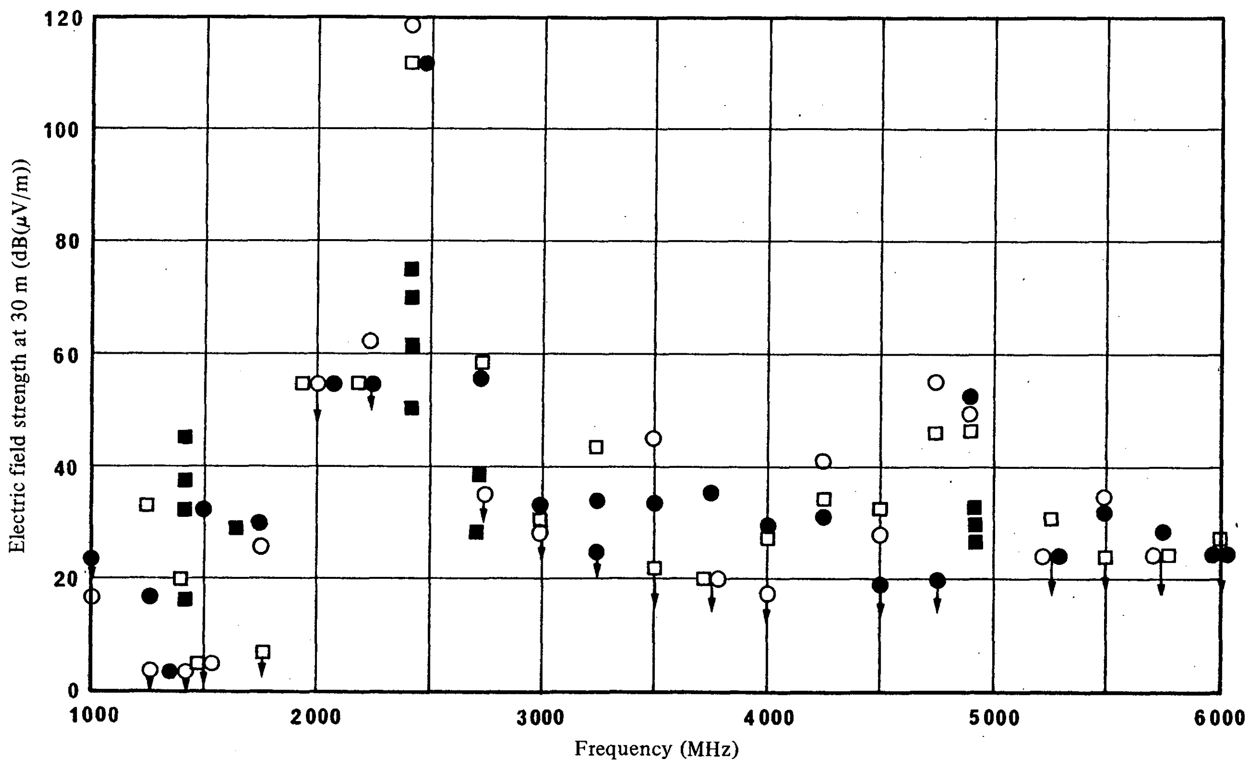
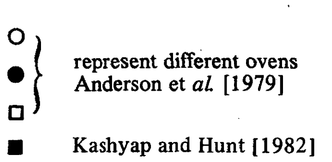


FIGURE 1 – *Field strengths in a bandwidth of 30 kHz, normalized from a measurement distance of 3 m*



Results of measurements of emissions from four microwave ovens have recently been published [Kashyap and Hunt, 1982]. The measurements on both horizontal and vertical polarization covered the range 30-10 000 MHz. Results obtained in the band 1000-6000 MHz are plotted in Fig. 1 as dB(μV/m) in a band of 30 kHz at a distance of 30 m. The observations were actually taken with a bandwidth of 100 kHz and 5 dB was subtracted from the measured values to convert to 30 kHz on the assumption of uniform spectral density within the 100 kHz band. If peak field strengths are independent of bandwidth then these values should have been plotted 5 dB higher in Fig. 1. The leakage at the fundamental frequency of 2450 MHz and at the second harmonic at 4900 MHz was lower in these tests than in those mentioned in the previous paragraph and no emissions were observed between 3000 MHz and 4900 MHz. All four ovens showed relatively strong spurious signals at 1413 MHz in the centre of the radioastronomy band.

Spurious emissions were also observed [Kashyap and Hunt, 1982] from two of the four ovens at 7350 MHz and 9800 MHz. The observed levels were close to those shown in Fig. 1 for 4900 MHz.

Attempts to measure the spurious emissions in the 30-1000 MHz range were hindered by high background noise levels. There was no noticeable radiation between 500 MHz and 1000 MHz from any of the ovens. Between 100 MHz and 500 MHz emissions were observed but at levels below the noise and only upper limits could be assigned. Below 100 MHz, spurious emissions were observed from all four ovens and from two of the ovens at measurable levels. The field strengths at a distance of 30 m were in the range 20-35 dB(μV/m) but were measured in a bandwidth of 1 MHz and are not directly comparable with the measurements at higher frequencies.

3. Interference to radioastronomy observations

Levels of harmful interference in the allocated radioastronomy bands are quoted in Report 224. Several factors have to be considered when applying these criteria to the case of microwave ovens:

- Microwave ovens will normally be operated inside buildings. In favourable circumstances this may provide an additional attenuation of 30 dB but it could be as little as 2 to 3 dB. For the present an additional attenuation of 15 dB will be assumed.
- With the currently increasing use of microwave ovens it is likely that a number of such devices will be within the vicinity of a radioastronomy observatory. An additional factor of +10 dB is included to allow for multiple interfering sources operating simultaneously.
- The pulsed nature of the radiation may be particularly serious for observations of, for example, the pulse-profile of pulsars or the scintillation spectrum of radio sources. In such cases the peak value of the interfering signal must be considered. On the other hand, for continuum observations using long time-constants the mean power is the relevant quantity. Consider, as two extreme cases:

  (a) continuum observations as described in Report 224, and

  (b) pulsar observations in which integrated pulse profiles are determined with a time resolution of 10^{-3} s and an effective integration time of 10 s, corresponding, for example, to observing a pulsar of pulse-period 0.1 s for 10^3 s.

The calculations have been made for three of the radioastronomy bands most likely to be affected and are based on the measurements of [Anderson *et al.*, 1979]. Table I gives, for each of the two cases (a) and (b):

- the level of harmful interference; and
- the corresponding mean and peak flux-densities measured in a 10 MHz band at a distance of 30 m from a microwave oven.

TABLE I – *Data relating to interference to radioastronomy from microwave ovens*

Nominal radioastronomy frequency (MHz)	Harmful level of interference (dB(W/m²)) in a 10 MHz band		Power flux-density in a 10 MHz band at 30 m from a microwave oven (dB(W/m²))	
	Continuum (1)	Pulsar measurement	Mean	Peak
1420	– 182	– 170	– 130	– 117
2700	– 177	– 165	– 108	– 85
5000	– 171	– 159	– 132	– 112

(1) Harmful levels for continuum are from Report 224, modified where necessary for a 10 MHz bandwidth.

Table II lists the respective distances within which a microwave oven would exceed the harmful level under the assumptions of:

– a factor of −15 dB for the attenuation provided by a building;
– a factor of 10 dB to allow for a number of ovens operating simultaneously; and
– free-space propagation between the interfering sources and the radioastronomy antenna.

TABLE II – *Estimated distance within which harmful interference would be experienced*

Frequency (MHz)	Continuum measurement (km)	Pulse-profile measurement (km)
1420	6.7	7.5
2700	47.5	168.7
5000	1.5	3.8

4. Conclusions

Although for distances of more than a few kilometres it is not valid to assume free-space propagation, it is nevertheless clear from Table II that microwave ovens are a potential source of interference to radioastronomical observations, particularly in the 2700 MHz band, and that further studies are called for. In particular, detailed measurements of the out-of-band emission from a large sample of ovens and investigation of the attenuation provided by buildings in typical installations would be valuable. Such data would allow more precise calculations of the probable levels of interference and be of value in assessing the suitability of particular observatory sites.

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REPORT 539-1 *

THE PROTECTION OF RADIOASTRONOMY OBSERVATIONS IN THE SHIELDED ZONE OF THE MOON **

(Question 7/2)

(1974–1978)

The electromagnetic spectrum is now so heavily used on Earth that much of its potential value for passive scientific research has already been seriously affected. Since all indications point to a general increase in radiocommunications over the next decade, especially with earth satellites, spacecraft, and deep-space probes, it is important that frequency allocations by the International Telecommunication Union be coordinated to minimize interference with radioastronomy. In particular, since the far side of the Moon is the remaining accessible place where radio observations of the Universe will be possible without interference over the whole radio spectrum; it will be necessary to allocate frequencies for active use by deep-space probes, lunar satellites, scientific instrument packages and research stations on the lunar surface in such a way, that interference with such passive observations is avoided.

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* This Report is brought to the attention of Study Group 1.

** Propagation aspects of this subject are discussed in Report 336, of Study Group 5.

Part of the Moon's surface is always protected from interfering signals generated on and near the Earth because the Moon always presents nearly the same side towards the Earth. It has a period of rotation about its axis equal to its period of revolution around the Earth, but because its orbit is slightly elliptical and inclined, observers on Earth can see somewhat more than half the surface of the Moon. If, in addition, the Moon is viewed from an earth satellite in an orbit of 100 000 km radius, another small fraction is seen. The remaining invisible portion of the Moon's surface is that defined as the shielded zone of the Moon in Article 29, No. 2632.1 of the Radio Regulations, and lies more than 23.2° beyond the mean limb of the Moon as seen from the centre of the Earth. The shielded zone of the Moon includes the shielded area of the Moon's surface and also includes an adjacent volume which is shielded from interference originating within a distance of 100 000 km from the centre of the Earth.

It is important that low-frequency radioastronomical studies be shielded from interfering signals from the Earth and satellites (such as very low frequency topside ionosonde experiments), since such observations are difficult to perform on Earth below 40 MHz, and particularly below 10 MHz, due to ionospheric opacity and inhomogeneities. These low-frequency studies are capable of providing important data on solar activity, cosmic rays and magnetic fields in our galaxy, and on the low frequency spectra of quasars and pulsars.

Radioastronomy observations are either difficult or impossible above 20 GHz because of atmospheric opacity due to strong transitions of H_2O and O_2. Although observations are feasible in the atmospheric windows. Some important observations of galactic and intergalactic objects and of complex and interesting interstellar molecules can only be made in the absence of an atmosphere, and the absence of interference of these transition frequencies is of great importance in the shielded zone of the Moon.

Terrestrial radioastronomical observations between 40 MHz and 20 GHz are difficult for two other reasons; one arising from the increased scale of operations of the active radio services, and the other from the increasing requirements of radioastronomy which tend to be augmented even further owing to the discovery of new types of celestial bodies and the invention of new observational methods and equipment.

The shielded zone of the Moon is expected to be free from terrestrial interference over the whole frequency spectrum. It is a unique site for scientific observations. As it is expected that radioastronomical and other scientific experiments will soon be carried out in this zone, it is essential to regulate the activities of the radio services whose facilities may illuminate it. Account must be taken of the requirements of Earth satellites, deep space probes and transmitters located in the shielded zone of the Moon, on the understanding, however, that it is desirable to maintain the shielded zone of the Moon as a zone free from radio interference and hence of great value for passive observations.

The use of the frequency spectrum by services with facilities which are located in the shielded zone of the Moon or which illuminate it could be based on the following preliminary set of guidelines, which will need to be reviewed as additional information is received.

The entire radio frequency spectrum in the shielded zone of the Moon is designated as available for passive users (the Radioastronomy Service and other passive users as defined in the Radio Regulations), with the following exceptions:

- Frequency bands currently available and allocated in the future to the Space Research Service, and those frequency bands in the Space Operation Service, the Earth Exploration-Satellite Service and the Radiodetermination-Satellite Service, that are required to support space research;

- Frequency bands currently available or allocated in the future for radiocommunication and for space research transmissions within the lunar shielded zone.

The proposed guidelines do not impose any restriction on existing or future terrestrial radio services or on existing or future space radio services, the transmitters of which are switched on at a distance of less than 100 000 km from the centre of the Earth.

Under the proposed guidelines, existing or future space radio services the transmitters of which are switched on at a distance of more than 100 000 km from the Earth and which operate in accordance with the Radio Regulations should coordinate their activities with the Radio Astronomy Service. It is essential that provisions governing compatibility between the Radio Astronomy Service and other services, based on the technical features of the services, be specified by a decision adopted by an ITU Administrative Conference.

RECOMMENDATION 479-2*

PROTECTION OF FREQUENCIES FOR RADIOASTRONOMICAL MEASUREMENTS IN THE SHIELDED ZONE OF THE MOON

(Question 7/2)

(1974-1978-1982)

The CCIR,

CONSIDERING

(a) that some radioastronomical and other scientific experiments are difficult, and in certain cases impossible, to carry out on the surface of the Earth because of tropospheric and ionospheric absorption, scintillation, and radio interference;

(b) that radioastronomical discoveries resulting from limited observations from spacecraft above the atmosphere of the Earth reveal unexpected new astronomical phenomena;

(c) that further developments will enable experiments to be carried out in the relatively quiet environment in the shielded zone of the Moon;

(d) that, in addition to the establishment of line-of-sight communication links for scientific and other purposes between the Earth and spacecraft, it may be necessary to establish links between stations on the far side of the Moon and other stations on or visible from the Earth;

(e) that the shielded zone of the Moon is free from terrestrial radiation at all radio frequencies;

(f) that Article 29, Nos. 2632-2635 of the Radio Regulations recognizes the necessity of maintaining the shielded zone of the Moon as an area of great potential for observations by the radioastronomy service and by passive space research and consequently as free as possible from transmissions;

(g) that earth satellites with high apogees, deep-space probes and transmitters located on the Moon may each illuminate the shielded zone;

(h) that Report 539 contains preliminary guidelines on the use of the frequency spectrum in the shielded zone of the Moon,

UNANIMOUSLY RECOMMENDS

1. that in planning the use of the radio spectrum, both nationally and internationally, account be taken of the need to provide for radioastronomy observations in the shielded zone of the Moon;

2. that, in taking account of such a need, special attention should be given to those frequency bands in which observations are difficult or impossible from the surface of the Earth;

3. that the frequency spectrum should be used in the shielded zone of the Moon in keeping with the preliminary guidelines contained in Report 539;

4. that in the frequency bands which would be considered for joint use by active and passive space stations in the shielded zone of the Moon, radioastronomy observations should be protected from harmful interference. To this end appropriate discussions between concerned administrations may be conducted.

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* This Recommendation is brought to the attention of Study Groups 1 and 5.

REPORT 226-5 *

FACTORS AFFECTING THE POSSIBILITY OF FREQUENCY SHARING BETWEEN RADAR ASTRONOMY AND OTHER SERVICES

(1963–1966–1970–1974–1978–1982)

1. Introduction

A radar astronomy system has a paradoxical nature with regard to factors affecting frequency sharing. Radar astronomy receivers have sensitivities comparable with the best radioastronomy receivers and also need to have protection from severe interference. Radar astronomy transmitters develop, and antennas radiate high power, so that they are capable of interfering with other services over significant distances, which may be appreciably extended by scattering from space objects such as the Moon and spacecraft, or by means of scattering media such as the troposphere and the ionosphere.

Although radar astronomy is a relatively new discipline, it is responsible for a number of notable achievements. For example, the accuracy of orbital information on the planets has been improved by a factor of more than one thousand by these means. It has likewise been shown that Venus rotates on its axis in the direction opposite to the rotation of most solar system objects (retrograde rotation). Contrary to the inference drawn from optical observations, it has been shown by radar observations that the rotation of the planet Mercury is synchronous at 2/3 of its orbital period. The radar reflectivity of the Sun varies with solar activity, and the spectrum of the echoes shows effects which are believed to be due to large mass motions of the solar plasma and outward flow of the solar wind. As with other advances made using radar astronomy, much of this knowledge is based on information that cannot at present be obtained using any other ground-based technique [Pettengill, 1978].

Radar astronomy systems in the past have generally been outgrowths of components developed for other services; indeed, many systems put to radar astronomy use have had some other primary purpose. This situation now appears to be changing however, with the most sensitive current systems being designed specifically to optimize radio and radar performance in astronomical research. Thus, the specific needs of radar astronomy should be separately stated.

Unlike a radioastronomy system detecting cosmic noise, the channel bandwidth required for radar astronomy can be much smaller, in general only that required to encompass the modulation band, Doppler spread, and Doppler shift encountered. Radio- and radar-astronomy systems are similar, in that they require large antennas, sensitive receivers and low tracking rates.

Many similarities exist between radar astronomy systems and deep-space tracking facilities. These, or other similar facilities on Earth, may also be used in a bistatic mode, where the second terminal (receiver or transmitter) is in a space probe, for important radar studies of the planets and the interplanetary medium.

2. The problem of radar astronomy

The salient problem in radar astronomy is the detection and study of targets at long ranges. These targets may be small in angular extent relative to the antenna beam, e.g. the planets; or extended, e.g. the terrestrial ionosphere.

The detection range of a system for a quasi-point target is as follows:

$$R^4 = \frac{Const.\ PA^2}{T\lambda^2} \tag{1}$$

where, R is the range, P the transmitted power, A the effective area of the duplexed antenna, T the operating noise-temperature and λ the wavelength. For extended targets, we have

$$R^2 = Const.\ PA/T \tag{2}$$

* This Report is brought to the attention of Study Group 1.

Both relations point to the fundamental importance of large powers, large antennas and sensitive receivers.

The detectability of the planets and of several asteroids by radar has been established by a number of observers. The detection of many other solar system objects may be expected in the future (Fig. 1) [Pettengill, 1970].

The problem of signal design for radar astronomy has been treated in a way that allows consideration of propagation, multipath, and reflection effects in the optimization of the modulation, as well as the associated detection features [Green, 1968]. In general, the frequency spectrum, occupied by such transmitted signals and those reflected from the target, is narrow compared with that desirable for observation of cosmic noise. The spectral width of radar astronomy signals is more akin to that commonly used in spectral-line radioastronomy. However, because of the coherent nature of radar signals, and because correlation with the transmitted wave form is generally used, several orders of magnitude of interference tolerance can be gained, as compared with radioastronomy. Unwanted narrow-band emissions are less likely to cause trouble because there is little probability that they will fall in the receiver passband. Incoherent interference can be suppressed to a degree by correlation techniques in signal processing.

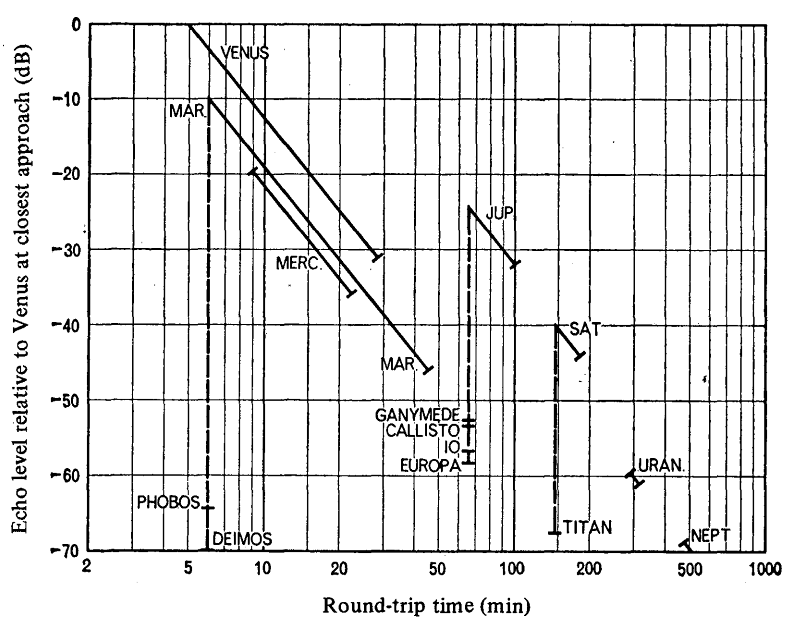

FIGURE 1 – *Guide to the detectability of the planets by radar; atmospheric absorption has not been considered in the figures and will greatly reduce the actual detectability of the giant planets*

An estimate of the channel bandwidth required to allow an adequate receiver offset for Doppler shift, can be obtained by considering a specific problem in planetary detection. Beyond this, little can be said regarding susceptibility of the system to interference without some detailed discussion of a particular system.

The radar Doppler shift is given approximately by: $f_d = f_c 2\ v/c$ where f_d is the Doppler frequency shift, f_c the carrier frequency, v the radial velocity of the target and c the speed of light. Considering the entire orbit of some planets, for example, the fraction $2\ v/c$ can be evaluated, and is about 3×10^{-4} for Mercury. The Doppler spread is a result of differing Doppler shifts from the various parts of a target reflecting volume.

Radar astronomy receivers have many features in common with the radiometers used in radioastronomy. Receiver designs have progressed to the point where the sensitivity of the system is limited by environmental background noise. As a result, any generalized approach to the appraisal of the susceptibility to interference of radar astronomy receiving systems would be along lines identical to those used for communication-satellite stations and for radioastronomy. Reports on this subject have already been prepared [Evans and Hagfors, 1968; Evans, 1969] (Report 224).

3. Frequency characteristics of experimental radar astronomy systems

Most experimental radar astronomy systems have operated at frequencies allocated to radiolocation services, because these services have borne the costs of transmitter component developments and radar astronomy makes use of the available equipment in the interest of economy. However, there are a few specific cases wherein the nature of the scientific study strongly affects the choice of frequency. For example, studies of the solar plasma to certain depths by radar astronomy techniques require the use of frequencies in the 20 to 60 MHz range.

4. Susceptibility of radar astronomy receiving systems to other signals

Any signal that significantly increases the operating noise-temperature of the receiving system would be troublesome to the radar astronomer. This effect is primarily a function of the average power of the interfering signal. As an illustration, a 400 MHz system at the Lincoln Laboratory's Millstone Hill site and airborne altimeters, shared the same band in the frequency allocation table. Ideally, in this specific case, the unwanted signal level at the output terminals of the radar astronomy antenna should not exceed 5×10^{-23} W/Hz. At higher frequencies, where the background noise is lower, the unwanted signal level should be reduced further. To achieve these levels of protection will require time sharing or other special arrangements that may not always be possible on a local basis.

5. Indirect sources of interference

Scattering of the transmitted signal (or harmonics thereof), for example from the Moon, troposphere, and orbiting objects, can, under certain conditions, be a hazard. In questions of sharing, these effects should be considered on a case-to-case basis.

6. Interference by radar astronomy to terrestrial receivers

High power is produced by radar astronomy transmitters and this power is usually confined to a fairly narrow beam by the large antenna. In many instances, the antenna beam is directed at such high elevation angles that interference is effectively limited to that radiated from the side lobes. (For large parabolic reflectors, a reference side-lobe pattern is contained in Recommendation 465.) This holds also for systems operating in the 20 to 60 MHz range, where the path angle of elevation limits ionosphere forward-scatter primarily to the side lobes. Typical powers for radar astronomy transmitters are given in Table I.

7. Conclusions

7.1 Adequate management of interference, involving high-power radars, is normally effected on a local basis.

7.2 Many functions of radar astronomy installations can be carried out on a frequency-sharing basis. There are instances, however, where a channel of modest bandwidth within the radiolocation bands concerned, may be cleared or protected on a local or regional area basis for certain radar astronomy experiments.

7.3 When the frequency range in use is dictated by natural phenomena (e.g., solar and other plasma investigations), local or regional arrangements may be required.

7.4 From the point of view of availability of equipment, it is desirable that radar astronomy systems be operated in or near frequency bands for which high-power transmitting technology has reached a suitable degree of development.

7.5 As with other high-power installations, radiolocation stations used for radar astronomy observations should be sited with great care, to minimize mutual interference problems with stations operating in the same and adjacent bands.

TABLE I – *Comparison of some systems of radar astronomy*

Organization	Location	Approximate frequency (MHz)	Antenna		Effective area (m^2)	Mean power (kW)	Peak power (kW)	Pulse duration	System noise-temperature (K)
			Diameter (m)	Gain (dB)					
Calif. Inst. Tech. JPL	Goldstone Lake, Calif.	2.4×10^3 8.5×10^3	64 64	62 72	2000 1500	400 375	400 375	CW ([1]) CW ([1])	20 25
Cornell Univ. National Astronomy and Ionosphere Center	Arecibo, Puerto Rico	2.4×10^3 4.3×10^2	214 304	72.0 60.0	20 000 39 000	400 150	400 2 500	CW 0.03 to 10.0 ms	40 120
Instituto de Geofisica de Peru	Jicamarca Radar Observatory Lima (Peru)	50	285 (Square array)	42.6	84 000	250	6 000	0.01-1000 ms	2 000-3 000

([1]) Radiates unmodulated carrier.

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QUESTIONS AND STUDY PROGRAMMES, RESOLUTIONS, OPINIONS AND DECISIONS

QUESTION 1-1/2

FREQUENCY SHARING BETWEEN SPACE RESEARCH LINKS AND OTHER SERVICES

(1961-1963-1970-1978)

The CCIR,

CONSIDERING

(a) that sharing of the radio spectrum between space research links and some other radio services may be necessary, because of the limited frequency spectrum available to support the world's communication requirements;

(b) that factors which determine the ability to share the frequency spectrum are strongly interdependent,

UNANIMOUSLY DECIDES that the following question should be studied:

1. to what extent is sharing feasible between Space Research and other Services;

2. how do the following factors, among others, affect the practicability of sharing:

2.1 location of earth and space stations of a space link and the resulting zone of mutual visibility;

2.2 time of use during periods of mutual visibility;

2.3 probability of occupancy of the zones of mutual visibility by space research links and those of other services, and the associated sharing problems;

2.4 Doppler frequency variations due to spacecraft velocities relative to earth stations and the consequent bandwidth requirements;

2.5 other system parameters such as modulation techniques, antenna directivity, etc.;

2.6 natural and man-made interference;

3. what are the technical factors relating to coordination procedures?

Note. – See Recommendation 578 and Reports 548, 581, 628, 684, 685, 687 and 985.

STUDY PROGRAMME 1C/2

PROTECTION CRITERIA FOR SPACE RESEARCH TELECOMMUNICATION LINKS

(1978)

The CCIR,

CONSIDERING

(a) that some of the bands allocated to space research are shared with terrestrial services;

(b) that bands allocated to other space services could be shared by the Space Research Service and terrestrial services;

(c) that suitable criteria should be established as a basis for the protection of space research from other space and terrestrial services;

(d) that such criteria should take into account the spectral characteristics of the interfering signals, the time pattern of the interference in relation to the time pattern of the system operation, and the protection afforded by the geometry of the interfering links;

(e) that the requirements for space research may be more stringent than those for other space systems, particularly for deep-space research which requires the reception of signals at much lower power flux-densities than are generally used in other radio systems and, hence, is subject to harmful interference at signal levels which could be tolerated by many other systems;

(f) that interfering signals from above the horizon may offset the partial protection to deep-space earth stations afforded by remotely located sites,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the practical interpretation of the definition of harmful interference to the Space Research Service with reference to Article 1, No. 163 of the Radio Regulations;

2. determination of minimum levels of wanted input signals for which receiving systems for space research are expected to be designed;

3. determination of the levels of signals which can cause harmful interference to space research receiving systems, taking into account modulation of wanted signals and spectral characteristics of the interfering signal;

4. development of interference protection criteria applicable to near-Earth and deep-space research systems, taking into account both the signal levels to be protected and the temporal probabilities of interference.

Note. – See Recommendation 609 and Reports 685 and 985.

STUDY PROGRAMME 1D-1/2

THE FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH SATELLITES AND TERRESTRIAL SYSTEMS

(1978–1986)

The CCIR,

CONSIDERING

(a) that satellites of the space research service share frequencies both on an equal and secondary basis with terrestrial systems;

(b) that many of the Regulations addressing the power flux-density levels, produced by satellites, were derived from studies of dense populations of geostationary and non-geostationary satellites. These studies may not be applicable to lesser population densities of low-orbit earth satellites considered separately (see Report 387);

(c) that low-orbit earth satellites with mean altitudes less than 1100 km are visible to terrestrial systems considerably less than 100% of the time (see Report 684);

(d) that the probability that a single 1100 km low-orbit earth satellite is within the main beam of a single terrestrial station is very low (see Report 684);

(e) that a recommended level/time distribution of permissible interference into a hypothetical reference terrestrial system, provides a boundary to be met by the aggregates of both long and short term interfering emissions produced by shaved services operating on an equal allocation basis;

(f) that low-orbit earth satellites, when seen from terrestrial system locations, are continuously in motion, resulting in continuously changing coupling factors such as path loss, transmit antenna gains, receive antenna gains and Doppler effects,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the conditions under which, and the extent to which, it may be feasible for space research satellite systems to share frequencies with terrestrial services;

2. the criteria that affect the selection of sites for earth stations in space research satellite systems, taking into account the various bands of the radio-frequency spectrum available for space research;

3. the determination of the preferred technical characteristics of transmitting and receiving antennas for spacecraft and for earth stations at fixed locations, from the standpoint of spectrum sharing with other services;

4. the criteria that affect the determination of the maximum power (in a reference bandwidth) which may be radiated in the horizontal plane by an earth station;

5. the criteria that affect the determination of the minimum angle of elevation which should be used at earth stations;

6. the degree to which physical modification of earth station sites will provide electromagnetic shielding between these earth stations and stations in other services;

7. the criteria that affect the determination of the minimum practicable separation between stations in the space research service and in other services, taking into account the modulation systems used;

8. the determination of the technical criteria that may be used for coordination purposes to avoid mutual interference;

9. the determination of the influence of the following factors on sharing between space research satellites and terrestrial systems including airborne terrestrial systems;

9.1 the population and orbital parameters of space research satellites;

9.2 the orbital motion of space research satellites;

9.3 the emission spectrum used on space research communications links and the interaction with the receiver transfer functions of terrestrial system receivers;

9.4 the configurations of terrestrial systems including antenna types, numbers of receivers and typical system locations and direction;

9.5 the typical flight and mission requirements for airborne terrestrial systems;

9.6 the atmospheric fading effects on, and diversity structures of, terrestrial systems;

10. the determination of the power flux-density which will not cause levels of interference exceeding those recommended as permissible (for primary or secondary allocation status) into terrestrial systems, including airborne systems, from space research satellites in the following orbits:

10.1 low,

10.2 elliptical,

10.3 geosynchronous;

11. the determination of the combined effects of the power flux-density from space research satellites in various orbits.

Note. – See Reports 684, 687, 981 and 985.

STUDY PROGRAMME 1E/2

FEASIBILITY OF FREQUENCY SHARING BETWEEN DEEP-SPACE RESEARCH STATIONS AND STATIONS OF OTHER SERVICES

(1978)

The CCIR,

CONSIDERING

(a) that deep-space research earth stations, in tracking and communications with deep-space spacecraft, must gradually move their antenna pointing from the eastern horizon to the western horizon each day to compensate for the Earth's rotation;

(b) that over a period of six months to a year of operation, each deep-space earth station antenna may point from 30° South declination to 30° North declination approximately;

(c) that during certain times of the year, the earth station antenna beam may point towards a given point on the geostationary satellite orbit for several minutes each day;

(d) that future deep-space missions out of the plane of the ecliptic will increase declination angles to near ± 90° at which time the earth station antenna will for long periods of time hold a nearly fixed direction relative to the Earth;

(e) that a deep-space research earth station with a 64 m diameter antenna may transmit a beam with an e.i.r.p. of 127 dBW;

(f) that the typical received signal from a deep-space spacecraft may have a power flux density as low as -250 dB(W/m^2) at the earth station antenna;

(g) that the gain of a typical earth station antenna is greater than 0 dBi over an angular region much larger than that covered by the main beam (see Recommendation 509);

(h) that the transmitter of a near-Earth space station operating on or near the receiving frequency of the deep-space research earth station, may illuminate the deep-space research earth station antenna with a power flux density that is 30 dB to 100 dB greater than that received from the deep-space spacecraft,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the conditions for which sharing may be feasible between deep-space research stations and stations of other Services;

2. determination of the probabilities of the power spectral flux densities with which deep-space research earth station antenna beams may illuminate the locations of geostationary, geosynchronous and non-synchronous near-Earth satellites;

3. determination of the probability of interference between stations of terrestrial Services and deep-space research stations in shared bands;

4. determination of the expected power flux densities from near Earth satellites, or aircraft stations, which will illuminate stations of deep-space research systems;

5. determination of the mutual interference probabilities as a result of the power flux densities and illumination probabilities given under § 2, 3 and 4 above;

6. determination of the preferred baseband and modulation characteristics which will reduce sharing problems.

Note. – See Report 685.

QUESTION 3/2*

EFFECTS OF PLASMA ON COMMUNICATIONS WITH SPACECRAFT

(1963-1970)

The CCIR,

CONSIDERING

(a) that ionospheric plasma has been observed to have a considerable effect upon the operation of transmitting and receiving antennas mounted on rockets and spacecraft;

(b) that the plasma produced by the shock wave resulting from the entry of a spacecraft into a planetary atmosphere may have analogous effects on the performance of the satellite equipment and on the propagation of radio waves near the spacecraft;

(c) that similar effects may be caused by the plasmas associated with propulsion systems,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the effects of plasmas on the operation of transmitters and receivers, and particularly of the antennas on board spacecraft;

2. what factors determine the formation and structure of the plasmas associated with a spacecraft;

3. what communication problems (wave propagation and noise) are represented (in particular during re-entry into the terrestrial atmosphere), as a result of the plasma;

4. what influence do these effects exert on the choice of usable frequencies, especially during the entry of a spacecraft into a planetary atmosphere?

Note. – See Recommendation 367 and Report 222.

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* The above Question is brought to the attention of URSI, by the Director, CCIR.

STUDY PROGRAMME 3A/2

FREQUENCY BANDS FOR RE-ENTRY COMMUNICATIONS

(1963-1970)

The CCIR,

CONSIDERING

(a) that communication with a spacecraft during the re-entry phase may be crucial during many missions;

(b) that the optimum frequency is dependent upon the configuration of the spacecraft and its re-entry speed;

(c) that Recommendation 367 emphasizes the potentialities of frequencies above 10 GHz for re-entry communications;

(d) that because the transparency of the plasma sheath increases with frequency, it is desirable to consider frequencies up to 50 GHz and the atmospheric windows above the oxygen absorption band at about 60 GHz;

(e) that Report 222 mentions the theoretical possibility of communicating at frequencies well below the critical frequency of the plasma sheath,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. investigation of the technical suitability of frequencies above 10 GHz for re-entry communications;

2. investigation into the feasibility of communicating at frequencies well below the critical frequency of the plasma sheath.

QUESTION 5-2/2

TECHNICAL FACTORS INVOLVED IN THE PROTECTION OF RADIOASTRONOMICAL OBSERVATIONS

(1961-1963-1970-1974-1982)

The CCIR,

CONSIDERING

(a) that radioastronomy is based on the reception of natural emissions at much lower power levels than are generally used in other radio services, and may therefore suffer harmful interference which could be tolerated by many other services;

(b) that, for an understanding of astronomical phenomena, radio astronomers must observe both at specific and immutable line frequencies and also in a series of bands throughout the continuum spectrum,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the general areas of interest in the radio-frequency spectrum to the radioastronomy service;

2. what are the characteristics of radioastronomical sources and observational techniques;

3. what are the factors which affect the practicability of frequency sharing between radioastronomy and other radio services;

4. in what ways can radioastronomy observations be affected by spurious and other out-of-band emissions from radio transmitters located in other frequency bands and by other electrical equipment?

Note. – See Recommendations 314, 611 and Reports 224, 696, 697, 699, 852, 853 and 854.

STUDY PROGRAMME 5A-1/2

CRITERIA FOR EVALUATION OF INTERFERENCE TO RADIOASTRONOMY

(1974–1982)

The CCIR,

CONSIDERING

(a) that under the Radio Regulations, frequency bands have been allocated to radioastronomy for both line and continuum observations;

(b) that harmful interference to radioastronomy observations may be caused by unwanted signals of very low power;

(c) that other services operate in many of the bands in which radioastronomy has allocations, or use high-power transmitters in bands adjacent to, or harmonically related to, those used for radioastronomy;

(d) that the increasing number of transmissions from spacecraft may introduce problems of interference to radioastronomy and that these cannot be avoided by choice of site for an observatory or by local protection;

(e) that Recommendation No. 61 of the Radio Regulations requests information relating to criteria for harmful interference to radioastronomy;

(f) that Resolution No. 63 of the Radio Regulations invites the CCIR to continue studies relating to industrial, scientific and medical (ISM) equipment, to ensure adequate protection of radiocommunication services,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the practical interpretation for the radioastronomy service, of harmful interference as defined in No. 163 of the Radio Regulations;

2. the threshold levels of unwanted signals which, if exceeded for more than specified percentages of time, will cause harmful interference, and the dependence of the criteria on the nature of the radioastronomical observations;

3. the levels of interference which may occur at typical observatory sites*, due to various sources of interference, including:

3.1 transmissions of other services operating in the bands used for radioastronomy observations;

3.2 harmonics, intermodulation products, and sidebands from transmitters in other frequency bands;

3.3 other sources of electrical interference including ISM equipment;

4. the influence of reflections from aircraft and earth satellites in increasing the risk of interference;

5. the response of typical radioastronomy receivers to signals in frequency bands adjacent to the nominal receiver acceptance band;

6. the special precautions which may be necessary, on the part of radio astronomers and the operators of the other services, when a transmitter which is a potential source of interference is in a spacecraft or an aircraft within the field of a radioastronomical observatory.

Note. – See Recommendation 611 and Reports 224, 696, 697 and 853.

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* Propagation data for this study will be required from Study Groups 5 and 6. The existence of Study Programme 29C/6 (Man-made radio noise) should also be noted.

QUESTION 6-1/2

RADAR ASTRONOMY

(1963–1970–1974)

The CCIR,

CONSIDERING

(a) that radar astronomy is a part of pure science, contributing to our knowledge through studies of the reflecting properties of natural and man-made targets; advancing the study of celestial mechanics by direct measurements with great precision, of the motions and distances of orbiting bodies; and through the study of the nature and effects of the propagating medium;

(b) that the receiving techniques of radar astronomy require sensitivities equivalent to those of radio astronomy;

(c) that the problems of detection, location, tracking and determination of ephemerides are common to radar astronomy and spacecraft tracking and communication systems;

(d) that radar astronomy transmitters, antennas and receivers are seldom developed solely for this application, but are ordinarily the outgrowths of the most advanced transmitter technology developed for other purposes;

(e) that radar astronomy has immediate application to spacecraft missions in providing basic data required for the computation of trajectories and ephemerides for space objects;

(f) that radar astronomy frequencies are not generally tied to the frequencies associated with natural phenomena, the exception being special experiments on the atmospheres of the Earth and the planets,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the performance characteristics of radar astronomy systems;

2. what levels and durations of interfering signals are tolerable in radar astronomy reception;

3. what factors, both technological and scientific, are fundamental in the selection of frequencies for radar astronomy experiments?

QUESTION 7-3/2

FREQUENCY UTILIZATION ABOVE THE IONOSPHERE AND ON THE FAR SIDE OF THE MOON*

(1965–1966–1970–1974–1982–1986)

The CCIR,

CONSIDERING

(a) that some radioastronomical and other scientific experiments are difficult, and perhaps impossible, to carry out on the surface of the Earth by reason of tropospheric absorption and scintillation;

(b) that the advent of spacecraft has already permitted scientific observations to be made from vantage points above the ionosphere, and that further developments will enable experiments to be carried out in the relatively quiet environment on the far side of the Moon;

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* Information in Report 336 of Study Group 5 is relevant to this Question.

(c) that in addition to the establishment of line-of-sight communication links for scientific and other purposes between the Earth and spacecraft, it may be necessary to establish links between spacecraft above the ionosphere and also to establish links between stations on the far side of the Moon and other stations either on or visible from the Earth;

(d) that at frequencies below the critical penetration frequency of the ionosphere, the region above the ionosphere is relatively isolated from terrestrial noise and communication signals;

(e) that on the far side of the Moon an even greater degree of isolation from terrestrial radiation is provided at all radio frequencies;

(f) that Nos. 2632-2635 of the Radio Regulations recognize the necessity of maintaining the shielded zone of the Moon as an area of great potential for observations by the radioastronomy service and for passive space research and, consequently, as free as possible from transmissions,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the preferred means and routes for communicating between:

1.1 a station on the far side of the Moon and a station just above the ionosphere;

1.2 a station on the far side of the Moon and an earth station;

2. in what frequency bands would radioastronomical measurements have marked advantages as compared with observations from the surface of the Earth, if carried out:

2.1 on a station above the ionosphere;

2.2 on the far side of the Moon;

3. what frequency protection criteria should be adopted for:

3.1 a station above the ionosphere;

3.2 a station on the far side of the Moon?

STUDY PROGRAMME 7B/2*

SHIELDING EFFECTS DUE TO THE MOON

(1978)

The CCIR,

CONSIDERING

Question 7/2, and the fact that optimum utilization of frequencies on the far side of the Moon requires better understanding of the shielding effects due to the presence of the Moon,

UNANIMOUSLY DECIDES that the following studies should be carried out:

the variation of the shielding caused by the Moon, as a function of frequency, angular distance from the limb of the Moon to the centre of the far side, and the distance above the surface of the Moon.

Note. – See Recommendation 479 and Report 539.

* This Study Programme should be brought to the attention of Study Group 5.

QUESTION 10-2/2

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(1968–1970–1978–1986)

The CCIR,

CONSIDERING

(a) that studies are desirable in the field of radio propagation from spacecraft, with the object of enhancing our knowledge of the transmission of radio waves by and through the ionized and non-ionized regions of the atmosphere;

(b) that satellite radio beacon systems operating on either one frequency or two or more fixed frequencies which may or may not be harmonically related, now provide a powerful technique for enhancing our knowledge of the nature of the ionospheric conditions which are relevant to space research;

(c) that radio methods of measurement using spacecraft beacons provide for the determination of the orbital elements of satellites,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what regions of the spectrum are suitable for radio beacons which are used for:

1.1 radio-wave propagation studies;

1.2 atmospheric measurements;

1.3 tracking measurements for scientific purposes;

2. which of the above investigations would require long-term observations;

3. what specific relationships should exist between the various frequencies used for these investigations;

4. what is the maximum interference that can be tolerated in each of these investigations;

5. what are the factors affecting the sharing of the required frequencies with other radio services, and with other users in the Space Research Service;

6. what degree of coordination in the location of earth stations will be required if frequency sharing is deemed to be practicable?

Note 1. – Use of satellite beacons for geodetic applications is to be considered under Question 12/2.

Note 2. – See Recommendation 513 and Report 456.

STUDY PROGRAMME 10A/2

PROTECTION OF FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(1968–1970)

The CCIR,

CONSIDERING

that the protection from interference required for research based on the use of spacecraft transmitters as beacons is not necessarily the same as that required for the reception of space research telemetry and for tracking (see Recommendation 364),

UNANIMOUSLY DECIDES that the following study should be carried out:

the criteria to be adopted for the protection from interference ("noise-like" or "CW-type") of observations of beacon transmissions from spacecraft.

QUESTION 11-2/2

RADIO LINKS BETWEEN EARTH STATIONS AND SPACECRAFT BY MEANS OF DATA RELAY SATELLITES

(1970–1978–1982)

The CCIR,

CONSIDERING

(a) that some space research and earth exploration spacecraft (particularly those in low orbit) and some launch vehicles, will require continuous communication with the Earth;

(b) that such continuous communication using direct links between the Earth and spacecraft requires many earth stations;

(c) that the use of space stations in earth satellites for the purpose of control and data relay can considerably reduce the number of earth stations required;

(d) that the development of a space research data relay satellite system has been shown to be feasible;

(e) that the technical characteristics of links via space stations may be different from those of direct links between earth stations and spacecraft;

(f) that there may be particular advantages in the use of geostationary satellites as relay stations;

(g) that such satellites may be required to relay information to and from several satellites and launch vehicles simultaneously, particularly those in low orbit;

(h) that the use of data relay satellites may require the use of the same frequency bands in multiple directions;

(j) that this use of frequency bands may introduce new problems of interference within the various space services, and with other services in shared bands;

(k) that data relay satellites may be used for two-way communication with manned as well as unmanned spacecraft, particularly those in low orbit,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the operational and technical requirements for radio links between earth stations and spacecraft, particularly those in low orbit, by means of geostationary data relay satellites;

2. what are the desired technical characteristics of radio links between earth stations and spacecraft by means of geostationary data relay satellites;

3. what interference problems may arise within the various space services from the use of data relay satellites, particularly when these are used with several low-orbit satellites simultaneously;

4. what problems of frequency sharing with other services could arise in the operation of data relay satellite systems if the same frequency bands are used in multiple directions;

5. what constraints need to be placed on the operation of data relay satellites and the associated satellites or launch vehicles to enable frequencies to be shared with other services?

Note. – See Recommendation 510 and Reports 692, 846, 847, 848, 982 and 983.

STUDY PROGRAMME 11A-1/2

DATA RELAY SATELLITE SYSTEMS AND FACTORS WHICH AFFECT FREQUENCY SHARING WITH OTHER SERVICES

(1978–1982)

The CCIR,

CONSIDERING

(a) that continuous communications to and from spacecraft used for space research and earth exploration and to and from launch vehicles are desirable;

(b) that with available land-based tracking stations, various factors combine to limit coverage to only a fraction of a given orbit;

(c) that frequently critical decision points in a space mission occur when the spacecraft is beyond the line-of-sight of the earth stations;

(d) that expansion of the ground network is geographically and economically not feasible;

(e) that Report 848 concludes that with a few strategically located earth stations, utilization of a data relay satellite (DRS) can provide continuous or near continuous communication between spacecraft and the Earth;

(f) that experiments and studies, such as those mentioned in Report 848, have demonstrated the feasibility of a DRS system;

(g) that frequency requirements between the mission spacecraft and the data relay satellite may be satisfied by the frequencies which would normally be used for direct communication between the mission spacecraft and the earth stations;

(h) that the data relay satellite could relay mission-gathered data, television and voice communications in manned missions, orbit-tracking data such as position and velocity of the spacecraft, and telecommands for guidance and control of the spacecraft;

(j) that use of frequencies in bands 9 and 10 permit both the near-Earth satellite and the DRS to use antennas with substantial gain and directivity;

(k) that frequency bands below about 20 GHz are heavily occupied with existing and planned services;

(l) that frequency bands between 20 and 30 GHz are becoming more heavily occupied by existing and planned services;

(m) that frequency band 11 is only just becoming useful for spacecraft telecommunications and is not yet heavily occupied;

(n) that atmospheric attenuation at the higher frequencies tends to shield space-to-space services from terrestrial services;

(o) that antennas of a given diameter will have a narrower beamwidth at higher frequencies, thus allowing more efficient use of the spectrum and the geostationary satellite orbit;

(p) that the technology for the use of frequencies above 20 GHz is being developed;

(q) that use of the DRS could reduce future frequency requirements for near-Earth space research;

(r) that use of a DRS could result in a reduction of the number of required near-Earth satellite earth stations;

(s) that Report 847 concludes that sharing is feasible between a space research system involving a space station relay and terrestrial systems provided:

– that there are appropriate power flux-density limits for the relay satellite and the mission satellite;
– that careful selection of relay satellite and user spacecraft antenna will provide the required off-beam discrimination in the direction of terrestrial systems,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the parts of the radio frequency spectrum and the bandwidths preferred for data relay satellites;

2. the technical problems associated with the use of frequency bands above 20 GHz for data relay satellites;

3. the conditions under which and with what other services the sharing of the preferred frequencies for data relay satellites is practicable;

4. the preferred technical characteristics of telecommunications links for data relay satellites operating above 20 GHz;

5. the limits of power flux-density from the data relay satellites needed to protect other services sharing frequencies in bands 9, 10 and 11;

6. the necessary values for the data relay satellites and user spacecraft off-beam discrimination, especially in the direction of the stations of the shared terrestrial services in bands 9, 10 and 11.

Note. – See Reports 847 and 848.

QUESTION 12-2/2

RADIOCOMMUNICATION SYSTEMS FOR EARTH EXPLORATION, INCLUDING METEOROLOGICAL SATELLITES

(1970–1974–1978)

The CCIR,

CONSIDERING

(a) that the value of meteorological satellites has been demonstrated and that some types are now operating in a routine manner;

(b) that the use of satellites to survey the Earth is of great value in the discovery, assessment, development and management of the mineral, petroleum, water, timber, agricultural and fish resources of the Earth; in locating and tracking sea ice; in monitoring phenomena of nature such as earthquakes and volcanic eruptions; in monitoring air and water pollution; in geodetical studies; and in monitoring natural disasters (forest fires, tidal waves, floods), etc.,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the preferred characteristics of radiocommunication systems for obtaining information by earth exploration satellites and returning that information to Earth;

2. what is the feasibility of frequency sharing within the earth exploration satellite service;

3. what is the feasibility of frequency sharing with other Services?

Note. – See Recommendations 362, 514, 515, 516 and 577 and Reports 395, 692, 693, 694, 695, 987 and 988.

STUDY PROGRAMME 12A-2/2

RADIOCOMMUNICATION SYSTEMS FOR EARTH EXPLORATION SATELLITES (NOT INCLUDING METEOROLOGICAL SATELLITES)

(1970–1978–1982)

The CCIR,

CONSIDERING

(a) that experimental earth exploration satellite systems have demonstrated their value for obtaining data for aiding food production and the improvement, use and conservation of natural resources;

(b) that these satellites may be placed in different types of orbits;

(c) that the frequency requirements of radiocommunication systems for earth exploration satellites should be subject to international agreement;

(d) that active and passive sensors may require wide bandwidths;

(e) that radiocommunication systems employed by these satellites may require wide bandwidths substantially greater than those currently used for television transmissions,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the preferred technical characteristics and regions of the spectrum for earth exploration satellite radiocommunication systems;

2. determination of preferred types of radiocommunications for different orbits that earth exploration satellites may employ;

3. determination of criteria for sharing frequencies;

4. determination of techniques for efficient spectrum utilization.

Note. – See Reports 535, 540 and 692.

STUDY PROGRAMME 12B-1/2

SENSORS USED BY EARTH EXPLORATION AND METEOROLOGICAL SATELLITES

(1978–1986)

The CCIR,

CONSIDERING

(a) that many of the sensors used on Earth exploration and meteorological satellites depend on the detection, and in some cases the radiation, of radio signals;

(b) that the frequencies at which these sensors operate are determined largely by the physical characteristics of the materials or environment that are under investigation;

(c) that harmful interference to passive sensors may be caused by unwanted radiations of very low power;

(d) that some active sensing systems transmit signals that may interfere with other services;

(e) that active and passive sensors may require considerable spectrum space;

(f) that the frequency requirements of sensor systems for Earth-exploration satellites should be subject to international agreement,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the technical characteristics and suitability of frequency bands for active and passive sensors used by Earth-exploration satellites;

2. determination of the requirements for spectrum space that may be needed for active and passive sensors used by Earth-exploration satellites;

3. determination of the levels of interference that can be tolerated by the various types of sensors in the different frequency bands of interest;

4. determination of the power levels and signal characteristics of the active sensors that are under development or that have been proposed, and the level and nature of the interference caused by such signals to other services;

5. determination of the criteria for sharing active and passive sensor frequency bands with those used by other radio services.

Note. – See Recommendations 516 and 577 and Reports 693, 694, 695 and 850.

STUDY PROGRAMME 12C/2

RADIOCOMMUNICATION SYSTEMS FOR THE METEOROLOGICAL-SATELLITE SERVICE

(1963–1970–1978)

The CCIR,

CONSIDERING

(a) that meteorological-satellite systems are an important means of world-wide weather forecasting (World Weather Watch);

(b) that meteorological information is now gathered by meteorological satellites and relayed to earth stations;

(c) that these satellites may employ different type orbits – polar, equatorial or at intermediate angles and altitudes up to and including the synchronous altitude (36 000 km);

(d) that all of these orbits pass over, or are in view of, many different countries;

(e) that the international character of these systems dictates that the frequency bands employed to relay their collected meteorological data to Earth should be subject to international agreement;

(f) that this would facilitate the establishment of an international weather system and would minimize interference situations;

(g) that the evolution of such systems would be facilitated if frequency sharing with other services is practical,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the parts of the radio-frequency spectrum to be preferred for meteorological-satellite systems;

2. determination of the preferred types and characteristics of radiocommunication for such systems, both under development and in planning;

3. practicability of the sharing of frequencies and if so, with what services and under what conditions.

Note. – See Recommendation 362 and Reports 395, 541 and 851.

STUDY PROGRAMME 12D/2

RADIOCOMMUNICATIONS FOR EARTH EXPLORATION SATELLITES

Data collection and position location systems

(1978)

The CCIR,

CONSIDERING

(a) that data collection systems for relaying data from fixed and mobile platforms, and for position location of such platforms have been proven to be feasible;

(b) that operational data collection systems are now in being, or planned, for implementation by several administrations as part of a world-wide environmental data collection system;

(c) that a need for operational systems in addition to those operating and planned in the Meteorological Satellite Service has been identified by some administrations;

(d) that the choice of preferred frequency bands for systems to meet new requirements is determined by a number of factors, including propagation effects, receiver characteristics, the feasibility of frequency sharing with other services, antenna characteristics, and power limitations,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the preferred technical characteristics and regions of the spectrum for satellite data collection and position location systems;

2. determination of preferred radiocommunication systems for data collection and position location satellites at different orbital altitudes;

3. determination of criteria for sharing frequencies with those used by other radio services.

Note. – See Report 538.

STUDY PROGRAMME 12E/2

RADIOCOMMUNICATIONS FOR SATELLITE SYSTEMS FOR GEODESY AND GEODYNAMICS

(1986)

The CCIR,

CONSIDERING

(a) that it has been demonstrated that radio measurement methods using spacecraft permit the highly accurate determination of:

– orbital elements of satellites,
– geocentric positions of points on the Earth's surface,
– terrestrial distances, particularly intercontinental distances,
– the spacecraft altitude over the oceans and over ice,
– the gravitational field of the Earth;

(b) that such measurements provide essential information for research and applications in geodesy and geodynamics;

(c) that several administrations have already operated, or are planning, specific systems for providing such information;

(d) that certain radionavigation-satellite systems can provide information of the same kind;

(e) that the choice of preferred frequency bands for such systems depends particularly on the precision sought, available technology, propagation effects, the possibilities of sharing frequencies with other systems and power flux-density limits,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the preferred technical characteristics of satellite systems for geodesy and geodynamics;

2. determination of the preferred regions of the spectrum for radiocommunications for such systems;

3. determination of criteria for frequency sharing with other radio systems.

Note. – See Report 988.

QUESTION 14-3/2

FEASIBILITY OF FREQUENCY SHARING WITHIN AND AMONG SPACE RESEARCH SYSTEMS

(1972–1974–1978–1982)

The CCIR,

CONSIDERING

(a) that some space research frequency bands are presently used for both deep-space systems and for near-Earth systems;

(b) that it may not in all cases be possible for such systems to operate in the same frequency bands without harmful mutual interference;

(c) that the types of orbit occupied by deep-space probes and by near-Earth spacecraft have a marked influence on the feasibility of operating in the same frequency bands;

(d) that the geostationary satellite orbit is of particular interest to space system designers;

(e) that space research frequency allocations do not necessarily specify the spacecraft orbits in which they are to be used;

(f) that the classification of and subsequent frequency assignment for near-Earth and deep-space systems depends upon the definition of these terms,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the general problems associated with sharing between space research systems, taking into consideration both technical and operational characteristics;

2. how do the types of orbit, and system characteristics, including those of sensors, affect sharing involving near-Earth manned and unmanned systems, and deep-space manned and unmanned systems;

3. under what conditions and to what extent is it possible for space research systems to share frequency bands with each other;

4. what are suitable calculation and prediction methods to be used by system designers in complying with the applicable criteria for interference (see Recommendation No. 708 of the Radio Regulations);

5. what are the definitions of distances that will be most useful in the classification of space research missions and systems, for purposes of frequency allocation and frequency assignment, and for studies of sharing and of protection criteria?

Note. – See Recommendation 610 and Report 986.

STUDY PROGRAMME 14A/2

STUDY OF THE EFFICIENT USE OF VARIOUS ORBITS FOR SPACE RESEARCH

(1978)

The CCIR,

CONSIDERING

(a) that numerous spacecraft will be required to operate simultaneously for space research purposes;

(b) that substantial simultaneous transmission from space-research spacecraft will place a heavy burden on portions of the spectrum allocated to this purpose;

(c) that space-research spacecraft in orbits of about the same mean altitude and inclination may be phased so that they are not visible from the same ground point at the same time;

(d) that by utilizing spacecraft telemetering transmitters, the frequency of which may be changed by telecommand, several space-research spacecraft may communicate with geographically adjacent earth stations without mutual interference,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the effects of various types of orbits, communication and sensor characteristics upon frequency sharing between space-research systems;

2. the advantage of spacing of satellites in orbit in frequency sharing;

3. the advantages of switchable frequencies in telemetering transmissions from space-research spacecraft with respect to frequency utilization in the space-research service.

STUDY PROGRAMME 14B-1/2

FREQUENCY SHARING BETWEEN DEEP-SPACE AND OTHER SPACE RESEARCH SYSTEMS

(1978–1982)

The CCIR,

CONSIDERING

(a) that, with few exceptions, frequency allocations for space research are available for both near-Earth satellites and deep-space probes;

(b) that protection requirements for deep-space research may make frequency sharing between deep-space probes and near-Earth satellites difficult, and may involve serious problems of coordination;

(c) that the classification of and frequency assignment for near-Earth and deep-space systems depends upon the definition of these terms,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the practicability of frequency sharing between deep-space and near-Earth space research activities, taking into account:
- the statistical probability of interference between deep space bidirectional links, and the directions of transmissions of near-Earth space research systems;
- the fact that near-Earth satellites operate in various orbits either in the same or in different systems including geostationary satellites, and non-geostationary satellites, phased or unphased;

2. the criteria which affect the determination of the minimum elevation angles and other pointing constraints which may be required at earth stations to facilitate frequency sharing among space research systems;

3. the transmitter powers of space and earth stations, as they affect frequency sharing among space research systems;

4. the preferred technical characteristics of transmitting and receiving antennas for earth stations, from the standpoint of frequency sharing within the same system and with other space research systems;

5. the effects of baseband and modulation characteristics on frequency sharing among space research systems;

6. the definitions of distances that will be most useful in the classification of space research missions and systems, for purposes of frequency allocation and assignment, and for studies of sharing and protection criteria.

QUESTION 15-1/2

RESEARCH IN SPACE SYSTEMS TECHNOLOGY

(1974–1982)

The CCIR,

CONSIDERING

(a) that advances in technology will affect the application of space systems in most, if not all, the functional service areas of telecommunications;

(b) that these advances will generally result from the space research programmes of administrations,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what is the current state of space systems technology in such areas as attitude control, station keeping, spacecraft and earth station antennas, primary and secondary power systems, generation of radio-frequency power, thermal control, modulation techniques, problems of the space environment, and technical aspects of radio-frequency radiation hazards;

2. what improvements in performance are foreseen in these areas?

Note. – See Recommendation 509 and Reports 546, 672, 673, 674, 675, 676, 677 and 843.

STUDY PROGRAMME 15A/2*

ANTENNAS FOR SPACE RESEARCH SYSTEMS

(1978)

The CCIR,

CONSIDERING

(a) that the limitations on the physical size and beamwidth of antennas for earth and space stations are important factors in determining the useful frequency range for space systems;

(b) that ionospheric and other atmospheric effects, and techniques of fabrication, may limit the sizes of antennas and their minimum beamwidths;

(c) that interference to and from terrestrial as well as other space services is an important problem,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. what limitations to antenna beamwidth result from ionospheric and other atmospheric effects;

2. what is the state of relevant development in antenna design and fabrication;

3. what is the state of development of antennas with improved side-lobe and back-lobe characteristics;

4. what are the polarization characteristics of antennas, particularly in the side-lobe regions and in planes other than the principal planes;

5. what are the pointing accuracies and antenna beamwidth restrictions which result from system characteristics such as spacecraft attitude control and search and acquisition times;

6. what other factors limit spacecraft antennas usable gains, aperture and pointing accuracy.

Note. – See Recommendation 509 and Reports 675, 676 and 677.

STUDY PROGRAMME 15B-1/2**

SAFETY ASPECTS OF RADIO-FREQUENCY RADIATION FROM SPACE RESEARCH STATIONS

(1974–1982)

The CCIR,

CONSIDERING

(a) that radio-frequency energy is known to have harmful effects on the human body when absorbed in sufficient quantity;

(b) that determinations of hazardous radiation levels have been made by competent authorities;

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* This Study Programme should be brought to the attention of Study Groups 5 and 6.

** See Question 52/1 of Study Group 1. This Study Programme was formerly Study Programme 16A/2.

(c) that radio-frequency power flux-densities in excess of safe exposure levels may exist at a considerable distance* from space research earth stations;

(d) that persons not associated with earth stations may be exposed inadvertently to such radiation, including travellers by air,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the radio-frequency power flux-densities to be expected from space research earth stations;

2. the design precautions and technical operational procedures at space research transmitting stations which are necessary to prevent the exposure of human beings to hazardous radio-frequency radiation.

Note. – See Reports 543 and 682.

STUDY PROGRAMME 15C-1/2**

PROTECTION OF TELECOMMUNICATIONS EQUIPMENT FROM RADIO-FREQUENCY RADIATION FROM SPACE RESEARCH EARTH STATIONS

(1978-1982)

The CCIR,

CONSIDERING

(a) that radio-frequency energy is known to have degrading effects on electronic equipment when such equipment is irradiated above certain specified energy levels;

(b) that determinations of degrading radiation levels will be made by competent authorities assuming specific design or operational control procedures;

(c) that radio-frequency power flux-densities in excess of allowable exposure levels may exist at a considerable distance from space-research earth transmitting stations;

(d) that electronic equipment not associated with space research earth stations may be exposed inadvertently to such radiation,

UNANIMOUSLY DECIDES that the following studies should be carried out:

the design precautions and technical operational procedures at space research transmitting stations necessary to prevent the exposure of electronic equipments to harmful levels of radio-frequency radiation.

QUESTION 17-1/2

RADIOCOMMUNICATION REQUIREMENTS FOR SYSTEMS TO SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE

(1976-1982)

The CCIR,

CONSIDERING

(a) that many scientists believe intelligent life to be common in our galaxy;

(b) that electromagnetic waves are presently the only practical means of detecting the existence of intelligent extraterrestrial life;

(c) that it is believed to be technically possible to receive radio signals from extraterrestrial civilizations;

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* For example, the power flux-density in the antenna beam will be greater than 10 mW/cm^2 at a distance of 20 km from the 64 m diameter earth-station antenna at Goldstone, USA, when using a transmitter power of 500 kW.

** The attention of Study Groups 1, 4, 7, 8, 9, 10 and 11 is drawn to this Study Programme which was formerly Study Programme 16B/2. See also Question 52/1 of Study Group 1.

(d) that, although it is not possible to know the characteristics nor to predict the time or duration of these signals in advance, it is reasonable to believe that artificial signals will be recognizable;

(e) that, while an artificial radio signal of extraterrestrial origin may be transmitted at any frequency, it is technologically impractical to search the entire radio spectrum, but the band searched should be sufficiently wide to make detection of a signal reasonably probable;

(f) that technological and natural factors which are dependent on frequency determine our ability to receive weak radio signals;

(g) that the search for radio signals from extraterrestrial civilizations will use increasingly sensitive systems which could receive harmful interference from very weak man-made signals;

(h) that it is necessary to share with other services the bands in which the search is conducted;

(j) that available technology will allow a search for these signals from the Earth, from earth-orbit, and, eventually, from the Moon, and to minimize interference, certain locations on Earth and in space may be preferred,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the most probable characteristics of radio signals which might be broadcast by extraterrestrial civilizations and the technical characteristics and requirements of a system to search for them;

2. what are the preferred frequency bands to be searched and the criteria from which they are determined;

3. what protection is necessary for receiving systems conducting a search for artificial radio signals of extraterrestrial origin;

4. what criteria will make the operation of a search system feasible in shared, adjacent and harmonically related bands of other services;

5. what is the optimum search method;

6. what are the preferred locations, on Earth and in space, for a search system?

Note. – See Report 700.

QUESTION 18-2/2*

PROTECTION CRITERIA FOR SYSTEMS PROVIDING SPACE OPERATION FUNCTIONS

(1978-1982-1986)

The CCIR,

CONSIDERING

(a) that some of the frequency bands allocated to telemetering, tracking and telecommand for space research and for experimental and operational spacecraft (space operation) are shared with other services;

(b) that suitable criteria should be established as a basis for the protection of telemetering, tracking and telecommand receivers against interference from other transmissions of the space and terrestrial services;

(c) that such criteria should take into account the spectral characteristics of the interfering signals, for example, whether "CW-type" or "noise-like", and the time pattern of the interference in relation to the time pattern of the system operation;

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* This Question should be brought to the attention of Study Groups 1, 4, 8, 9, 10 and 11.

(d) that the requirements for space operation may be less stringent than those for the transmission of research data,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the minimum levels of wanted signal input for which receiving systems for telemetering, tracking and telecommand (space operation) should be designed;

2. what are the permissible ratios of wanted signal level to interfering signal level for such receiving systems for appropriate modulation of wanted signals and for various time patterns and spectral characteristics of the interfering signals;

3. what are the protection criteria applicable to systems providing space operation functions;

4. what coordination procedure should be used to avoid mutual interference between the space operation service and other services when they share frequencies?

Note. – See Recommendation 363 and Reports 396 and 845.

QUESTION 19-1/2*

SPURIOUS EMISSIONS RADIATED FROM AND RECEIVED BY STATIONS OF SPACE SERVICES

(1978–1982)

The CCIR,

CONSIDERING

(a) that the radiation of spurious emissions by space stations or earth stations of all space services could cause interference to other services;

(b) that the radiation of spurious emissions by other services could cause interference to space stations and/or earth stations of the various space services;

(c) that suppression of spurious emissions to very low levels, in particular from space stations, may involve major technical problems;

(d) that the various radio services differ greatly in the sensitivity of their stations to interference;

(e) that the Radio Regulations do not define limits on spurious emissions for space systems transmitters operating on fundamental frequencies above 960 MHz,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what limits, based upon practical considerations, should be placed upon the power of spurious emissions radiated by space and earth stations of space services** in order to protect other services;

2. what levels of power flux-densities resulting from spurious emissions of stations of other services are acceptable at space and earth stations of the various space services?**

Note. – See Reports 844 and 980.

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* This Question should be brought to the attention of Study Groups 1, 4, 7, 8, 9, 10 and 11.

** This concerns mainly the space research and Earth exploration services.

QUESTION 20-1/2*

CHARACTERISTICS AND EFFECTS OF RADIO TECHNIQUES FOR THE TRANSMISSION OF ENERGY

(1978-1982)

The CCIR,

CONSIDERING

(a) that it is feasible to transfer energy from satellites to Earth, between satellites, and between points on the surface of the Earth by means of radio techniques;

(b) that the transmission of energy by these techniques may be of great value in delivering energy to otherwise inaccessible locations, and also in the importation of energy from space;

(c) that the efficiency of the system depends on the frequency used;

(d) that development work has demonstrated the technical possibilities of delivering large amounts of energy over distances of several kilometres with reasonable efficiency;

(e) that the transmission of energy by radio techniques may produce biological hazards (see Study Programme 15B/2), and harmful interference to radiocommunication systems;

(f) that high intensity radio-frequency power radiated from solar-power satellites (SPS) may induce changes in the ionosphere or, in the lower atmosphere, which may adversely affect the propagation of radio waves for other telecommunication services,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the performance characteristics of systems for the transfer of energy by radio techniques;

2. what are the preferred frequency bands for the radio transmission of energy;

3. what are the factors which affect the practicability of frequency sharing between energy transmission systems and radiocommunication services;

4. in what ways can radiocommunication services be affected by spurious and other out-of-band emissions and what power flux-density limits if any, should be adopted;

5. what biological or other hazards would be posed by energy transmission systems utilizing radio techniques, both in the design mode and in conditions of malfunction?

Note. – See Report 679.

QUESTION 21-1/2

CHARACTERISTICS AND TELECOMMUNICATIONS REQUIREMENTS OF SYSTEMS FOR SPACE RESEARCH

(1978-1986)

The CCIR,

CONSIDERING

(a) that space research is carried out by using sounding rockets, Earth satellites, and deep space probes for both scientific and technological research;

(b) that the purpose of scientific space research is to investigate natural and man-made phenomena occurring on the Earth or in space;

(c) that the purpose of technological space research is the development and testing of new space techniques;

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* This Question should be brought to the attention of Study Groups 5 and 6.

(d) that space research systems often lead to space applications;

(e) that space research utilizes sensors of many types;

(f) that for some sensing techniques involving certain natural phenomena, operation of the sensors at specific frequencies is required;

(g) that space research is conducted by means of both manned and unmanned spacecraft,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the requirements for radiocommunications between earth stations and space stations for space research;

2. what are the preferred characteristics of these radio links;

3. what are the requirements for space research sensors operating at radio frequencies;

4. what are the characteristics of these sensors?

Note. – See Reports 536 and 548.

QUESTION 22/2

PREFERRED FREQUENCY BANDS FOR SPACE RESEARCH

(1978)

The CCIR,

CONSIDERING

(a) that space research systems are used extensively for scientific investigation and exploration of space and the Earth;

(b) that such research investigation and exploration involves the transmission of data over radiocommunication links from spacecraft to Earth;

(c) that operation of the spacecraft requires radio telecommand links from Earth to spacecraft;

(d) that the characteristics of these radio links are critical to the success of the space research missions;

(e) that the distances to deep-space vehicles typically involve attenuations of 200 dB to 300 dB, and, to near-Earth vehicles, attenuations of 100 dB to 200 dB;

(f) that the designs of the space research radio communication links may leave performance margins as low as +0.5 to +1.0 dB on a statistical basis;

(g) that the performance of a space research radio link is strongly related to the frequency dependent effects of weather, ionospheric effects, Rayleigh scattering, antenna efficiencies, and the efficiencies of radio-frequency power generation on power limited spacecraft;

(h) that space research involves both manned and unmanned missions;

(j) that both active and passive spaceborne sensors are required for the investigation of certain phenomena,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the characteristics of the space research radio links which affect the choice of frequencies;

2. what factors affect space research radio links in a frequency-dependent manner;

3. what are the relationships of these factors to the communication capability over space research radio links;

4. what are the preferred frequencies for use in space research radio links, for near-Earth and deep-space missions;

5. what are the required frequencies and bandwidths, or preferred frequency bands, which are most suitable for space research active and passive sensors?

Note. – See Recommendations 364 and 576 and Reports 548, 683, 849 and 984.

STUDY PROGRAMME 22A/2

PREFERRED FREQUENCY BANDS FOR DEEP-SPACE RESEARCH MANNED AND UNMANNED SPACECRAFT

(1978)

The CCIR,

CONSIDERING

(a) that deep-space craft must communicate allowing for basic transmission losses of from 200 dB to 300 dB;

(b) that certain operations during planetary missions must be carried out at critical times and within very limited time periods;

(c) that unplanned interruption of deep-space communications could be catastrophic to the mission, the equipment or the personnel of the spacecraft;

(d) that only specific frequency bands are substantially immune to natural interruption of space communications due to weather, ionospheric or solar effects or galactic noise;

(e) that deep-space tracking may require the simultaneous use of three frequencies to determine the effects of space electron or ion propagation delay;

(f) that deep-space manned missions may require communications on frequencies suited to direct spacecraft-to-Earth links as well as to local spacecraft-to-astronaut communications,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the link geometry between earth stations and deep-space manned and unmanned missions;

2. determination of the statistical degradation of performance for these links as a function of frequency, taking into account the effects of the atmosphere, scattering from space plasma of free electrons or ions, fragmentary and particulate matter, etc.;

3. determination of the preferred bands of frequencies for deep-space manned and unmanned space research missions.

Note. – See Recommendation 576 and Reports 683 and 849.

STUDY PROGRAMME 22B/2

PREFERRED FREQUENCY BANDS FOR NEAR-EARTH MANNED AND UNMANNED SPACECRAFT

(1978)

The CCIR,

CONSIDERING

(a) that near-Earth manned and unmanned satellites are used extensively for space research purposes;

(b) that use of such satellites for space research purposes places heavy demands upon the available radio frequency spectrum,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the preferred methods of transmission for near-Earth manned and unmanned spacecraft;

2. determination of the frequency bands preferred for transmission to and from near-Earth manned and unmanned spacecraft.

Note. – See Recommendation 364 and Reports 548 and 984.

QUESTION 24/2*

CHARACTERISTICS OF INTER-SATELLITE LINKS

(1982)

The CCIR,

CONSIDERING

(a) that links between satellites have applications in several services, including the inter-satellite service, the space research service, the space operation service, the earth-exploration satellite service, the fixed-satellite service and the mobile satellite services;

(b) that frequencies for inter-satellite links may be shared among the above services and with other services;

(c) that Recommendation No. 707 of the Radio Regulations requests that the CCIR carry out specific studies in regard to sharing criteria with a view to later inclusion of such sharing criteria in Article 28 of the Radio Regulations,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the characteristics required for such inter-satellite links;

2. what sharing criteria are necessary and appropriate, including sharing with passive services?

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* This Question should be brought to the attention of Study Groups 4, 8 and 9.

QUESTION 25/2*

SPACE TELECOMMUNICATION SYSTEMS OPERATING AT INFRA-RED AND VISIBLE LIGHT FREQUENCIES

(1982)

The CCIR,

CONSIDERING

(a) that systems for space telecommunication operating at infra-red and visible light frequencies, will make it possible to use a wider frequency band than conventional systems operating in the radio frequency spectrum, and that realization of these systems will contribute to alleviating the present congestion in the use of radio waves;

(b) that, if such systems are used for communications relating to space vehicles, it will be a matter of great importance whether international technical standards to keep the operation of these systems in good order will be necessary or not (see Reports 680 and 681),

UNANIMOUSLY DECIDES that the following question should be studied:

what are the technical characteristics of systems for space communication that operate at infra-red and visible light frequencies, and what are the technical problems, including atmospheric effects on propagation, in the realization of these systems?

Note. – See Reports 680 and 681.

DECISION 73

CCIR STUDIES TO BE CARRIED OUT IN THE INTER-SESSIONAL PERIOD FOR SUBMISSION TO THE SECOND SESSION OF THE WARC-ORB-88

(1985)

This Decision, adopted by Study Groups 1, 2, 4, 5, 8, 9, 10 and 11 at the Final Meetings in 1985, was reviewed by the Plenary Assembly and replaced by Resolution 90 which appears in Volume XIV.

* This Question should be brought to the attention of Study Group 1.

QUESTION 26/2*

SHARING BETWEEN THE EARTH EXPLORATION-SATELLITE SERVICE OR THE METEOROLOGICAL-SATELLITE SERVICE ON THE ONE HAND AND OTHER SPACE SERVICES OR THE METEOROLOGICAL AIDS SERVICE ON THE OTHER

(1987)

The International Frequency Registration Board (IFRB),

CONSIDERING

(a) the provisions of No. 326 of the International Telecommunication Convention (Nairobi, 1982);

(b) that Question 12-2/2 and Study Programmes 12A-2/2, 12B-1/2, 12C/2 and associated Reports and Recommendations do not provide the necessary information for the application of Appendices 28 and 29 to the Radio Regulations to frequency assignment notices to space or earth stations in the Earth exploration-satellite service and the meteorological-satellite service when the Board has to examine them with respect to the provisions of No. 1060 and No. 1107 of the Radio Regulations, as well as in cases where the Board has to apply other procedures, such as the procedure of Article 14, to these notices;

(c) that in view of the urgency to treat the concerned frequency assignment notices, the Board adopted provisional Rules of Procedure in these cases (see Note);

(d) that it is necessary for the Board to develop its Technical Standards to have the required information through appropriate Recommendations of the CCIR (see No. 1582 of the Radio Regulations),

REQUESTS THE CCIR:

to study the parameters which need to be used in application of Appendices 28 and 29 to the Radio Regulations when the Earth exploration-satellite service or the meteorological-satellite service shares the same frequency bands with the meteorological aids service or with other space services.

Note. – The provisional Rules of Procedure have been published in Documents 2/39, 4/129, 8/27, 9/136, IFRB (1986-1990).

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* An identical text is allocated to Study Group 4 as Question 37/4, to Study Group 8 as Question 80/8.

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ABBREVIATIONS

A

AAFE . . . . . . advanced applications flight experiments
ACARS . . . . . ARINC communication addressing reporting system
ACS . . . . attitude control system
ADM . . . . adaptive delta modulation
AEM . . . . applications explorer mission
AGC . . . . automatic gain control
ALC . . . . automatic light control
ALSEP . . . . . . Apollo lunar surface experimental packages
ALT . . . . altimeter (radar)
AM . . . . amplitude modulation
AMI . . . . active microwave instrument
AMSU . . . . . . advance microwave sounding unit
AOCS . . . . . . attitude and orbital control system
APT . . . . automatic picture transmission
ARINC . . . . . . aeronautical radio incorporated
ARSR . . . . . . air route surveillance radar
ASAR . . . . . . advanced synthetic aperture radar
ASDAR . . . . . aircraft-to-satellite data relay
ATS . . . . applications technology satellite
ATSR-M . . . . . along track scanning radiometer and microwave sounder
AVCS . . . . . . advanced vidicon camera system
AVHRR . . . . . advanced very high resolution radiometer

B

BCH . . . . Bose-Chaudhuri-Hocquenghem
BER . . . . bit error ratio
BPSK . . . . . . binary phase-shift keying
BR . . . . bit rate
BSE . . . . broadcasting satellite for experimental purposes
BSS . . . . broadcasting-satellite service
BSU . . . . basic sounding unit
BUV . . . . backscatter ultraviolet spectrometer
BW . . . . bandwidth

C

CCD . . . . charge coupled devices
CDA . . . . command and data acquisition
CDAS . . . . . . command and data acquisition station
CDH . . . . communications and data handling
CGMS . . . . . . coordination of geostationary meteorological satellites
CM . . . . carrier margin
CMG . . . . control moment gyros
CNES . . . . . . Centre national d'études spatiales
CRC . . . . Communications Research Center
CRPE . . . . . . Centre de Recherches en Physique de l'Environnement terrestre et planétaire
CRT . . . . cathode-ray tube
CS . . . . communications satellite
CW . . . . continuous wave
CZCS . . . . . . coastal zone colour scanner

D

DATTS . . . . . data acquisition telecommand and tracking station
DCDR . . . . . . data collection and data relay
DCP . . . . data collection platform
DCS . . . . data collection system
DEM . . . . demodulator
DEMX . . . . . . demultiplexer
DISCOS . . . . . disturbance compensation system
DRGS . . . . . . direct read-out ground station
DRS . . . . data relay satellite
DSCS . . . . . . defense satellite communications system
DSN . . . . deep-space network
DSNR . . . . . . degradation of signal-to-noise ratio
DTS . . . . digital termination system
DUS . . . . data utilization station

E

ECH . . . . Earth coverage horn
EESS . . . . Earth exploration-satellite service
e.i.r.p. . . . . . . equivalent isotropically radiated power
EM . . . . electromagnetic
EMI . . . . electromagnetic interference
EOS . . . . Earth observation satellite
ERB . . . . Earth radiation budget
EREP . . . . . . Earth resources experiment packages
e.r.p. . . . . effective radiated power
ERS . . . . Earth remote sensing
ES . . . . electrostatic
ESA . . . . European Space Agency
ESMR . . . . . . electrically scanning microwave radiometer
ETI . . . . extra-terrestrial intelligence
ETZ . . . . Eastern Time Zone

F

FC . . . . forecast centre
FDM . . . . frequency division multiplex
FGGE . . . . . . first GARP global experiment
FM . . . . frequency modulation
FMFB . . . . . . frequency modulation feedback
FPR . . . . flat plate radiometer
FSK . . . . frequency shift keying
FSS . . . . fixed-satellite service
FWS . . . . filter wedge spectrometer

G

GARP . . . . . . global atmospheric research programme
GEOS . . . . . . geodetic Earth orbiting satellite
GM . . . . geostationary model
GMS . . . . geostationary meteorological satellite
GOES . . . . . . geosynchronous operational environmental satellite
GOMS . . . . . . geostationary operational meteorological satellite
GPS . . . . global positioning system
GRM . . . . geopotential research mission
GSO . . . . geostationary-satellite orbit
GTL . . . . geomagnetic tail laboratory
GVHRR . . . . . geosynchronous very high resolution radiometer

H

HET . . . . health, education, and telecommunication experiment
HH . . . . horizontal transmit/horizontal receive
HIPEHT . . . . . high performance hydrazine thrusters
HIRS . . . . high resolution infra-red sounder
HRPI . . . . high resolution pointable imager
HRPT . . . . . . high resolution picture transmission
HRV . . . . high resolution visible
HV . . . . horizontal transmit/vertical receive

I

IAU . . . . International Astronomical Union
ICEX . . . . ice experiment
ICR . . . . interference-to-carrier ratio
IDCS . . . . image dissector camera system
IFOV . . . . instantaneous field-of-view
IFRB . . . . International Frequency Registration Board
IGMSDCS . . . international geostationary meteorological satellite data collection system
IMP . . . . intermodulation products
INR . . . . interference-to-noise ratio
IPL . . . . interplanetary physics laboratory
IR . . . . infra-red
IRIS . . . . infra-red interferometer/spectrometer
IRLS . . . . interrogation, recording and location system
ISM . . . . industrial, scientific and medical
ISR . . . . interference-to-signal ratio
ITOS . . . . improved TIROS operational system
ITPR . . . . infra-red temperature profile radiometer
ITT . . . . International Telephone and Telegraph

K

KSA . . . . K-band single access

L

LAGEOS . . . . laser geodynamic satellite
LAS . . . . low-altitude observation satellite
LASER . . . . . light amplification by stimulated emission of radiation
LBT . . . . land-based transponder
LIDAR . . . . . . light detection and ranging
LIMS . . . . . . limb infra-red measurements in the stratosphere
LOS . . . . line-of-site
LRIR . . . . limb radiance inversion radiometer
LSI . . . . large scale integration

M

MA . . . . multiple access
MAPS . . . . . . measurement of air pollution from satellites
MDS . . . . minimum detectable signal
MDUS . . . . . . medium scale data utilization station
MESC . . . . . . magneto-electrostatic containment
MESSR . . . . . multi-spectral electronic self-scanning radiometer
METEOSAT . . meteorological satellite
MLS . . . . maximum linear sequence
MOS . . . . marine observation satellite
MPD . . . . magnetoplasma dynamic
MSK . . . . minimum shift keying
MSR . . . . microwave scanning radiometer
MSS . . . . multi-spectral scanner
MSU . . . . microwave sounding unit
MTI . . . . moving target indicator
MUSE . . . . . . monitor of ultra violet solar energy
MWS . . . . . . microwave scatterometer

N

NASA	National Aeronautics and Space Administration
NB	narrow-band
NEMS	microwave spectrometer
NGM	non-geostationary model
NOAA	National Oceanic Atmospheric Administration
NRAO	National Radio Astronomical Observatory
N-ROSS	navy-remote ocean sensing system
NRZ	non-return to zero
NTS	navigation technology satellite

O

OAO	Orbiting Astronomical Observatory
OBRF	out-of-band rejection factor
OPLE	omega position location equipment

P

PCM	pulse code modulation
PD	pulse duration
PD1US	primary data user station
pfd	power flux-density
PM	phase modulation
PMR	pressure modulated radiometer
PN	pseudo noise
POPSAT	precise orbit positioning satellite
PPI	plan position indicator
PRARE	precise range and range rate experiment
PRF	pulse-repetition frequency
PSK	phase-shift keying
PSURAO	Pennsylvania State University Radio Astronomy Observatory

Q

QPDD	quadri-phase demodulator/demultiplexer
QPSK	quadrature phase-shift keying

R

RA	radar altimeter
RADARSAT	radar satellite
RADHAZ	radiation hazards
RADSCAT	radiometer, scatterometer, altimeter
RARC	Regional Administrative Radio Conference
RF	radio frequency
RFI	radio-frequency interference
RNG	ranging
RTG	radioisotope thermoelectric generators

S

SAGE	stratospheric aerosol and gas experiment
SAM	stratospheric aerosol measurement
SAMS	stratospheric and mesospheric sounder
SAR	synthetic aperture radar
SARSAT	search and rescue satellite-aided tracking system
SBUV/TOMS	solar backscatter ultraviolet/total O_3 mapper system
SCAMS	scanning microwave spectrometer
SCATHA	spacecraft charging at high altitude
SCR	selective chopper radiometer
SDUS	secondary data user station
SEC	secondary emission control
SEM	space environment monitor
SERT	space electrical rocket test
SETI	search for extra-terrestrial intelligence
SI	specific impulse
SIRS	satellite infra-red spectrometer
SJM	Special Joint Meeting
SMMR	scanning multichannel microwave radiometer
SMS	synchronous meteorological satellite
SPM	solar proton monitor
SPOT	satellite pour l'observation de la Terre
SR	scanning radiometer
SRS	space research service
SRS	synchronous relay satellite
SS	steady state
SSA	S-band single access
SSM	second surface mirror
SSPS	satellite solar power station
SST	satellite-to-satellite tracking
SS/TDMA	satellite-switched time division multiple access
SSU	stratospheric sounding unit
SWE	spherical wave expansion

T

TARS	turn-around ranging station
TC	telecommand
TCTP	telecommand transmitting power
TDAS	tracking and data acquisition system
TDRE	tracking and data relay experiment
TDRS	tracking and data relay satellite
TDRSS	tracking and data relay satellite system
THIR	temperature/humidity infra-red radiometer
TIROS	television infra-red observational satellite
TLM SS	telemetry sub-system
TLM	telemetry

TM . . . . thematic mapper

TMTP . . . . . . telemetering transmitting power

TOPEX . . . . . topographic experiment

TOS . . . . TIROS operational satellite

TOVS . . . . . . TIROS operational vertical sounder

TPM . . . . transient pulse monitor

TRW . . . . Thompson Ramo Wooldridge

TTC . . . . tracking, telemetry and telecommand

TV . . . . television

TWERLE . . . . tropical wind, energy conversion, reference level experiment

TWT . . . . travelling wave tube

U

UHF . . . . ultra high frequency

UQPSK . . . . . unbalanced QPSK

UTC . . . . coordinated universal time

V

VAS . . . . VISSR atmospheric sounder

VH . . . . vertical transmit/horizontal receive

VHF . . . . very high frequency

VHRR . . . . . . very high resolution radiometer

VISSR . . . . . . visual infra-red spin-scan radiometer

VLBI . . . . very long baseline iterferometry

VTIR . . . . visible and thermal-infra-red radiometer

VTPR . . . . . . vertical temperature profile radiometer

VV . . . . vertical transmit/vertical receive

W

WARC . . . . . . World Administrative Radio Conference

WEFAX . . . . . weather facsimile

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