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INTERNATIONAL TELECOMMUNICATION UNION

CCIR

INTERNATIONAL
RADIO CONSULTATIVE
COMMITTEE

RECOMMENDATIONS AND REPORTS OF THE CCIR, 1978

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

XIVth PLENARY ASSEMBLY
KYOTO, 1978

VOLUME II

SPACE RESEARCH AND RADIOASTRONOMY

Geneva, 1978

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ISBN 92-61-00671-X

PLAN OF VOLUMES I TO XIII
XIVth PLENARY ASSEMBLY OF THE C.C.I.R.

(Kyoto, 1978)

VOLUME I	Spectrum utilization and monitoring.
VOLUME II	Space research and radioastronomy.
VOLUME III	Fixed service at frequencies below about 30 MHz.
VOLUME IV	Fixed service using communication satellites.
VOLUME V	Propagation in non-ionized media.
VOLUME VI	Propagation in ionized media.
VOLUME VII	Standard frequencies and time signals.
VOLUME VIII	Mobile services.
VOLUME IX	Fixed service using radio-relay systems. Frequency sharing and coordination between systems in the fixed satellite service and radio-relay systems.
VOLUME X	Broadcasting service (sound).
VOLUME XI	Broadcasting service (television).
VOLUME XII	Transmission of sound broadcasting and television signals over long distances (CMTT). Vocabulary (CMV).
VOLUME XIII	Information concerning the XIVth Plenary Assembly: Minutes of the Plenary Sessions. Texts of general interest. Structure of the C.C.I.R. Complete list of C.C.I.R. texts. Alphabetical index of technical terms appearing in Volumes I to XII.

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DISTRIBUTION OF TEXTS OF THE XIVth PLENARY ASSEMBLY OF THE C.C.I.R. IN VOLUMES I TO XIII

Volumes I to XIII, XIVth Plenary Assembly, contain all the valid texts of the C.C.I.R. and succeed those of the XIIIth Plenary Assembly, Geneva, 1974.

1. Recommendations, Reports, Decisions, Resolutions, Opinions

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.

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 XIII.

1.2 *Recommendations*

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80	X	355-359	IX	463	IX
100	I	361	VIII	464-466	IV
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139, 140	X	367	II	469-472	XI
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205	X	374-376	VII	478	VIII
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218, 219	VIII	380-393	IX	480	III
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1.3 *Reports*

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319	VIII	491	XII (CMTT)		

(1) Published separately.

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 *Decisions*

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1.4.1 *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".

1.5 *Resolutions*

Number	Volume	Number	Volume	Number	Volume
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20	VIII	61	XIII		
23	XII (CMV)	62	I		
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1.6 *Opinions*

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24	VIII	45, 46	VI	61-63	XIII
26-28	VII	49	VIII		
29	I	50	IX		
32	I	51	X		

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.

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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SPACE RESEARCH AND RADIOASTRONOMY SERVICES

STUDY GROUP 2

Terms of reference:

To study questions relating to:

1. systems for space research, Earth exploration, meteorological and amateur satellites including the associated technologies;
2. systems for radioastronomy and radar astronomy with particular reference to associated interference problems.

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 2 (1974-1978)

1974-1978			1978-1982	
Chairman:	I. RANZI (Italy)	———	*Chairman:*	J. P. HAGEN (USA)
Vice-Chairman:	J.P. HAGEN (USA)		*Vice-Chairman:*	F. HORNER (United Kingdom)

All the texts of CCIR Study Group 2 approved by the XIVth Plenary Assembly may be divided into four main classes:

A. General matters

B. Space research

C. Earth exploration satellites

D. Radio and radar astronomy.

The particular topic of the amateur satellite service is also assigned to Study Group 2.

In each class sections corresponding to the various topics may be identified.

A. General matters

A1. *Space systems technology in the space research service*

The presented texts include a revision and an updating of Report 546 on spacecraft attitude technology, which already provided useful information also to other Study Groups. New Reports on a forecast for space technology, on space electrical power systems and on spacecraft charging were also presented.

As regards the technical characteristics of the antennae for space research systems, a new Study Programme is given, together with Reports on radiation diagrams, on shaped beam antennae and on low side-lobe antennae; we have also a new Recommendation on the generalized space research earth station radiation pattern to be used in coordination procedures.

A2. *Space operation*

A new Question is included on frequency sharing between space operation and other services, together with a new Report on the same subject and a revision of Report 396-2; Recommendation 363-1 is maintained.

A3. *Transmission of energy from space*

On this new and interesting topic, a Question and a related Report are given; in the Report all the technical aspects of the problem of transmitting to the Earth's surface, by means of highly collimated microwave beams, the energy collected by very large solar cell arrays are discussed, especially in connection with the high powers involved and the need of a high efficiency of the system.

A4. *Telecommunication systems using infra-red and visible light*

A general Question on this topic has been adopted for Study Group 1 (Question 53-1/1); two relevant Reports now exist in the documents of Study Group 2. As regards the use of such systems in the space research service, it is shown, in particular, that there is as yet no need for regulations concerning the use of these frequencies.

A5. *Plasma effects on telecommunications with spacecraft*

A revision has been made of Report 222-3, which now becomes Report 222-4.

A6. *Safety aspects of radio frequency radiation*

A general Question on this topic has been adopted for Study Group 1 (Question 52-1/1); a relevant Study Programme and a Report on the safety aspects of radiation from space research earth stations is now available from Study Group 2, together with a Study Programme on the protection of telecommunication equipments from radiation.

B. Space research

B1. *Near-earth and deep space research*

New Questions, Study Programmes and Reports, together with revision of existing Reports, are to be found. These concern the technical characteristics of the various telecommunication systems, preferred frequency bands for space research and the feasibility of frequency sharing with other services. As regards frequency bandwidths and protection criteria for space links, we have now Recommendation 364-2 concerning near-earth satellites and Recommendation 365-3 concerning deep space research.

B2. *Radio links between the Earth's surface and research spacecraft by means of space stations (data relay satellite systems)*

Various Reports on frequency sharing for certain frequency bands between these systems and other services are included.

A Resolution now exists on frequency sharing with terrestrial services, as well as three Recommendations concerning frequency sharing near 13, 14 and 15 GHz respectively.

As regards the preferred frequency bands for space transmitters used as beacons, a Recommendation is now available together with Report 456-2.

B3. *Systems to search for extra-terrestrial life*

A Question had been adopted by correspondence on this new topic, and a Report is now available on the radiocommunication requirements for such systems; as known, there are several programmes in progress concerning the detection of very weak signals which may be attributed to other civilizations.

C. Earth exploration satellite service

There appears to be sufficient technical justification to consider modifying the scope of the definition of the earth exploration satellite service. Administrations are therefore invited to consider the following two matters with a view to arriving at appropriate conclusions.

(1) Adding the under-lined phrase and punctuation in the first point of the existing definition (RR 84ASA):

"– information relating to the characteristics of the Earth, its natural phenomena, and its atmospheric environment, is obtained from instruments on earth satellites."

(2) The technical need for associated definitions to cover "active sensors" and "passive sensors" used on earth exploration satellites.

In addition, there are a number of technical problems to be considered in the use of aircraft and ground-based stations for earth exploration purposes and Administrations are also invited to devote some attention to these problems with a view to further consideration of the matter.

The increasing development and importance of satellite systems for meteorological applications and for the survey of the Earth's surface is shown by new Reports and by the updating of existing Reports; in particular, the remarkable progress in the field of active and passive microwave sensors is well documented.

A Recommendation is now included on the preferred frequency bands and protection criteria for the earth exploration satellite systems, as well as a Recommendation on frequency sharing and protection criteria for passive microwave sensors; a revision has been also adopted of Recommendation 362 on frequencies technically suitable for meteorological satellites.

On the subject of satellite systems for disaster warning and relief operations, a new Question is included.

D. Radio and radar astronomy

Careful revision and updating of the previous texts were carried out, in particular on the topics of frequency sharing with other services, on the problem of interference from transmitters in other frequency bands, and on line frequencies of interest to radioastronomy.

Recommendation 314-3 on protection of frequency used for radioastronomical measurements was revised, and a new Recommendation on protection in adjacent bands was approved.

As regards the topic of frequency utilization above the ionosphere and on the far side of the Moon, a new Report on shielding due to the ionosphere is given as well as revisions of Report 539 and of Recommendation 479 on protection of frequencies for observations in the shielded side of the Moon.

On the subject of radar astronomy, a revision was approved of Report 226-3 on the feasibility of frequency sharing with other services.

E. Amateur satellite service

A revision of Report 542 has been approved.

SECTION 2A: SUBJECT OF GENERAL INTEREST

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.

* See Report 700.

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 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.

In deep space, on missions requiring fast reaction time, round trip propogation 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.

REFERENCE

NASA [January, 1976] A forecast of space technology, 1980-2000. NASA-SP-387 (for sale by the Superintendent of Documents, US Government Printing Office, Washington, D.C. 20402, Stock Number 3300-00641-1; Catalog Number NAS-1.21:387).

REPORT 546-1 *

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

(Question 15/2)

(1974 - 1978)

1. Introduction

The determination and maintenance of proper spacecraft orientation is essential to the fulfilment of nearly all space research missions. The accuracy and reliability of a spacecraft's attitude control system (ACS) affects many other satellite subsystems: above all, narrow beam antennae 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 used in the United States space research programme 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 antennae 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 antennae 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 accounted for, may induce errors in local vertical determination.

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, Orbiting Solar Observatory and the MARINER and VIKING planetary missions, use stars or the Sun as reference points. 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.

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

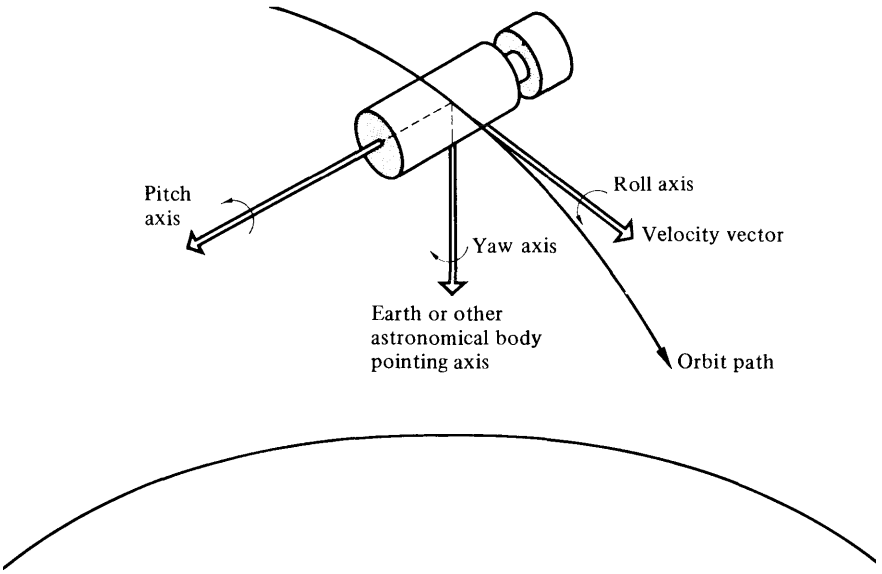

FIGURE 1 – *Attitude frame of reference*

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 inertially cyclic if the spacecraft is Earth oriented, will be a maximum for complete reflective surfaces and smaller in the case of an absorbent body. 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 antennae, 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 and other near bodies (satellites in the geostationary satellite orbit)*

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 after 1980. 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 antennae 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 antennae [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 antennae 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 furthermore a new attitude-determination method has been proposed [Aruga and Igarashi, 1977]. 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.

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. Also, as in passive-spin stabilization, damping of spacecraft conical wobble 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 antennae; as compared with electronically de-spun antennae 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.

Through the multipurpose use of a single, speed-modulated, double-gimballed, control-moment gyroscope, MOLNIYA-I communication satellite, has achieved a 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 "Stabilite", 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.

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 of 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-orbit satellite. During these position corrections, the attitude stability of the satellite may be temporarily degraded.

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 mode.

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).

TABLE 1 – *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°	0.26°	0.05°
Control accuracy — 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.

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.

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

Fig. 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*

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

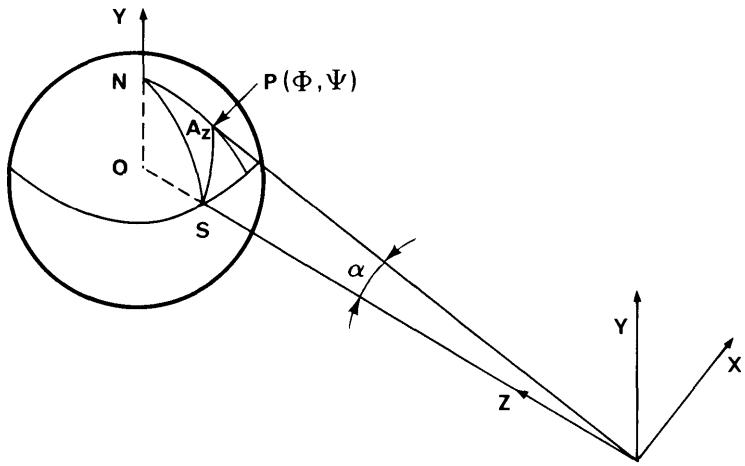

FIGURE 2 – *Satellite coordinate system*

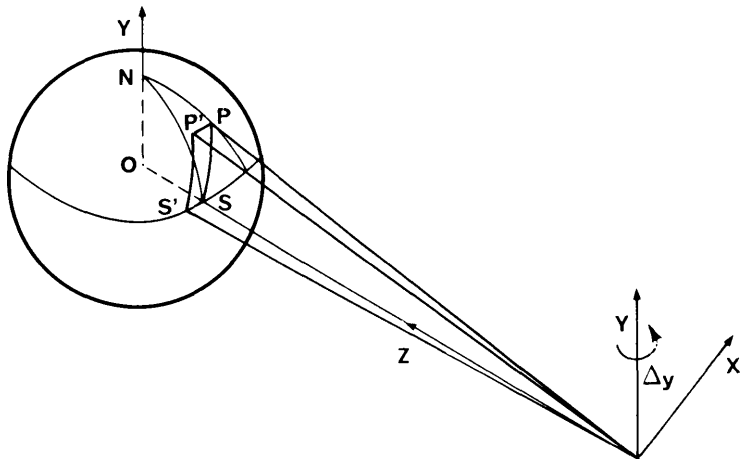

FIGURE 3 – *Pointing error due to pitch axis error*

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 of the order of:

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

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), and

Δy: rotational error about pitch or Y axis

Fig. 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:

$$d_y \approx \Delta y\,(k - 1)\,R_e \quad \text{km} \qquad (2)$$

where: Δy is expressed in radians.

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

Fig. 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).

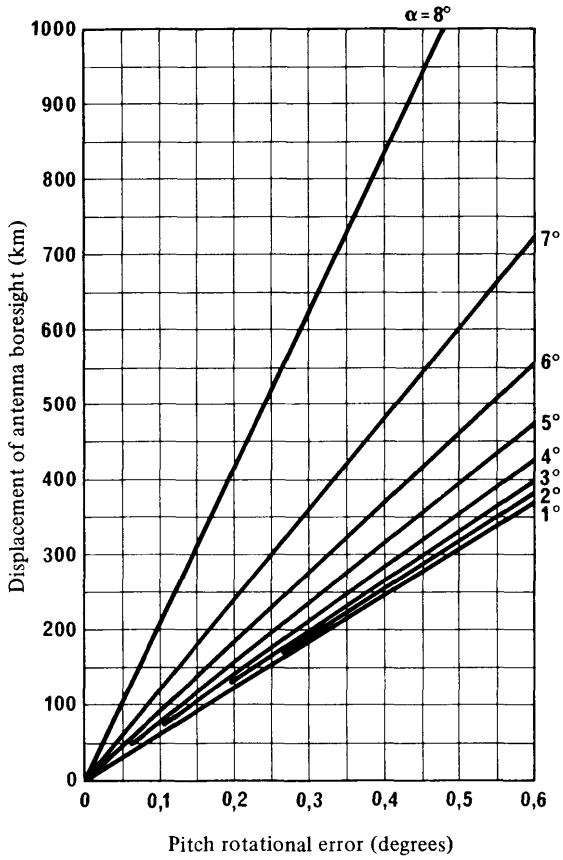

FIGURE 4 – *Pointing error as a function of pitch rotational error; azimuth = 90°*

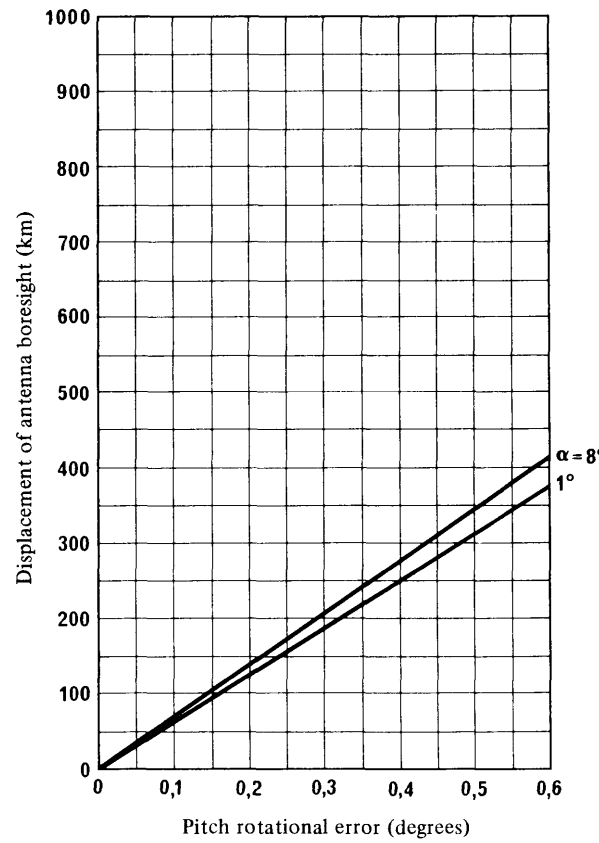

FIGURE 5 – *Pointing error as a function of pitch rotational error; azimuth = 0°*

2.2 *Roll axis*

Fig. 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. Fig. 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°.

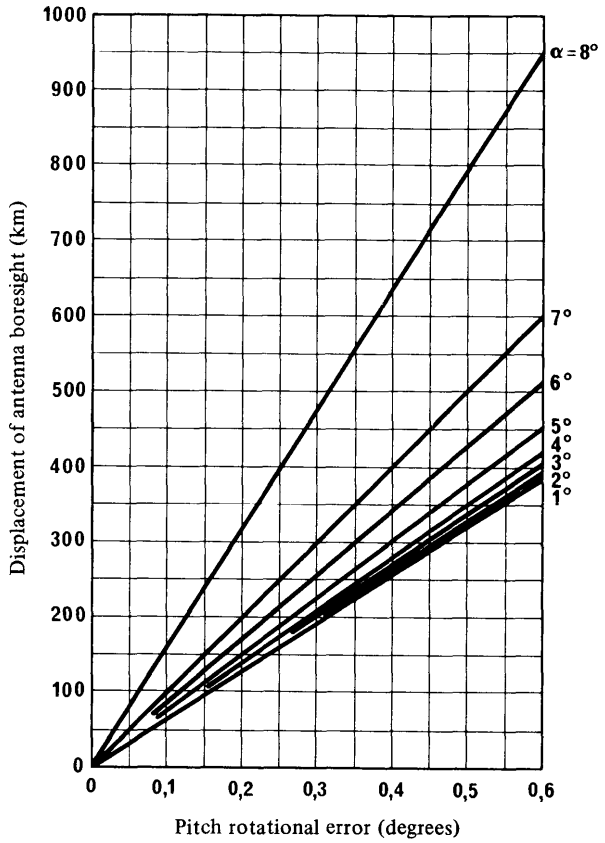

FIGURE 6 – *Pointing error as a function of pitch rotational error; azimuth = 45°*

2.3 *Yaw axis*

Fig. 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.

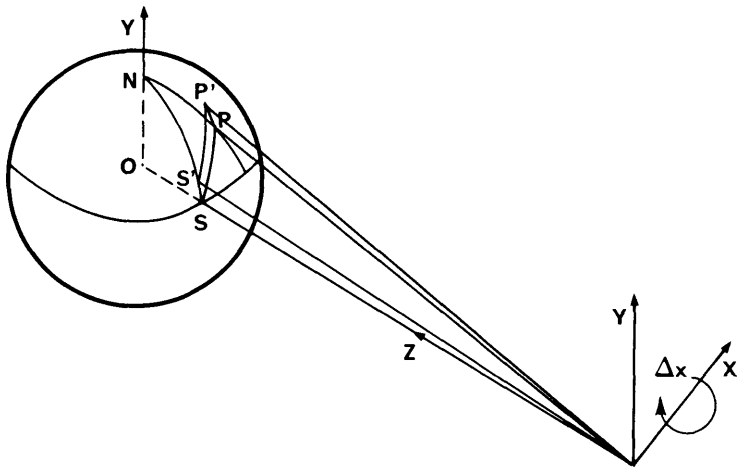

FIGURE 7 – *Pointing error due to roll axis error*

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:

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

where:

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

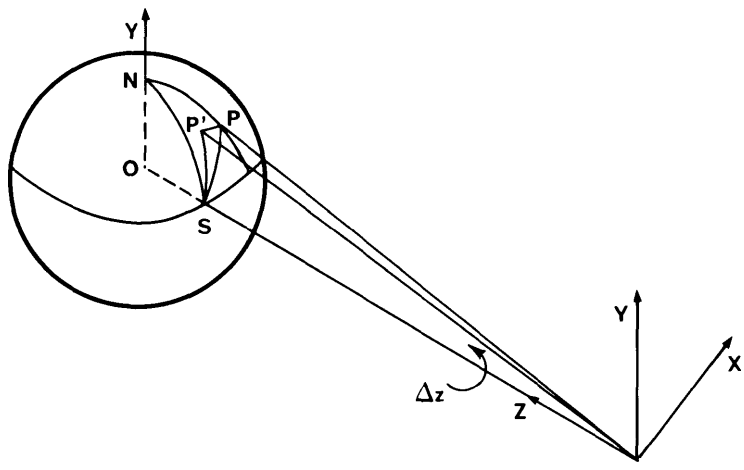

FIGURE 8 – *Pointing error due to yaw axis error*

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.

Fig. 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.

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°.

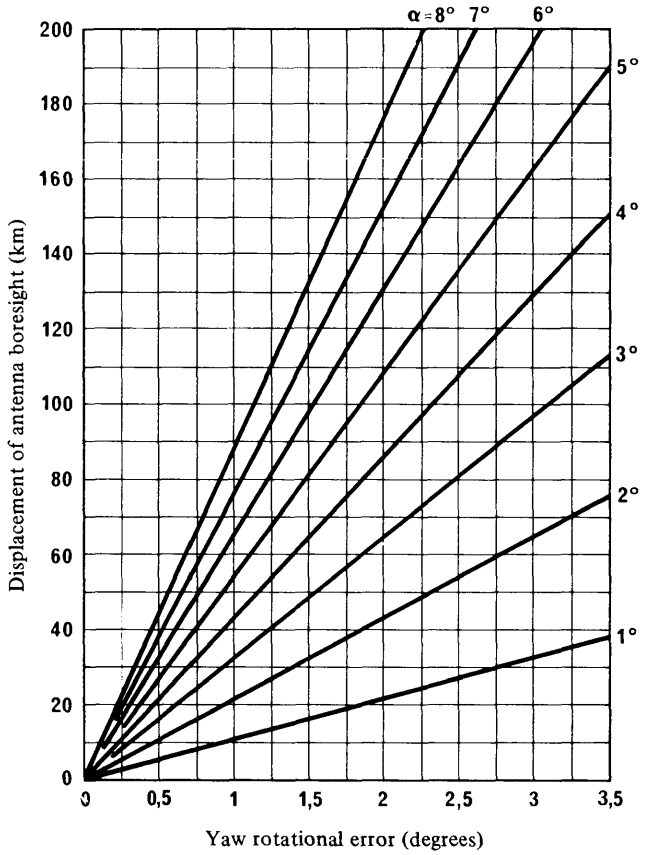

FIGURE 9 – *Pointing error as a function of yaw rotational errors – all azimuths*

[Parameter: elevation angle, α]

REPORT 673

ELECTRICAL POWER SYSTEMS FOR SPACECRAFT

(Question 15/2)

(1978)

1. Introduction

The purpose of this Report is to provide information on past, current, and future (1980-1990) satellite electrical power systems. The paper is confined to those systems which have received extensive study and which are considered feasible for application in space during the 1980-1990 time frame.

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 the low multi-kilowatt (1 to 2 kW) level for large capacity communications satellite systems, with this level being delivered through application of conventional or advanced photovoltaic conversion systems. In some circumstances, photovoltaic conversion systems are "backed up" with battery power supplies, particularly for satellites in the geostationary orbit, which are eclipsed by the Earth during equinoctial periods.

Unmanned interplanetary space flights, where solar electrical conversion becomes impractical, have necessitated the developement and implementation of nuclear power systems in the 100 W range [Dick, 1974]. Nuclear power systems may also have applications for Earth-oriented satellites (such as high power broadcasting-satellites) requiring large amounts of primary power and which must operate during eclipse periods.

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. Arrays mounted on paddles extended from the spacecraft have a power range up to about 1.5 kW_e. Large rigid oriented arrays having a power capability as high as 16 kW_e have been built and successfully used in space (Skylab). In the area of flexible solar arrays (cells mounted on flexible substrates) there have been roll-up, flat pack and rigid folding designs. Power systems that use body mounted arrays have provided up to 7.7 W_e per kilogram at a mass of 5.4 kg/m^2. An experimental flexible roll-up solar array has produced over 20 W_e per kilogram at a mass of 4 kg/m^2.

In general, the state-of-the-art of photovoltaic energy conversion is at the 20 to 30 W_e/kg level at a distance of 1 AU from the Sun with an associated cost of approximately 300 to 500 U.S. dollars, 1976, per W_e.

The primary on-going research in solar array power systems is focused on solar cell and cover glass improvements. The most influential factor in solar array mass and cost is the solar cell efficiency, with current solar cell efficiency in the range of 10%.

New developments in silicon solar cell technology [Lindmayer and Allison, 1973] have produced the Violet cell and the Non-reflective cell, respectively. The improvement in efficiency of the Violet cell is a direct result of the elimination of a non-reactive layer at the cell surface which suppressed the cells' response in the blue and violet portion of the spectrum. Additional developments in silicon etching techniques which produce a non-reflecting surface comprised of a uniform distribution of microscopic tetrahedra of high density have been also made. The combination of this surface preparation with elements of the Violet cell technology produced the Non-reflective cell which is 50% more efficient than the conventional satellite solar cell (i.e., an overall efficiency of 12 to 15%).

In conjunction with improvements in solar cell efficiency, much effort has been directed toward development of lightweight, deployable solar arrays [Curtin and Billerbeck, 1974]. Two different array structures have been studied, namely, deployed rigid arrays and deployed flexible arrays, with the latter having the advantage of greater stowability. Efforts have resulted in substantially advanced technologies in these areas which should result in greater electrical energy-to-weight ratios of advanced solar panels.

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.

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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.

Radioisotope thermoelectric generator technology growth has reached the point where kilowatt levels of electric power for spacecraft are now practical for consideration. 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*

Although several generic types of nuclear fission reactors have undergone study for space applications, the most likely system within the foreseeable future is the Uranium Zirconium Hydride (UZrH) reactor. Several experimental systems have been developed in the 50 to 500 kW_t range. Based on current estimates, the UZrH reactor may be ready for space applications by the 1980's.

Over the past several years, a large amount of attention has been given to thermoelectric power conversion systems for the UZrH reactor. The Rankine and Brayton power conversion systems appear to be capable of delivering conversion efficiencies of the order of 15 to 20%, compared with 6 to 10% for thermoelectric conversion systems.

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.

TABLE I – *Estimated power system performance parameters*

System	Technology status	Year of availability	Performance and cost parameters(1)	
			kg/W_e	U.S. dollar/W_e
Photovoltaic cells				
< 5 kW units	In use	–	3×10^{-2}	5×10^{2}
5 – 100 kW units (lightweight)	In development	1980	2×10^{-2}	8×10^{2}
> 100 kW units (low cost)	Future development	1985–1990	5×10^{-3}	5×10
Radioisotopes				
Thermoelectric Conversion				
0.1 – 10 kW_e units	In use	–	3×10^{-1}	1.5×10^{4}
Brayton Conversion				
0.5 – 15 kW_e units	In use	–	1.5×10^{-1}	2×10^{4}
Reactors				
Thermoelectric Conversion				
3 kW_e units	In development	1985–1990	2.5×10^{-1}	1.5×10^{2}
1000 kW_e units	In development	1985–1990	2.5×10^{-1}	1.5×10^{2}
Brayton Conversion				
5–100 kW_e units	In development	1985	6×10^{-2}	1×10^{3}

(1) Estimated performance parameter uncertainty, ± 20–100 %.

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 (7-10 year lifetime) of utilizing nuclear power systems, 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 parameters listed in Table I illustrate the influence of two of these factors.

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 all must 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.

It is estimated that technological advances in both of these generic power systems and subsystems will clarify applicability of both systems to the various types of space missions in the foreseeable future, with solar arrays playing the dominant near-future roles, and nuclear systems, if safety procedures are fully understood, playing the dominant role in the 1980-1990 time frame for high power (> 5 kW_e) space power systems.

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REPORT 674

SPACECRAFT CHARGING

(Question 15/2)

(1978)

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 6 electron and proton spectrometers can be 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 also show 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 USAF and NASA are jointly building the Spacecraft Charging At High Altitude (SCATHA) spacecraft for the sole purpose of investigating spacecraft charging and its effects on spacecraft systems and materials. At the Communications Research Centre (CRC) Ottawa, a laboratory simulation experiment is being conducted. In addition, work is proceeding on material properties and modifications, the electromagnetic emission from the discharges plus theoretical work on the charge distribution in dielectrics.

Investigations now underway can be grouped into five categories: environment, mathematical models, laboratory simulation experiments, material research and SCATHA. 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.

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 are being obtained from ATS 5 and 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.

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 DSCS 9431 used a laboratory experiment to demonstrate to the aerospace industry the danger in spacecraft charging. The group at NASA Lewis Research Centre have a very good experiment with theoretical and hardware support, and they are able to test new ideas and materials quickly. European Space Technology Centre is testing large samples of flexible solar arrays. The experiment at the Communications Research Centre will be used to determine the energy in the discharges off dielectric surfaces, and the energy and spectrum of the electromagnetic radiation. It will also be used to test ideas on material modifications.

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*

The SCATHA spacecraft is due to be launched in mid-1978. It is instrumented to obtain a comprehensive set of data on the environment, the charging of external surfaces, materials deteoriation, and the electronic effects of charging and discharges.

The spacecraft apogee is 7.6 Earth radii and perigee is 5.6 Earth radii, bracketing the synchronous orbit (6.6 Earth radii).

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 link ATS-5 and 6 have experienced no anomalies attributable to spacecraft charging.

The Hermes spacecraft is a very light weight design and only two anomalies have been 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 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 391-3. 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 $\varphi \geq 1°$. The equation is valid for $G \geq -10$ 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 465-1) 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.

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

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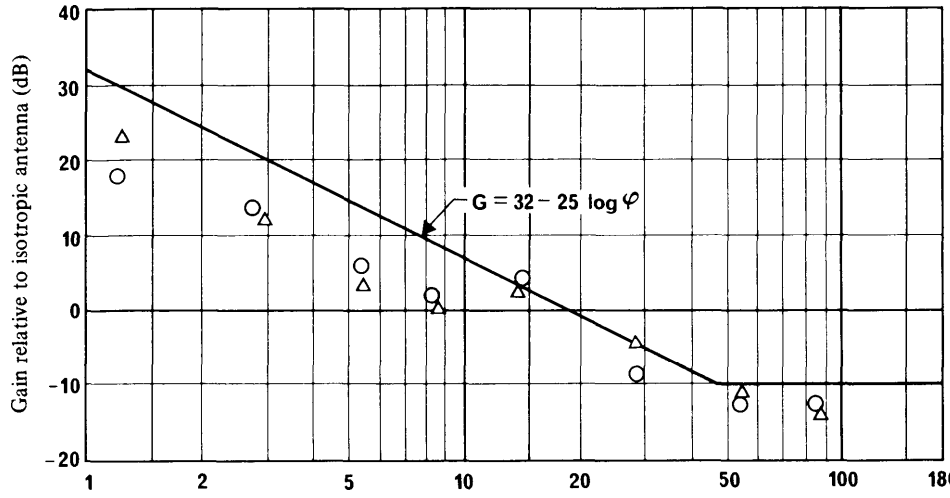

FIGURE 1 – *Statistical data from earth-station antenna diagrams*

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

Δ : 11.5 GHz, $D/\lambda \approx 380$
○ : 34.5 GHz, $D/\lambda \approx 1150$

Antenna type: Cassegrain; polarization, right-hand circular

REPORT 676 *

SHAPED BEAM ANTENNAE

(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 antennae.

Another factor which is not so well defined is the generation of asymmetrically shaped beams for spacecraft antennae. 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.

2. Beam shaping techniques

The following sections discuss beam shaping techniques as applied to reflector, lens and array antennae. 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.

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

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 antennae 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 558-1, 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 antennae 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 558-1.

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 antennae 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 antennae 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 antennae 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 antennae 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 antennae. 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 antennae.

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 antennae to meet specified far-field pattern characteristics such as pattern contour, null positions, and side lobe level.

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

- high beam efficiency (low sidelobe) antennae for radiometric land/sea observations,
- shaped beam antennae for reducing pointing loss of spacecraft antennae,
- fixed beamwidth (within a reasonable bandwidth) antennae 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 parabolae 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 and Mittra, 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.

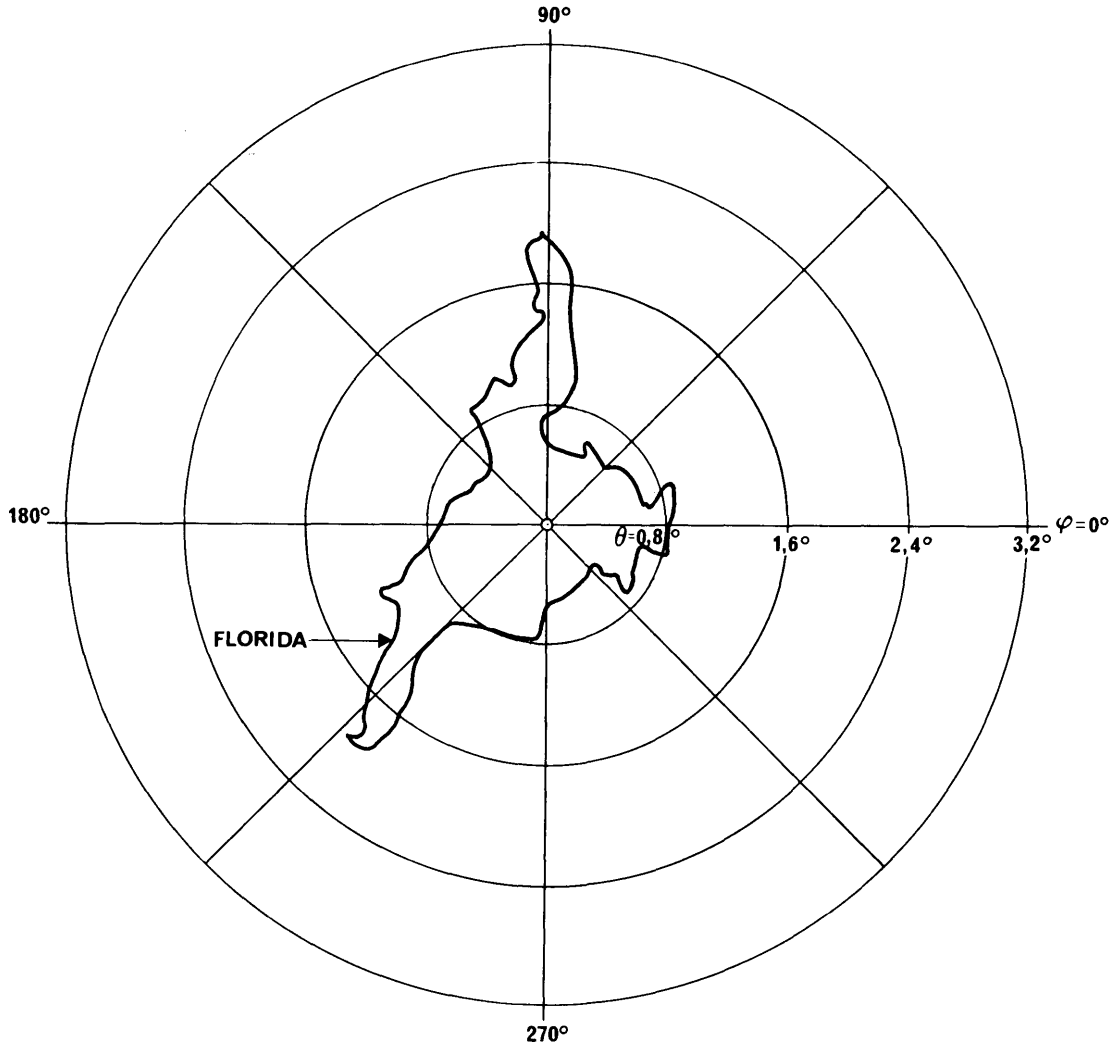

FIGURE 1 – *Eastern Time Zone (ETZ) of USA in Antenna Co-ordinates*

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

Fig. 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.

Fig. 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.

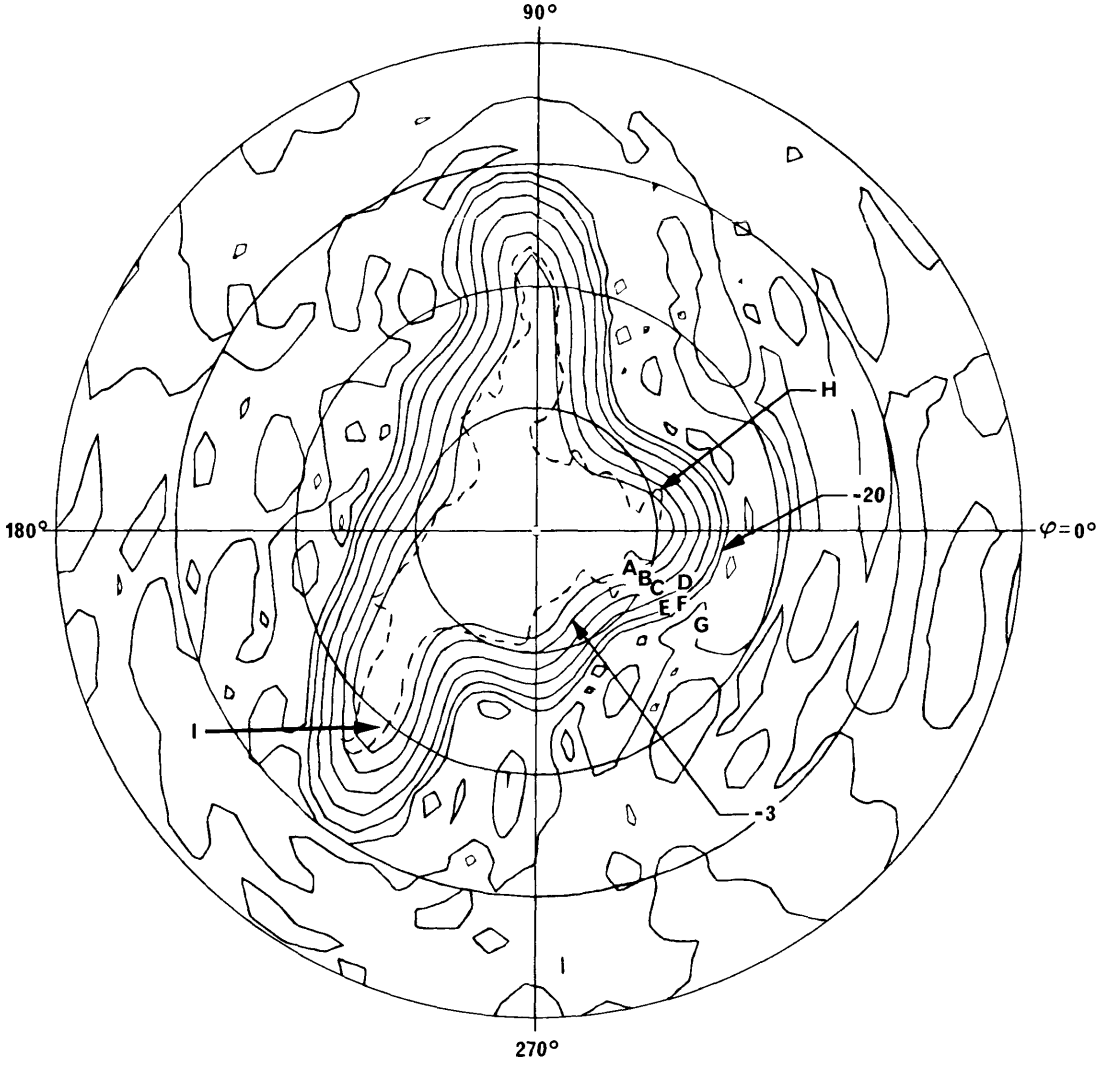

FIGURE 2 – *Far-field antenna pattern utilizing a 7 × 9 element feed structure*

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

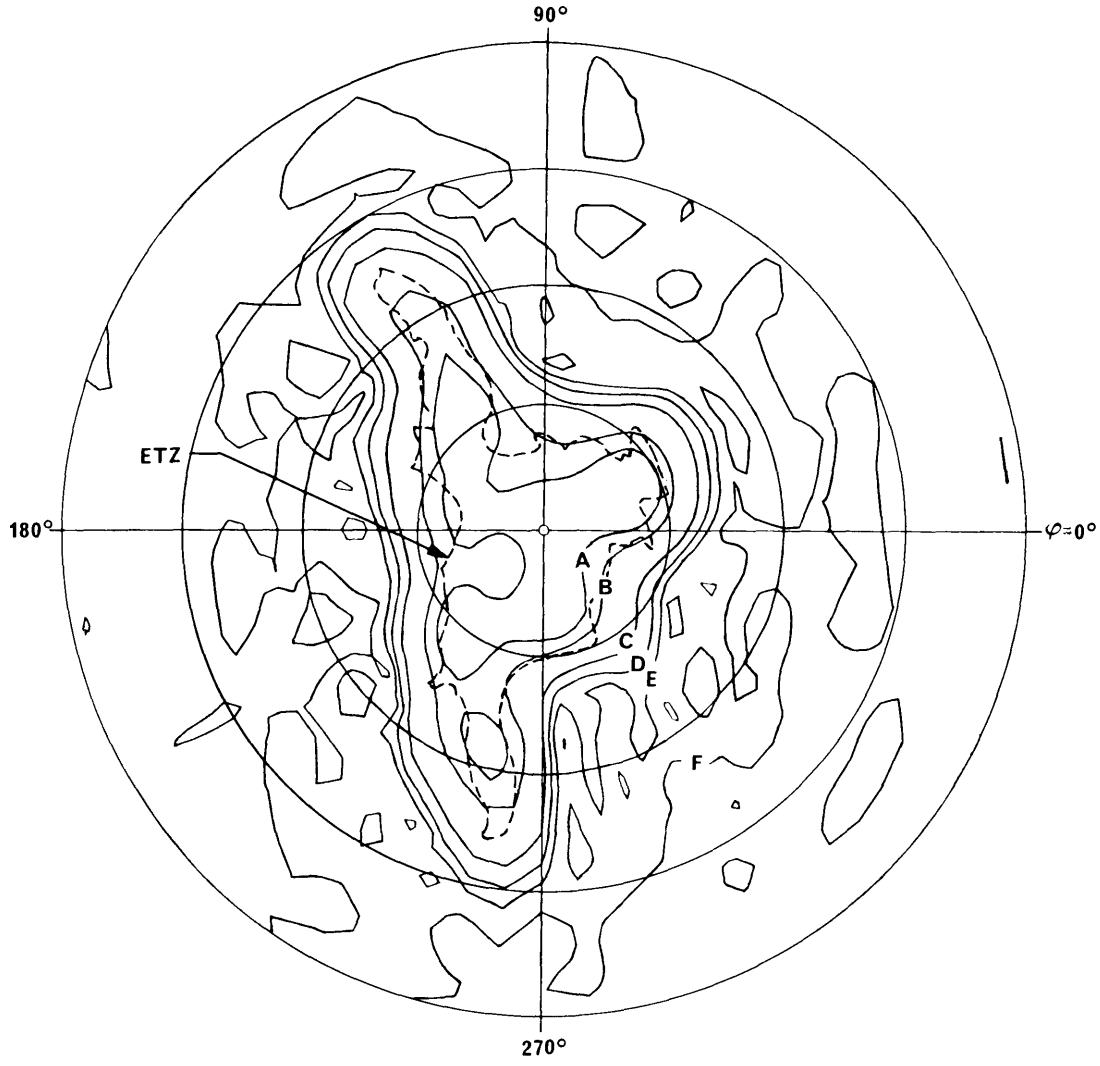

FIGURE 3 – *ETZ, using feed pattern of 12 × 12 array*

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.

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 antennae. 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.

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REPORT 677

LOW SIDE-LOBE ANTENNAE FOR SPACE RESEARCH EARTH STATIONS

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

(1978)

1. Introduction

This Report describes the performance characteristics of an offset Gregorian antenna with very low side-lobes, which may be suitable for space research earth station antennae.

The use of an offset reflector configuration with a low side-lobe primary radiator is a very effective way to reduce side-lobes. In addition to this, the use of microwave absorber attached around the outer edge of reflectors and primary radiator enables the antenna to keep side-lobe levels extremely low. The possible noise temperature increase due to the microwave absorber is estimated to be small.

2. Side-lobe characteristics of offset-reflector antenna

Offset reflector configuration is known to be very effective in reducing side-lobes, because it is free from aperture blockage. It is also effective to use the low side-lobe primary radiator for suppressing the spill-over rays from the edge of the sub-reflector which cause wide-angle side-lobes. As an example of offset reflector antennae, an experimental offset Gregorian antenna with a diameter of 80 cm was fabricated and tested at 34 GHz [Mizugutch *et al.*, 1976].

Fig. 1 shows the geometrical configuration of the test antenna. Fig. 2 shows the side-lobe characteristics in the horizontal plane of the offset Gregorian antenna and a typical Cassegrain antenna compared to the reference radiation diagram. It is seen from this Figure that the side-lobe level of the offset Gregorian antenna is much lower than that of a conventional Cassegrain antenna. Curves A and B are reproduced from the data in Report 390-3.

Relatively high side-lobes observed in the offset Gregorian antenna around the normalized angle of 50° are attributed to the spill-over rays from the edge of sub-reflector.

Although the test antenna was of a diameter of 80 cm, such offset configuration may be applicable to a larger diameter antenna.

3. Side-lobe reduction by microwave absorber

Though offset Gregorian antennae 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. A series of experiments has been made using the same antenna. Fig. 3 shows the antenna with microwave absorber attached. Fig. 4 shows the comparison of the envelope patterns in the horizontal plane of an offset Gregorian antenna with and without microwave absorber. 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 absorber. 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 absorber, since it is attached to the area where illumination level is very low. The measured efficiency of the test antenna was about 70%.

4. Discussion of noise temperature increase due to microwave absorber

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

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

where,

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

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

T_0: temperature of microwave absorber (≈ 290 K).

The noise temperature increase ΔT is evaluated to be 4.4 K by using the equation above. If the elevation angle is lower than 90°, the value ΔT decreases.

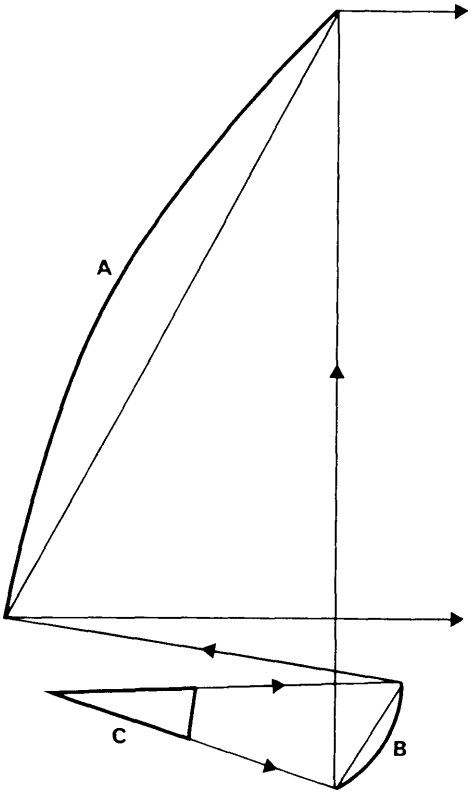

FIGURE 1 – *Geometrical configuration of offset Gregorian antenna*

A : Main reflector (offset paraboloid)
B : Sub-reflector (ellipsoid)
C : Primary horn

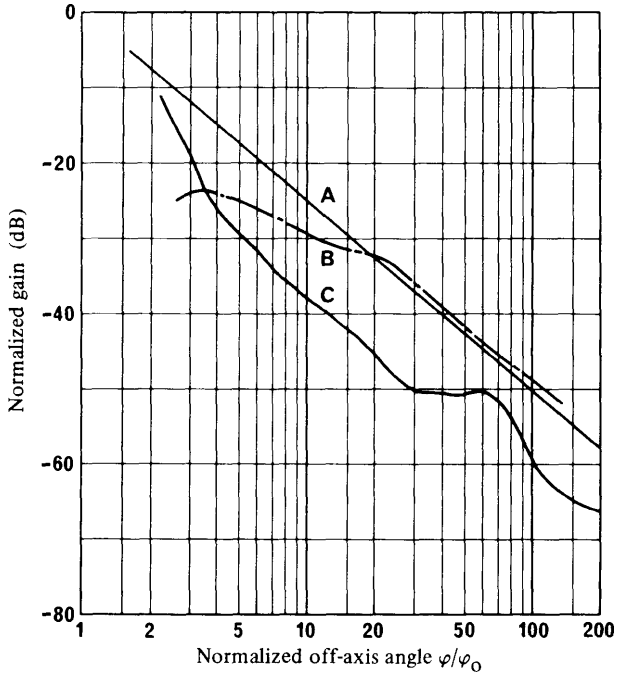

FIGURE 2 – *Measured envelope patterns*

φ : angle off the axis of the main beam
$2\varphi_0$: half-power beamwidth of the antenna
A : $G = [1 + (\varphi/\varphi_0)^{2,5}]^{-1}$
B : Cassegrain antenna
C : Offset Gregorian antenna

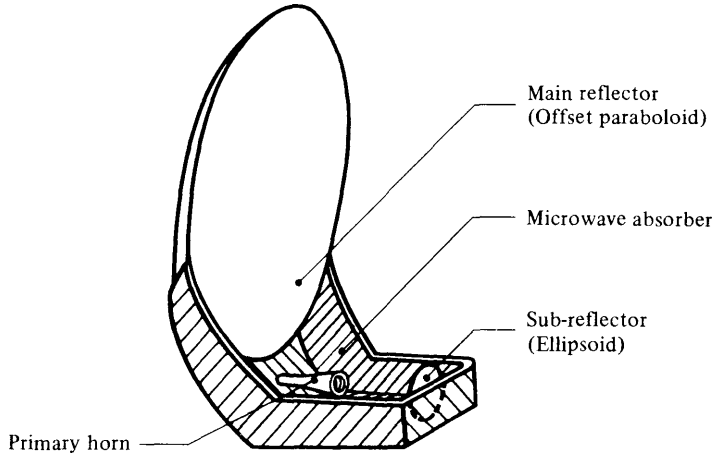

FIGURE 3 – *Offset Gregorian antenna with microwave absorber*

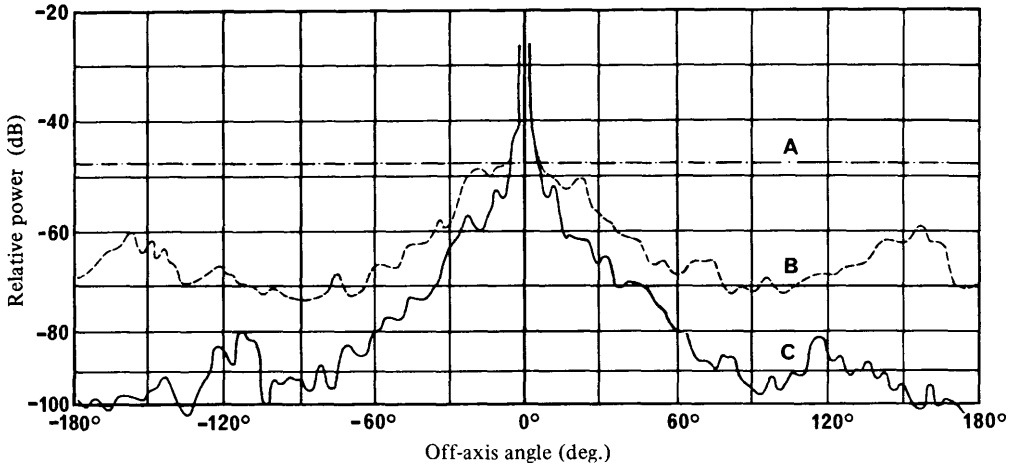

FIGURE 4 – *Measured side-lobe patterns of offset Gregorian antenna with and without microwave absorber*

A : Isotropic level
B : Without microwave absorber
C : With microwave absorber

5. Conclusion

This Report shows the measured radiation patterns of an experimental offset Gregorian antenna with and without microwave absorber, as a possible candidate for space research earth station antennae. 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 the microwave absorber 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 absorber 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 worth-while to pay attention to such techniques for reducing interference in the Space Research Service.

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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 465-1) be used to represent provisionally the space research earth station side-lobe response;

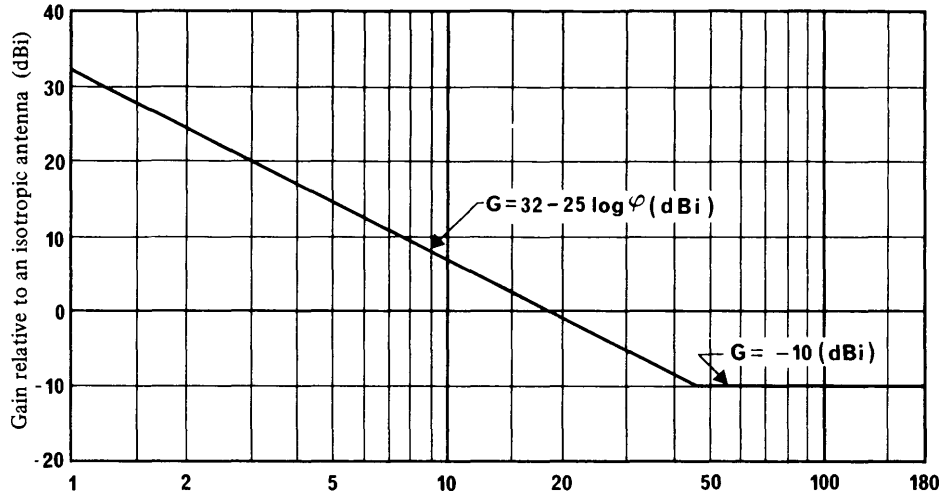

FIGURE 1 – *Provisional reference radiation diagram*

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 396-3

MAINTENANCE TELEMETERING, TRACKING AND TELECOMMAND FOR DEVELOPMENTAL AND OPERATIONAL SATELLITES

Possibilities of frequency sharing between earth-satellite telemetering or telecommand links and terrestrial services

(Questions 1-1/2, 12-2/2 and 18/2)

(1966 - 1970 - 1974 - 1978)

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 for Space Telecommunications, Geneva, 1971, 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). In addition, the equipment reliability aspects of a unified system of maintenance telemetering and telecommunications are discussed in Annex V.

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 cannot be proposed in any general allocation of bands.

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 is the minimum permissible median level (dBW) of the wanted signal at the input to the receiver which may experience interference,

and Y is the 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:

$$M = P_I - (P_T + G_T - L + G_R) \qquad \text{dB} \qquad (1)$$

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 239-4. 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 of 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 systems 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 antennae. 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 antennae, it is assumed that omnidirectional telemetering and telecommand antennae 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 antennae 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 antennae 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 364-3 and Report 548-1 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 satellite and receiving in others, is considered as unacceptable; 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.

Problems at VHF are discussed in Annex IV. Maintenance telemetering, tracking and telecommand in frequency bands in which space-to-space communications are permitted are discussed in Report 548-1. 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 appears that the most practical procedure will generally be to carry out maintenance functions in the operational bands allocated to the service concerned. Nevertheless, there will continue to be some requirements for space operations in specially designated bands, especially at frequencies of the order of 1 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.

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.

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 or narrow-band
	Wideband	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 364-3 and Report 548-1. 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 364-3. 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 has 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.

REFERENCE

CCIR Documents

[1966-69]: IV/75 (Germany, (Federal Republic of)).

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
TX: Transmitter
RX: Receiver
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				Transmitting system						System safety factor (dB) (2)
				System WB or NB (1)	Bandwidth (Hz)		Factor X (dBW)	Antenna gain G_R (dB)	Radiated power P_T (dBW)	Antenna gain G_T (dB)	Attenuation L (dB)		Received power $P_R = P_T + G_T + G_R - L$ (dBW)	
					Pre-detector	Post-detector					Zenith	Max. slant-range		
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 antennae 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 on page 46.

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	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 on page 46.

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 [Dietz *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 co-ordination 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 co-ordination 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.

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. 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 antennae, 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.

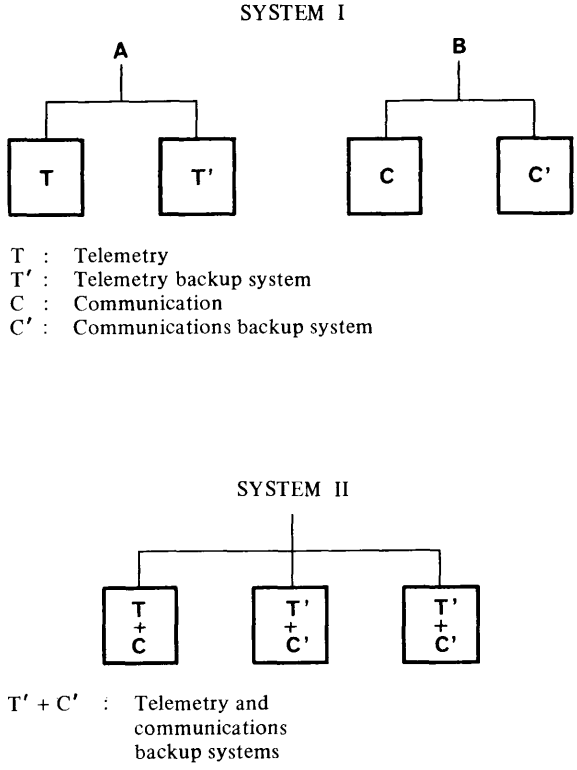

FIGURE 1 – *Examples of the multi-system (I) and the unified system (II)*

3. The probability of the working of the two systems

The probability of System I being in workable order is as follows:

$$P_I = (1 - p^2) \times (1 - p^2) = 1 - 2p^2 + p^4 \quad (3)$$

where:

p: 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:

$$P_{II} = 1 - p^3 \quad (4)$$

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.

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REPORT 678

TECHNICAL FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE OPERATIONS SERVICE AND THE SPACE RESEARCH SERVICE IN THE 1 TO 10 GHz BAND

(Question 1-1/2)

(1978)

1. Introduction

The Space Operations 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 antennae 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 Operations Service.

The purpose of this Report is to demonstrate the technical feasibility of frequency sharing between the Space Operations 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 Operations Service. In this way the utilisation 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 Operations 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 Operations 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 Operations 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.

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 (below) provides a comparison of the system parameters of the Space Research Service (for near-Earth satellites and deep-space probes) and of the Space Operations Service.

TABLE I – *Typical system parameters (at 2 GHz)*

Mode	System parameters	Space Research		Space Operations (up to geostationary altitude)
		Near-Earth	Deep-space	
Reception at earth station	Telemetry bandwidth Tracking bandwidth G/T earth station	10 kHz – 30 MHz 400 kHz – 1 MHz 20 – 35 dBK	1 Hz – 4 MHz 1 Hz – 4 MHz 37 – 60 dBK	100 kHz 400 kHz ≈20 dBK
Transmission from earth station	Telecommand bandwidth Tracking bandwidth EIRP earth station	100 kHz – 1 MHz 400 kHz – 1 MHz 60 – 90 dBW	1 Hz – 3 MHz 1 Hz – 3 MHz 75 – 116 dBW	100 kHz 400 kHz ≈65 dBW

The system parameters of satellites in the Space Research Service (near-Earth) and the Space Operations Service are very similar, the Space Operations 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 Operations 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 Operations 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 Operations 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 (cf. ITU/RR/639 AA).

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 Operations 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 Operations 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 Operations (up to geostationary altitude)
		Near-Earth	Deep-space	
Reception at earth station	Telemetry bandwidth Tracking bandwidth G/T earth station	100 kHz – 30 MHz 100 kHz – 2 MHz 25 – 45 dBK	1 Hz – 4 MHz 1 Hz – 40 MHz ~58 dBK	100 kHz 500 kHz 26 – 30 dBK
Transmission from earth station	Telecommand bandwidth Tracking bandwidth EIRP earth station	100 kHz 100 kHz – 2 MHz 70 – 90 dBW	1 Hz – 3 MHz 1 Hz – 40 MHz 110 – 120 dBW	100 kHz 500 kHz 75 dBW

3. Conclusions

Sharing between the Space Research Service (near-Earth) and the Space Operations 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 Operations 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 9A of the Radio Regulations.

RECOMMENDATION 363-1

PREFERRED FREQUENCY BANDS FOR USE IN MAINTENANCE TELEMETERING, TRACKING AND TELECOMMAND OF DEVELOPMENTAL AND OPERATIONAL SATELLITES

(Question 2-1/2)

(1963 - 1974)

The CCIR,

CONSIDERING

(a) that the frequencies technically suitable for maintenance telemetering, tracking and telecommand of developmental and operational radionavigation, meteorological and communication satellites lie in the range from 100 MHz to 15 GHz; the lower part of this range being generally more suitable for lower altitude earth satellites and the higher part of this range being generally more suitable for higher altitude earth satellites;

(b) that the integration of maintenance telemetering, tracking and telecommand links with data transmision and communication systems has potential advantages which include, among others, efficient use of the spectrum;

(c) that the validity of this approach has been demonstrated in operational systems, in that command and telemetry functions originally conducted in band 8 were later incorporated successfully into the Fixed Satellite Service bands at 4 and 6 GHz,

UNANIMOUSLY RECOMMENDS

1. that bands of frequencies below 1 GHz are technically suitable for some types of maintenance telemetering, tracking and telecommand of developmental and operational satellites;

2. that bands of frequencies between 1 and 15 GHz are also technically suitable for maintenance telemetering, precision tracking systems, tracking and telecommand, particularly for high altitude satellites;

3. that bands of frequencies above about 10 GHz are technically suitable for maintenance telemetering, tracking and telecommand during the re-entry of satellites into the atmosphere of the Earth (see Report 222-4);

4. that, for satellite systems such as those used for meteorological, radionavigation and communication purposes, and taking account of requirements for reliability and economical use of the frequency spectrum, use of frequencies within the operational bands used for data transmission or communications should be considered for maintenance telemetering, tracking and telecommand, where feasible.

REPORT 679

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

(Question 20/2)

(1978)

1. Introduction

Free-space energy transmission by microwaves is defined as the point-to-point transfer of energy through free-space by a highly collimated microwave beam.

This technique differs from the use of microwaves in free-space for point-to-point communication purposes because of its very high efficiency and the magnitude of the power. The efficient collection and the 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 and location services.

The efficient free-space transfer of energy by an electromagnetic beam, brings a new three-dimensional aspect to the transfer of electrical energy and permits the coupling of terrestrial power transmission systems to power sources and sinks located in the Earth's atmosphere and in deep-space, as well as on the Earth's surface.

The concept of energy transfer by radio waves was first pioneered by Tesla [O'Neill, 1944; Hunt, 1964] at the turn of the century. An acknowledged genius in low-frequency electric power generation and distribution, 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 antennae at the optimum point.

With the advantage of historical perspective, it is now realized that these experiments were decades ahead of the unfolding of a technology that could accomplish his objective. This new technology was based upon the early microwave experiments of Hertz [Susskind, 1968], but had to await the development of efficient generators of microwave power. This capability began to emerge with the microwave generators developed for radiolocation and later for radiocommunications.

The event which directly precipitated interest in the use of microwaves for power transmission was the development of super-power generation at microwave frequencies in the early 1960's [Skowron, 1964; Luebke, 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 [IEEE Trans. AES, 1969; Robinson, 1970; Brown and Dickinson, 1975].

Purely from a technological viewpoint of the various criteria that could be used to evaluate the progress of microwave energy transmission, efficiency is perhaps the most important. By this standard, the product of the efficiencies of the three elements which make up the overall system has moved from 15 per cent in 1963 to a current value of 54 per cent [Brown and Dickinson, 1975]. Additional development activity on energy conversion components in the system is expected to bring the eventual overall efficiency close to 70 per cent.

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 at 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

In discussing the technology of a microwave energy transmission system, it is convenient to divide the system into three principal elements – each identified with a separate technology – which link together at their physical interfaces in the system. These elements consist of the following:

- Element (1): conversion of d.c. electrical energy to microwave energy,
- Element (2): transfer of microwave energy from the output of the microwave generator to the receiving aperture,
- Element (3): collection and rectification of the microwave energy at the receiving aperture *.

These elements and their interrelationship determine the power handling capability and the overall efficiency of the system.

The efficiencies associated with the principal elements will be referred to as η_g, η_t, and η_r, respectively. Thus, the overall efficiency of the system is:

$$\eta = \eta_g \eta_t \eta_r \quad (1)$$

In turn, each of the efficiencies η_g, η_t, and η_r is the product of sub-efficiencies peculiar to that portion of the system.

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* Element 3 consists in turn of collection and rectification by separate and distinct approaches, as discussed in § 2.4 below.

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

The first element in a microwave energy transmission system relates to the conversion of the d.c. energy into microwave energy. In the conversion process the efficiency should be as high as possible, not only to minimize the size of the prime source but also to minimize the difficulty of disposing of the heat which results from any inefficiency in the converter.

There are several methods of conversion but only one of them has demonstrated the order of efficiency deemed desirable for a power transmission system. This device is the so-called 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 which have operated at efficiencies of 80-90 per cent.

2.2 *The microwave beam link*

All elements of transmission from the output of the generator to the aperture area at the receiving point, as defined in the previous section, 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 per cent from a properly illuminated and contoured transmitting aperture to a receiving aperture. This relationship [Goubau, 1970] is shown in Fig. 1. The relationship between the parameters is:

$$\tau = \frac{\sqrt{A_r A_t}}{\lambda D} \tag{2}$$

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 indeed approach 100 per cent has been demonstrated experimentally [Degenford *et al.*, 1964]. One of the obvious conclusions is that the efficiency is independent of the distance between the transmitter and the receiver, if the aperture areas are appropriately scaled to keep τ a constant value. Hence, 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 – the phased array with corporate feed from a single microwave source, the active phased array in which the radiating elements are individually driven, an illuminating horn and lens, and the traditional illuminating horn and secondary reflector.

Due to the large amount of power involved, the active phased array stands out as superior. This finds its greatest area of application in 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 into some kind of a receiving antenna, and to convert the microwave energy thus captured, 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, 1969].

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, thus eliminating any phasing or heating problems.

There are a great number of advantages resulting from handling the collection and rectification problem in this manner:

- the receiving surface has little directivity and need not be precisely pointed at the transmitter;
- the mechanical tolerances in the construction of the receiving aperture are very relaxed;
- the problem of matching the illumination pattern, established by the incoming radiation, to the radiation, pattern of a conventional receiving antenna is eliminated;

* The term "rectenna" is a combination of the words "rectifier" and "antenna".

- non-uniform intensity and phase illumination of the receiving aperture which will result from a combination of a very large receiving aperture and non-uniform atmospheric conditions over the cross-section of the incoming beam, cause no problems;
- there is a good match between the amount of microwave energy received in local regions of the receiving aperture and the power-handling capability of solid-state microwave rectifiers; and
- any heat resulting from inefficient rectification in the rectifiers can be easily disposed of in the local region of the receiving aperture.

The rectenna concept makes it possible to collect and rectify the microwave energy at overall efficiency levels that would be difficult to attain by other means. The rectenna efficiency consists essentially of two parts – the microwave collection efficiency and the rectification efficiency. In theory, the collection efficiency can approach 100 per cent by matching the rectenna input impedance to that of free space, being limited only by care in design and manufacturing trimming. The rectification efficiency depends upon the efficiency of the rectifying diodes themselves and the ability to design a rectifying circuit which effectively represses reradiation of harmonics by converting them into useful energy.

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

3.1 *General applications*

The remarkable properties of microwave energy transmission are given in the following list:

- no mass either in the form of wire conductors or ferrying vehicles is required between the source of energy and the point of consumption;
- energy can be transferred at the velocity of light;
- 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.

In looking for applications of a technology it is natural to think in terms of existing technologies that it could replace. It does not seem feasible to replace systems such as the wire transmission lines, but there could well be some applications involving temporary or even permanent transmission of modest power to inaccessible locations, such as airborne vehicles in a more or less fixed location in the Earth's atmosphere for a long period of time.

A completely different type of terrestrial (as well as space) application would be one involving the transfer of energy between two points separated by a very hazardous environment, 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*

There is now a distinct possibility of a technologically and economically feasible system of bringing energy down from a synchronous satellite which converts large amounts of the Sun's energy to electrical energy. This development would provide nearly pollution-free energy from an inexhaustible source external to the Earth. [Glaser, 1968; Journ. Microwave Power, 1970].

The solar energy falling on the Earth is so diffuse and variable that it is difficult to use. However, in geostationary orbit a 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 base line 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 which would penetrate 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 level 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. Proposed satellite solar power station (SSPS)

A conceptual design of an SSPS 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 per cent.

The conceptual design of the geostationary transmitting antenna array has employed two techniques to achieve the goals. The 1 km diameter circular phased array antenna would use an estimate for τ of 1.62 (see Fig. 1). The power taper would be 10 dB (so that $P/P_0 = 0.1$), the power of the radiating elements would decrease in steps of approximately 1 dB, in 10 near equal area concentric rings around the centre of the transmitting array. Assuming an r.m.s. phase error ($\delta\Phi$) of 10°, an r.m.s. amplitude error ($\delta\Delta$) of ± 1 dB, and 2% random failures among the radiating elements, the antenna pattern is as shown in Fig. 2.

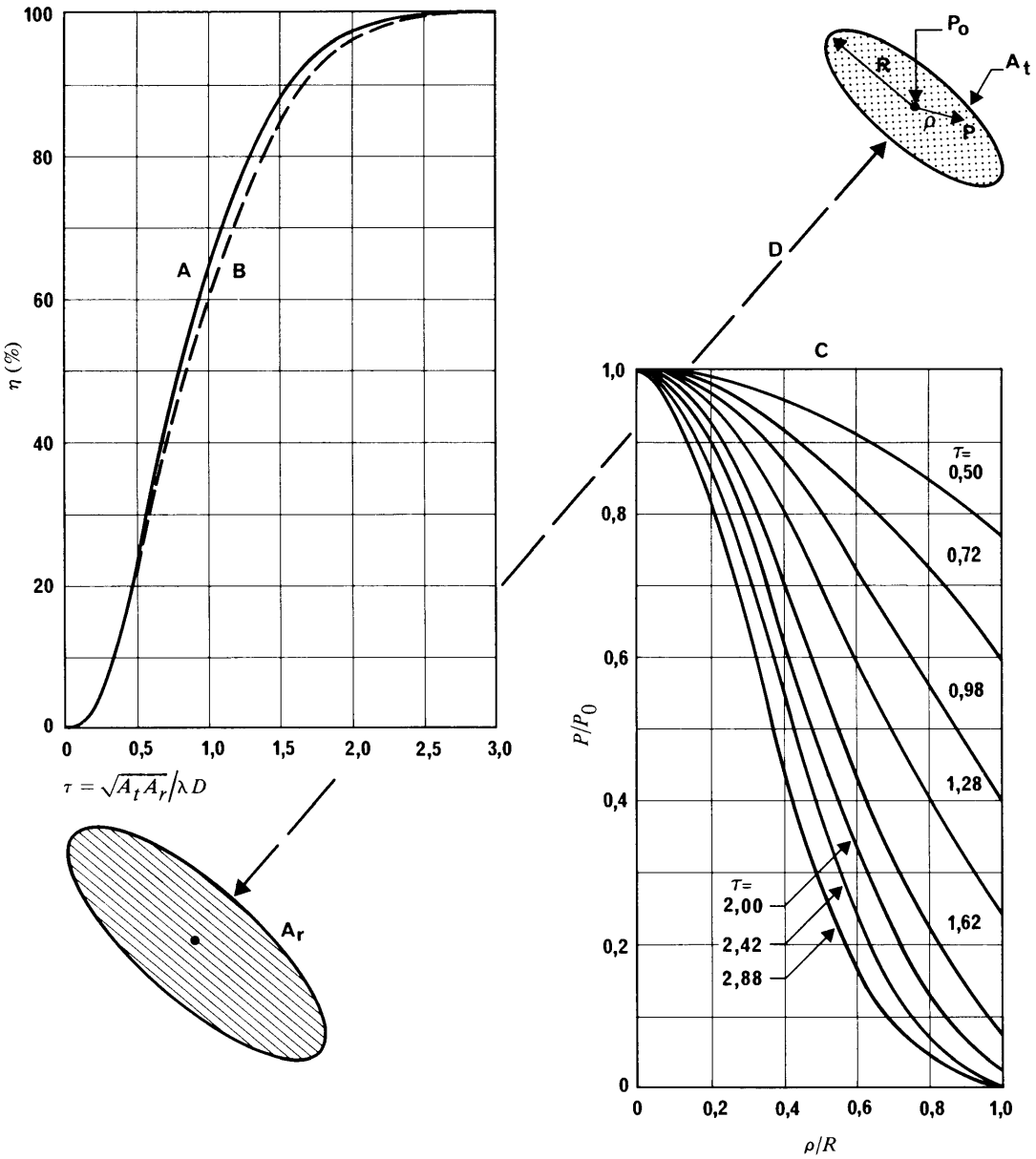

FIGURE 1 – *RF power beam transmission efficiency*

A: Circular aperture

B: Quadratic apertures

C: Optimum aperture taper

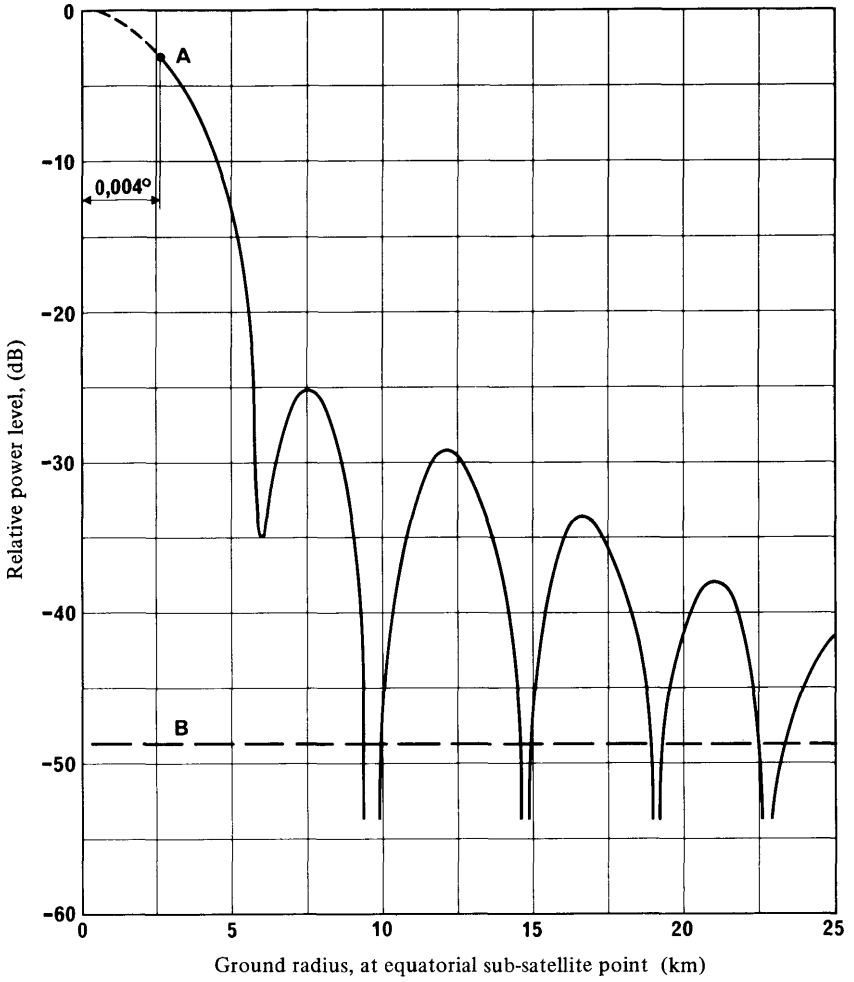

FIGURE 2 – *Antenna pattern resulting from the conceptual design of the SSPS transmitting array*

A: Half-power beamwidth

B: Average phase error sidelobe level

The half-power beamwidth is 0.008° and the side lobes decrease asymptotically to a level of −49 dB below the main beam.

The beam is focused upon a beacon transmitter at the centre of the collecting area on Earth. The power flux-density patterns on an equatorial collecting site on the same longitude as the transmitting antenna are shown in Fig. 3. The peak power flux-density at the centre of the collecting area is 20 mW/cm^2. A rectenna array 5 km in diameter will encompass the incident power approximately to the contour level D (0.5 mW/cm^2). A guard area extending out to a 10 km radius will encompass power flux-densities in excess of those shown for contour E (approximately 50 μW/cm^2).

The concentration of the antenna beam will provide protection to radio-communication services because the side lobe levels outside the collecting area, and adjacent guard areas on Earth, will be attenuated by 49 dB using the antenna characteristics 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. 4.

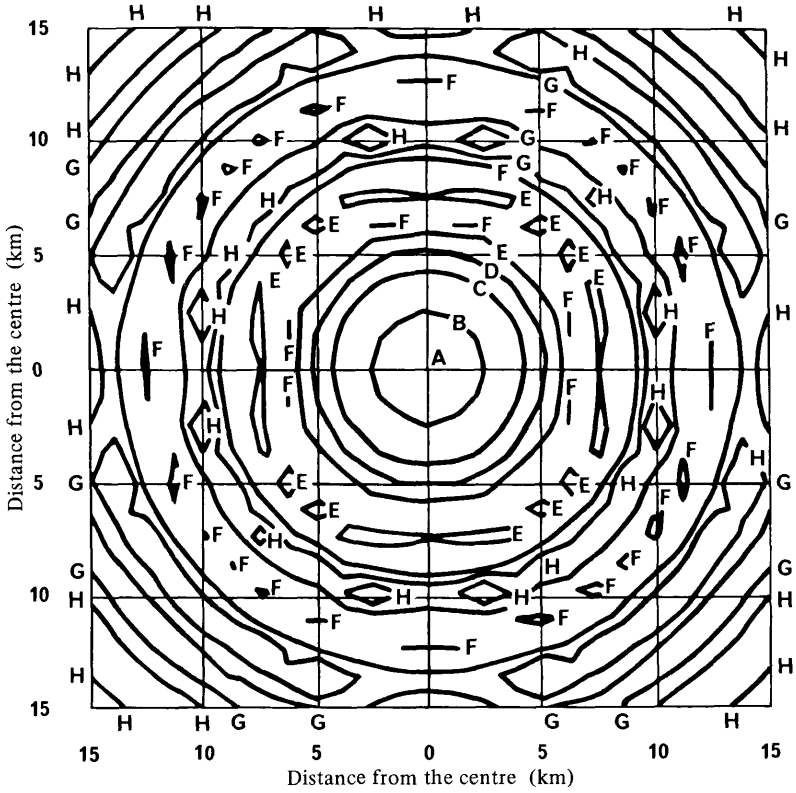

FIGURE 3 – *Microwave power energy distribution on rectenna at equatorial sub-satellite point*

Circular array 1 km diameter
6.5 GW at 2450 MHz
10.0 dB Gaussian taper
Uniform square elements, 10 meters
Phase error, 10.0° r.m.s.
Illumination error, ± 1.0 dB r.m.s.
Failure rate, 2%

Zones	*dB*	*mW/cm²*
A	0	20(1)
B	– 3	10
C	–10	2
D	–16	0.5
E	–25	0.063
F	–30	0.02
G	–35	0.0063
H	–40	0.002

(1)Includes waveguide and atmospheric loss

The transmitter power output is assumed to be 6.5 GW or +98.1 dBW at 2540 MHz. This is concentrated into a collecting area 5 km in diameter at the subsatellite point. The power flux-density at the edge of this collecting area is 7 dB(W/m^2). Outside this collecting area and the surrounding guard band, the power flux-density will be attenuated to a level of −13 dB(W/m^2).

Assume the transmitter spectrum energy is spread evenly over the band 2450 ± 10 MHz. The power flux-density in any 4 kHz band will be reduced by a factor of 37 dB. 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 transmitters in this frequency band to a power flux-density of −154 dB(W/m^2 · 4 kHz) (for low elevation angles) *. The transmitter filters must provide 104 dB attenuation

* See No. 470NE of the Radio Regulations.

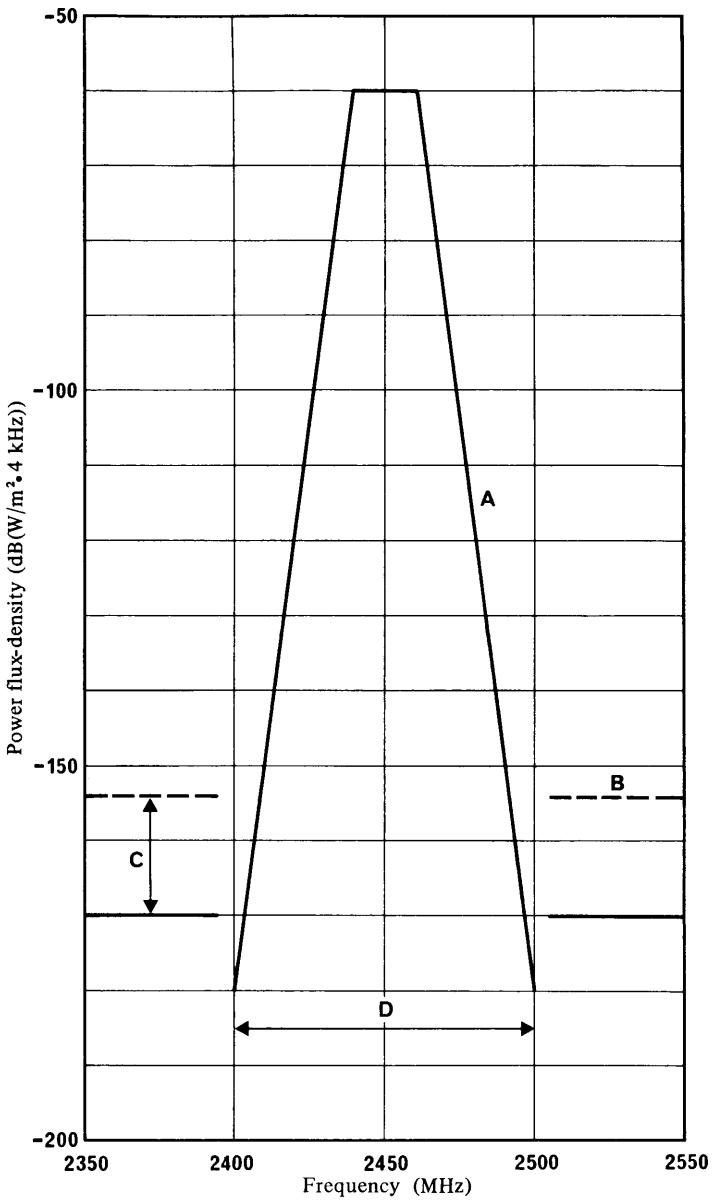

FIGURE 4 – *Conceptual design of solar power satellite power flux-density versus frequency outside of the 10 km radius guard area*

A: 5 cavity klystron transmitter system spectrum

B: ITU limit

C: 16 dB margin at band edge

D: ISM band

in the 40 MHz between the transmitter spectrum and the edge of the industrial, scientific and medical (ISM) band. Conceptual design for the SSPS envisages a 5-cavity klystron which provides 120 dB attenuation at the band edge (see Fig. 4). The margin of 16 dB appears to provide 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. 4.

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 rectennae 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.

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 CCIR Report 224-4. 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.

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 CCIR Report 224-4 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 *

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

(Question 53-1/1)

(1978)

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 make practical application of Planck's Law, i.e.

$$E = h \cdot \nu \quad (1)$$

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.

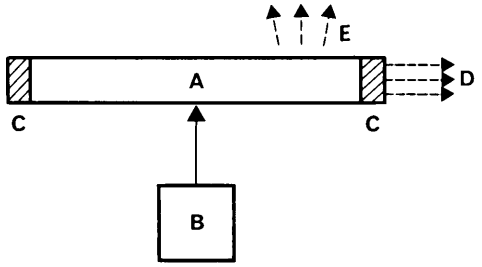


FIGURE 1 – *Typical laser cavity elements*

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.

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

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 more 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.

7. Echo ranging

Active echo ranging systems using laser emitters have been developed for terrestrial use and are now being proposed for space research. Figs. 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.

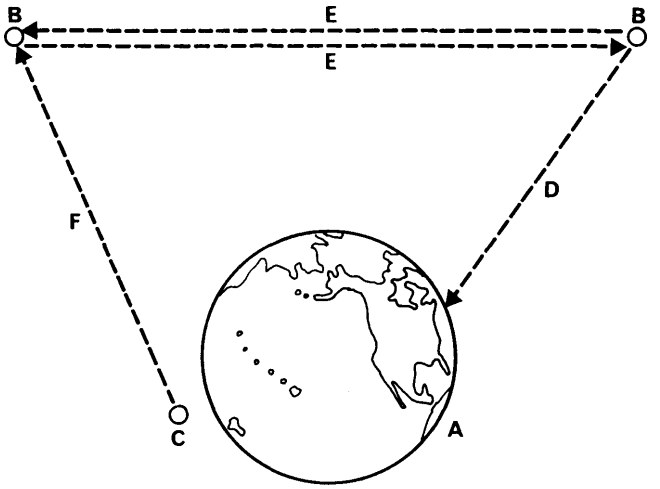


FIGURE 2 – *Space applications of laser communications*

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

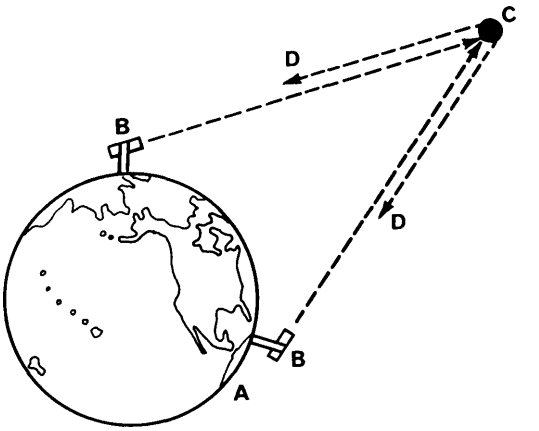


FIGURE 3 – *Earth-based laser applications – echo ranging*

A: Earth

B: Lidar tracking mount

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

D: Incident and reflected light

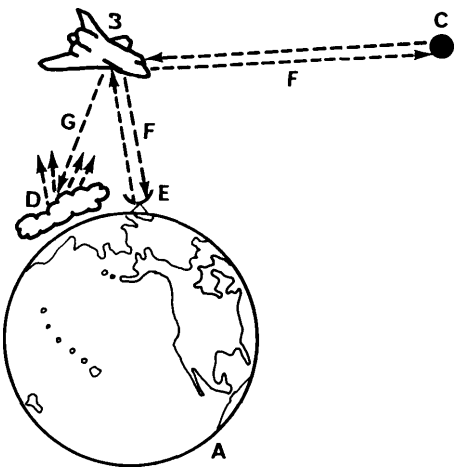


FIGURE 4 – *Spaceborne laser applications – echo ranging*

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.

TABLE II – *Possible laser applications*

Space radiocommunications
- Satellite-to-satellite
- Satellite-to-Earth
- Earth-to-satellite
- Intra spacecraft – fibre optics

Terrestrial radiocommunications
- Atmospheric point-to-point
- Underwater point-to-point
- Intra-system – fibre optics

Guidance
- Electro-optical image correlator guidance systems
- Infra-red imaging guidance
- Television guidance
- Laser trackers

Night vision
- Low light level television illuminators
- Image intensifier system illuminators
  - Night driving
  - Surveillance

Space remote sensing
- Geology and mineral resources
- Geography and cartography
- Oceanography
- Enrivonmental quality
- Agriculture and forestry
- Hydrology and mineral resources

Construction and surveying

Drilling, cutting, welding

Navigation

Measurement systems

Printing and graphics

Readers, recorders and displays

Medical systems – surgery and instrumentation

Materials processing

Nuclear fusion

Isotope separation

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.

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. Fig. 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.

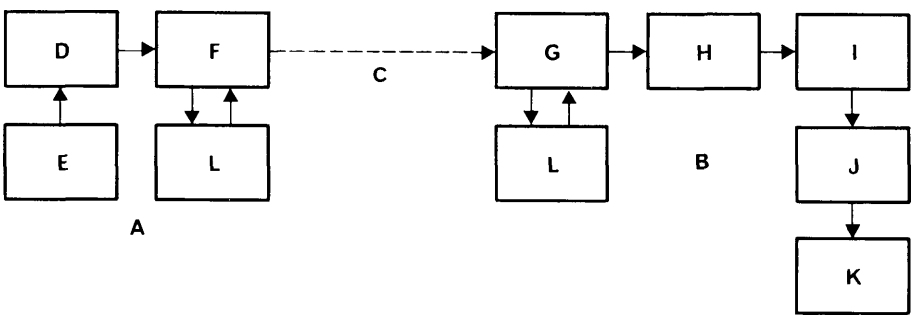


FIGURE 5 – *Functional block diagram of a typical optical communication system*

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.

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 important to system performance in this case, as it is in Earth-to-space and space-to-Earth links. Visible and 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 radiant energy, thus collected is focused on the sensitive surface of a photodector. 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. Examples of users are 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:

$$P_R = P_T\, G_T\, G_R \left(\frac{\lambda}{4\pi S}\right)^2 L \qquad (2)$$

$$L = \text{Loss factor} \qquad = \tau_A\, K$$

$$P_R = P_T \left(\frac{4\pi A_T}{\lambda^2}\right) \left(\frac{4\pi A_R}{\lambda^2}\right) \left(\frac{\lambda}{4\pi S}\right)^2 \tau_A\, K$$

$$P_R = \frac{P_T}{\lambda^2 S^2}\, \pi \left(\frac{D_T}{2}\right)^2 \pi \left(\frac{D_R}{2}\right)^2 \tau_A\, K$$

$$P_R = \frac{\pi^2 P_T D_T^2 D_R^2 \tau_A K}{16 \lambda^2 S^2}$$

and the signal-to-noise ratio is given by

$$S/N = \frac{\rho^2 P_R^2 R_L G^2}{2eB(\rho P_R + \rho P_B + I_d) R_L G^2 + 2FkTB} \qquad (3)$$

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 rate = 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

Fig. 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.

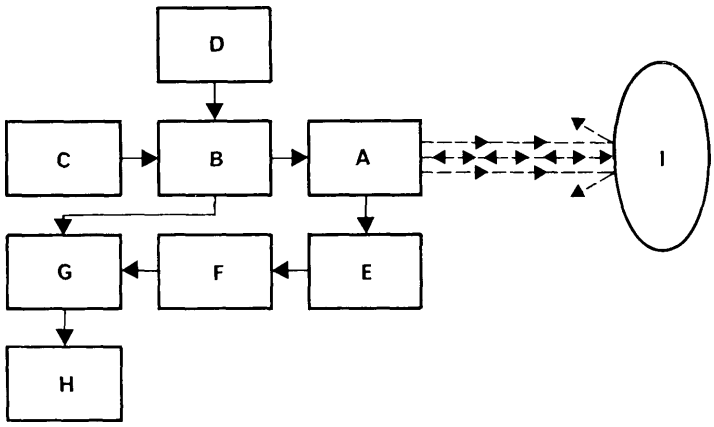


FIGURE 6 – *Functional block diagram, light detection and ranging (LIDAR) system*

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 fulfill 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:

$$\frac{\hat{S}}{N} \approx \frac{\beta^2 P_R}{2eB(\beta P_B + I_d) R_L G^2 + 2FkTB} \tag{5}$$

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) $\geq 0.5/t$
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

$$P_b = -\frac{\pi (H_{\lambda S} B_0 + H_S X) \alpha_R^2 D_R^2 \tau_R}{16} \left\{ \rho \exp(-\sigma S) + \frac{\sigma S}{4\sigma} [1 - \exp(-\sigma S)] \right\} \tag{6}$$

$H_{\lambda S}$: 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

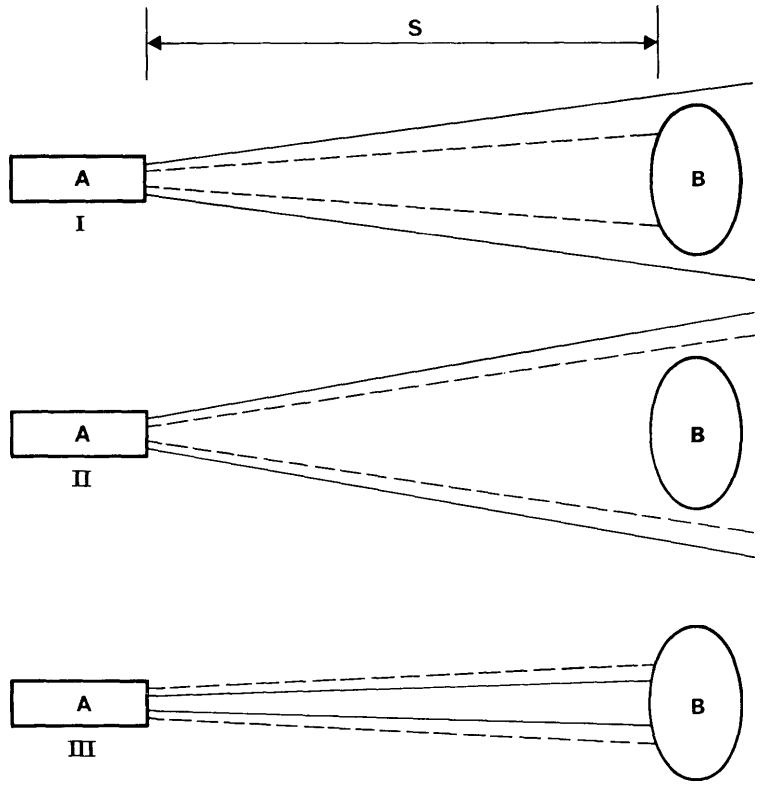
σ_S: atmospheric backscatter coefficient (m^{-1})

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 $M = 1$.



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 $\alpha_R \geq \alpha_T$

$$M = 1$$

FIGURE 7 – *Relationship between beam size, field of view, target size and geometry factor M*

Transmitter beamwidth

Receiver field-of-view

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

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	1000Ω
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 $\sigma(km^{-1})$	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) $\delta R = \frac{C}{2B\sqrt{S/N}}$ (single pulse)	0.82	0.82	0.82	0.82

REPORT 681*

THE POSSIBLE NEED FOR TECHNICAL STANDARDS OF SYSTEMS FOR TELECOMMUNICATION IN THE SPACE RESEARCH SERVICE (INCLUDING DETERMINATION AND OTHER PURPOSES), OPERATING IN THE INFRARED AND VISIBLE LIGHT REGIONS OF THE SPECTRUM

(Question 53-1/1)

(1978)

1. Introduction

Systems for telecommunication operating in the infrared 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 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 existant 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 infrared 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 infrared 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 intereference.

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 atmospheric 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 fog, 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

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

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. However, the limiting effects of the atmosphere can be demonstrated by using the following approximation:

$$\tau_A = \exp(-\sigma S) \quad (1)$$

where:

S: path length, km

σ: atmospheric attenuation coefficient, km^{-1}

This relationship gives reasonably good estimates of transmittance for monochromatic (very narrow band) emissions along horizontal paths through a uniform atmosphere, except at the wavelengths of specific molecular absorption lines where the value of transmittance can be much less than that predicted. Average values for the atmospheric attenuation coefficient (neglecting absorption by H_2O and CO_2) are plotted in Figure 1 for varying visibility conditions and for wavelengths between 0.4 μm and 4.0 μm. Using the value of σ for GaAs($\lambda \approx 0.9$ μm) on a clear day (15 km visibility) over a 10 km path gives a transmittance of approximately 15%. Over a 15 km path, the transmittance is only 6%, and at 25 km the transmittance is less than 1%. Thus the effect of the atmosphere in attenuating laser radiation is considerable. Note that this attenuation increases with frequency and with obscuration in the atmosphere. On a hazy day, the transmittance for GaAs over a 10 km path may be less than 0.01%.

The σ values plotted in Figure 1 account for ozone absorption, Rayleigh scattering and aerosol (Mie) scattering. Transmittance may be further limited by molecular absorption (e.g., water vapour and carbon dioxide), refraction, diffraction, and turbulence. Maximum σ ranges for visible radiation can be crudely estimated from the sea-level visibility figures associated with each curve. Ranges in excess of this number are extremley improbable using visible emissions. Ranges with infrared emissions can exceed the visibility range with a low frequency of occurrence. In general, the maximum probable range increases with wavelength.

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 infrared 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 infrared 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 infrared 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 infrared 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 the same band can be shown to be extremely unlikely.

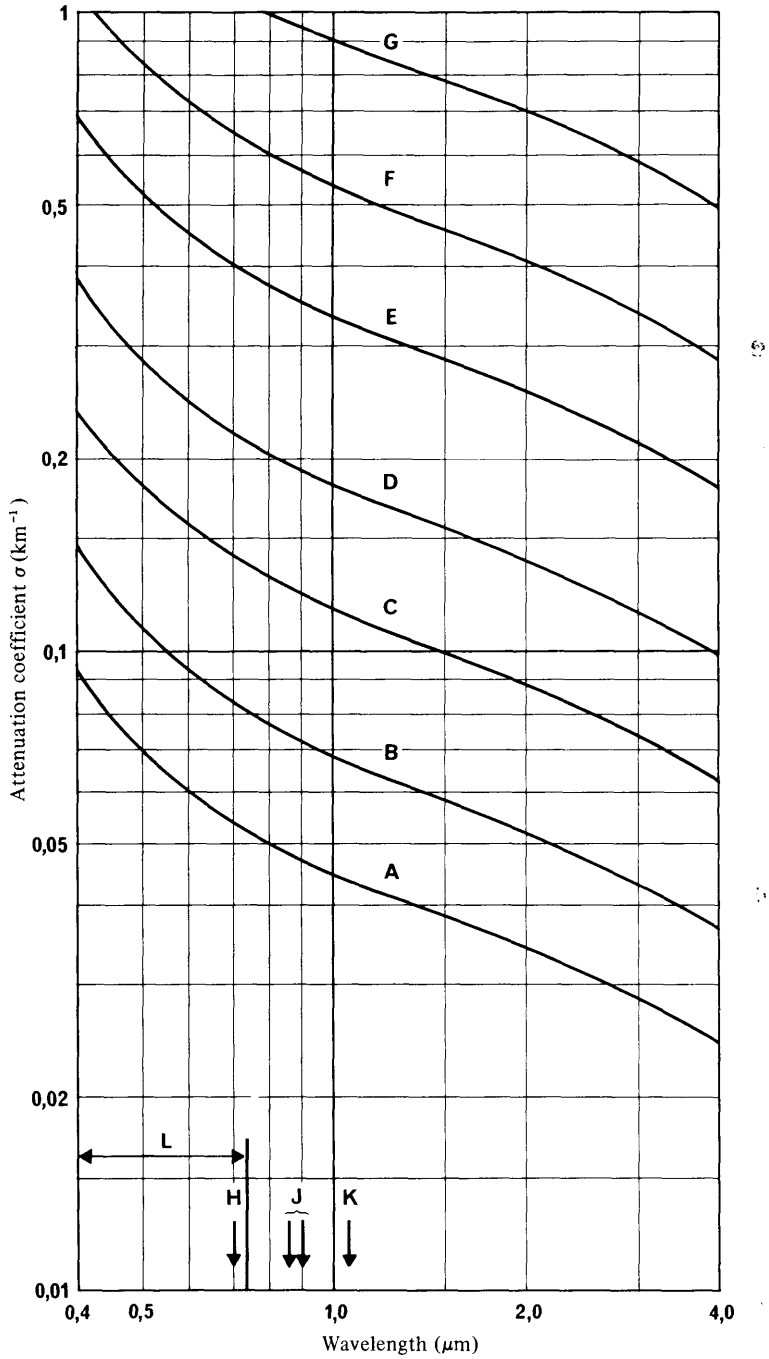


FIGURE 1 – *Attenuation coefficient versus wavelength (at sea-level) – Average curves*

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

Figure 2 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.

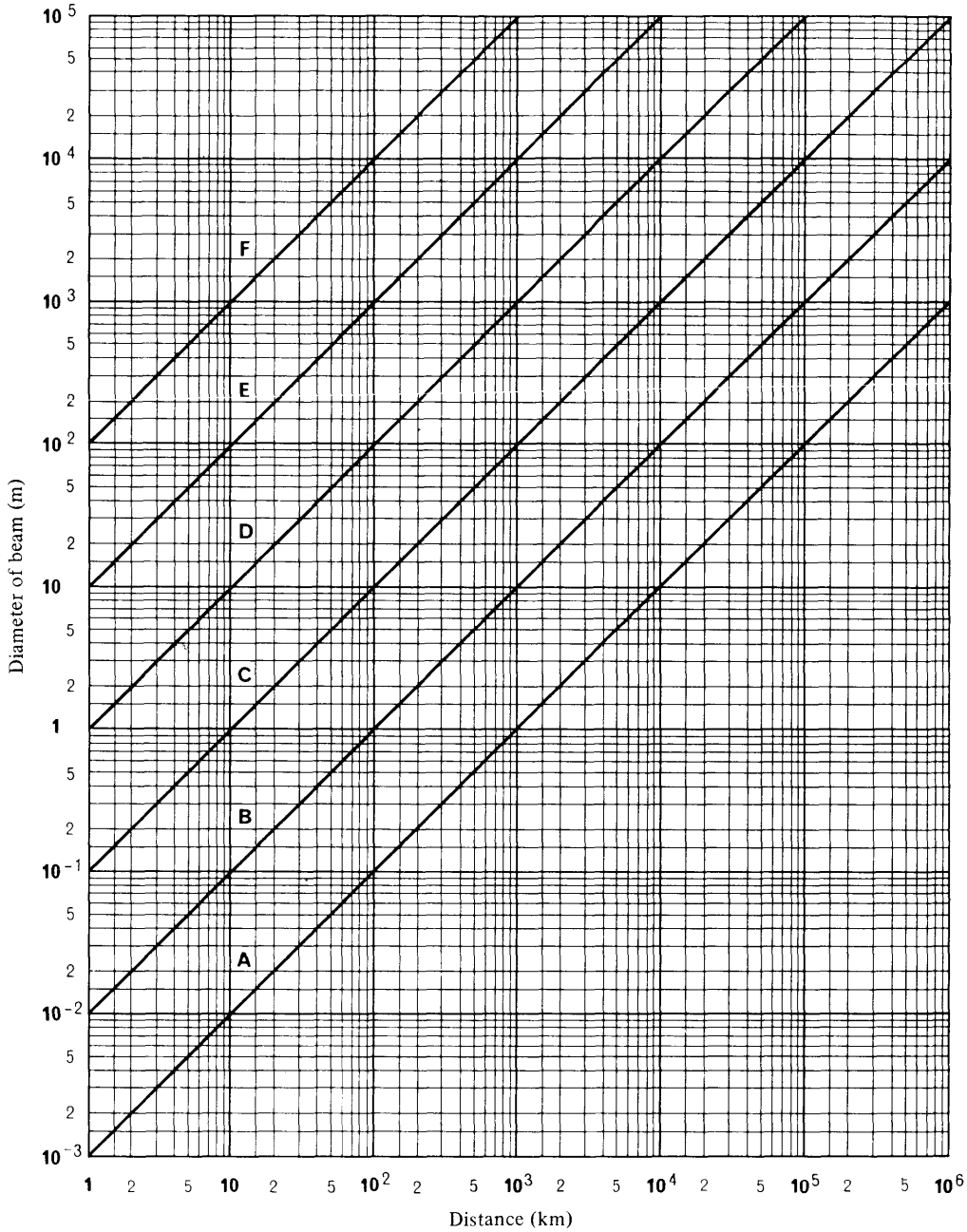


FIGURE 2 – *Beam diameter versus distance from source and beam divergence*

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 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 more graphically by the following analysis.

Figure 3 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 Figure 3.

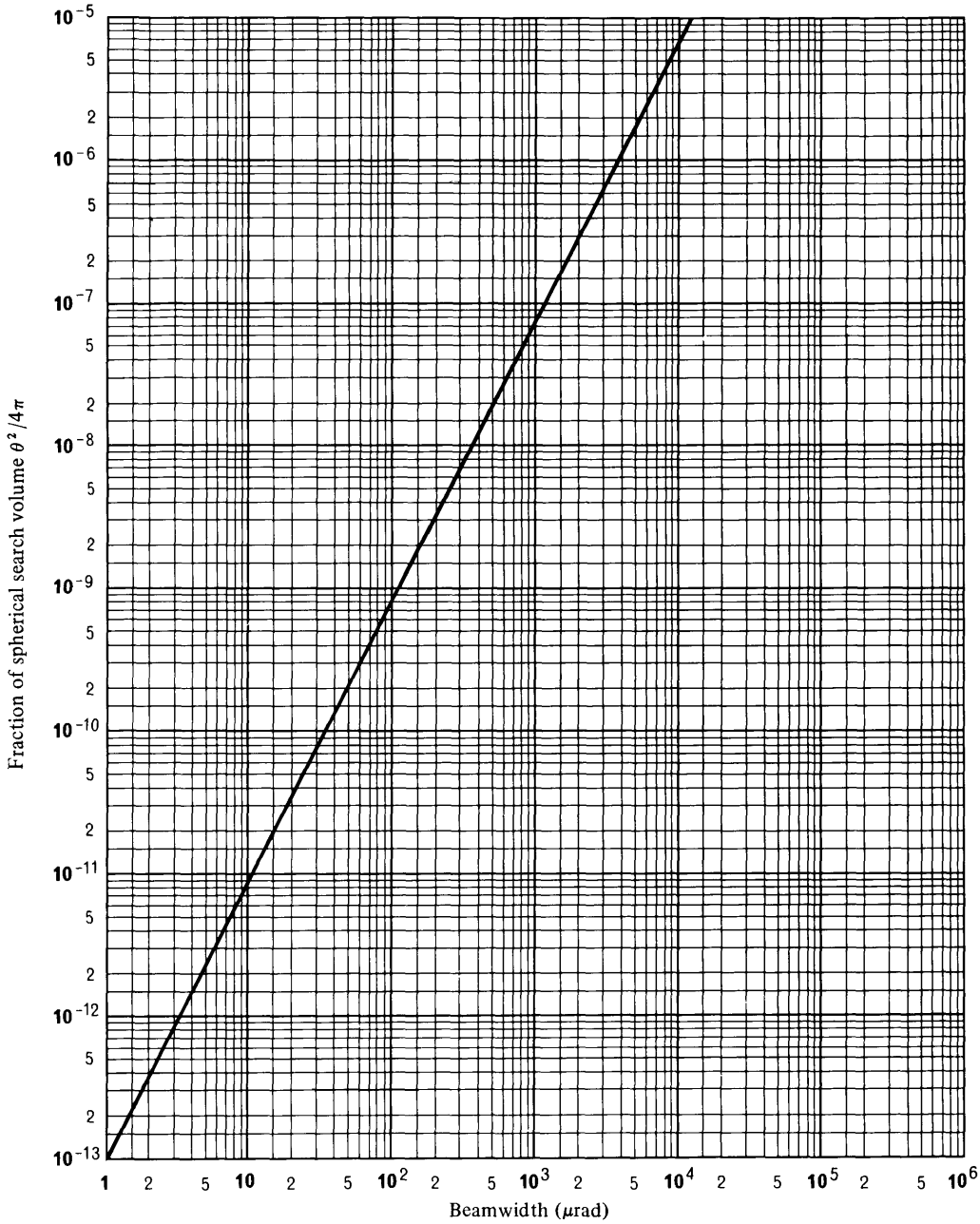


FIGURE 3 – *Fractional search volume versus beamwidth*

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.

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 the band is possible only at relatively short station separations ($<<$ 30 km) due to the limitations of the atmosphere and the high background noise.

The majority of natural and artificial sources which also emit radiation in the infrared 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.

REPORT 222-4 *

EFFECTS OF PLASMAS ON COMMUNICATIONS WITH SPACECRAFT **

(Question 3/2)

(1963 - 1966 - 1970 - 1974 - 1978)

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.

The study of the effects of a surrounding plasma medium is useful for predicting the performance of antenna systems used for tracking of and communication with vehicles entering Earth or other planetary atmospheres. However, due to the complexity of the equations describing the interaction of electromagnetic waves and plasmas, major simplifications are often made in order to obtain practical estimates. In this Report, a general description of the most common simplifications of the basic propagation characteristics of plasmas and a summary of the effects of re-entry plasmas upon the radiation characteristics of aperture antennae will be made. The regions of applicability of the formulae will be discussed. Experimental work related to the measurement of antenna impedance and the performance of antennae in the ionosphere is described elsewhere [CCIR, 1966-69].

Plasmas can be classified according to their electron density or plasma frequency and their electron temperature or velocity, i.e. collision frequency. The operating regions of several theoretically and experimentally encountered plasmas are discussed at length in [Shkarofsky *et al.*, 1966], and are shown in Fig. 1 with the defining formulae given in Table I.

2. Description of re-entry plasma sheaths

A missile or space vehicle that enters a planetary atmosphere at hypersonic velocities will dissipate most of its kinetic energy of flight as thermal energy in the gas flowing around the body (usually called the shock layer). In the case of blunt-nose vehicles, production of electrons and ions takes place primarily in the high temperature nose flow region behind the bow shock wave, and in the case of slender, sharp-nosed bodies, takes place primarily in the frictional heating layer near the body surface. In either case, the plasma, thus generated, can completely engulf the vehicle and persist far into the wake, precluding normal communications (telemetry and beacon track) and skin track because of the interaction between the free electrons in the plasma and the electric field of the electromagnetic wave (at radio frequencies, the ions can be considered immobile), (see Fig. 2 of Report 222-3 (Geneva, 1974)). Precise description of the re-entry plasma is very difficult, due to the complex interplay between the electron producing charge transfer and recombining process among the many species in the plasma, which occurs during the transient gas flow period over the body. It is necessary to employ detailed analytical methods in which the coupled effects of aerodynamics, thermodynamics, and chemical kinetics of the air and ablation species are included; before a meaningful specification of the plasma properties and their spatial distribution about the body can be obtained. It turns out, in reality, that there is seldom a re-entry problem which can be described by the simplified approaches of equilibrium or frozen flow, or by assuming a pure-air type plasma flow [Huber and Sims, 1964; Huber, 1967]. However, the simplification of a single-gas temperature to represent the various species and energy modes in the plasma is usually made and believed to be reasonably good for re-entry at orbital, or lower, velocities. In general, it can be said that ability to describe re-entry plasma is reasonably good for problems at velocities up to earth orbital, or slightly higher, and for altitudes up to the lower bound of the so-called viscous

* This Report is brought to the attention of Study Group 6.

** A more comprehensive discussion and list of references appears in Report 222-3 (Geneva, 1974).

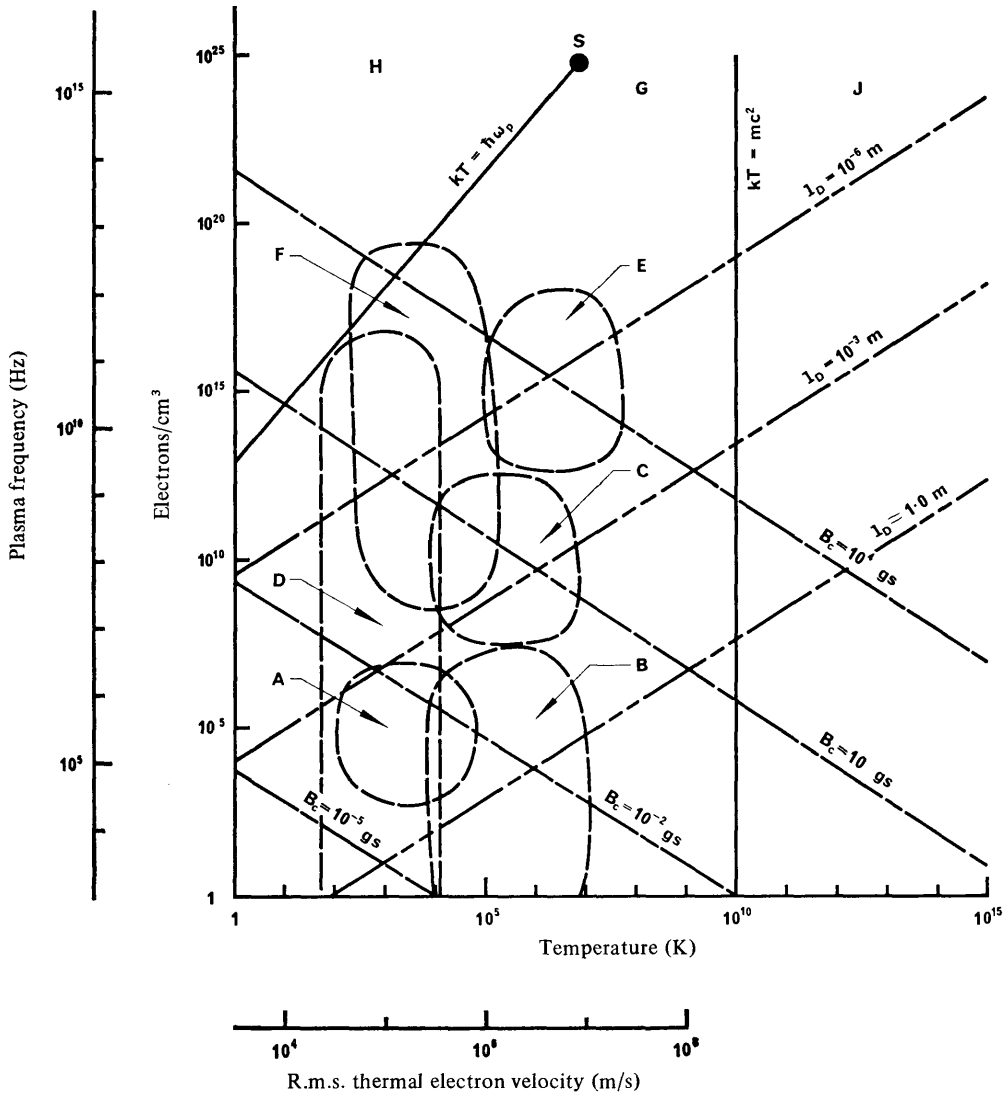


FIGURE 1 – *Operating regions of several theoretically and experimentally encountered plasmas*

A: ionosphere	F: re-entry plasma
B: interplanetary plasma	G: classical plasma
C: lab. discharges	H: quantum plasma
D: shock tube	J : relativistic plasma
E: controlled thermonuclear	S : Sun's centre

layer regime (where boundary layer fills the shock layer) [Mitchell, 1967 and Fig. 3 of Report 222-3 (Geneva, 1974)]. Analytical ability for problems at velocities and altitudes much higher than these, in the present state-of-the-art, involves many additional uncertainties, although in some cases the analysis has been surprisingly close, [Cheng, 1963; Heald and Wharton, 1965; Dunn *et al.*, 1966; Boyer, 1969 and Fig. 4 of Report 222-3 (Geneva, 1974)]. To maintain a tractable description of the interaction of the electromagnetic waves with the re-entry plasma sheath, the simplifications described below will be made.

2.1 *Plasma composition*

The re-entry plasma is assumed to consist of free electrons, relatively stationary positive ions, and neutral atoms and molecules of oxygen, nitrogen, ablation products, and noble gases. The plasma frequency is determined only by the electron density, n, and the collision frequency, ν, is determined only by collisions between electrons and neutral atoms, molecules, and positive ions. For other planetary atmospheric entries other species should be considered, such as CO_2.

2.2 *Homogeneous slab approximation*

While the plasma properties will vary with position in the sheath, it is convenient to assume that n and ν have constant values through the thickness of the sheath over the antenna. This is appropriate when the free-space wavelength exceeds the sheath thickness or when the plasma density varies slowly compared with the free-space signal wavelength. An inhomogeneous sheath can be treated as a succession of plasma slabs, each having a constant density, but this method may not be necessary since, with the present computer capabilities, the electromagnetic wave equations for an inhomogeneous medium can be solved numerically. A common practice is to use an equivalent homogeneous layer based upon an integrated electron density approximation to the inhomogeneous layer. Such an approximation is useful in predicting gross power transfer and propagation losses. The effective plasma slab thickness will vary with signal frequency, antenna location, vehicle bluntness, velocity and altitude. Cylindrical or conical plasma layers can give more realistic results than planar models for vehicles of small diameter; however, the assumption of a planar model gives good results in the prediction of antenna impedance for most practical size vehicles at VHF and higher frequencies.

2.3 *Adiabatic approximation*

The plasma sheath properties are assumed to vary slowly compared with the time required for transmission of the signal.

2.4 *Linear approximation*

The effective dielectric constant of the plasma, ε, is assumed to be independent of the incident electromagnetic field intensity. The applicability of this approximation will depend on the input power and the ambient plasma pressure.

2.5 *Compressibility*

Hydrodynamic and collective thermal effects will be discussed in § 3.

2.6 *Anisotropy*

The effects of an applied static magnetic field will be discussed in § 3.

3. Propagation in plasmas

A "warm" or compressible plasma allows for collective electron motions so that longitudinal or "plasma" waves can propagate in addition to the transverse electromagnetic waves which propagate in a "cold" or incompressible plasma [Ginzburg, 1960]. If the electromagnetic wavelength, λ, in the plasma is much greater than the Debye length, l_D, then the plasma is considered to be "cold". As seen from Fig. 1, it is possible that some re-entry and ionospheric plasmas may be considered "warm" for the propagation of microwaves. A "non-isotropic" plasma has a dielectric constant ε, which must be expressed as a tensor.

$$\varepsilon = (\varepsilon_{ij});\ i, j = 1, 2, 3$$

There are four cases which can be considered:

3.1 *Warm, non-isotropic plasma*

The full tensor, (ε_{ij}), must be used. The index of refraction, $N = (\varepsilon/\varepsilon_0)^{1/2}$, is given in Table II for the right-hand (+) and the left-hand (−) circularly polarized waves propagating parallel to the static, applied magnetic field, B_0.

3.2 *Cold, non-isotropic plasma*

Here $T \rightarrow 0$ and $\varepsilon_{12} = \varepsilon_{23} = \varepsilon_{31} = \varepsilon_{32} = 0$. The familiar Appleton-Hartree formula is given in Table II for the right and left-hand circularly polarized waves propagating at an angle θ with respect to B_0. The refractive index for right-hand wave propagation along the magnetic field ($\theta = 0°$) is shown in Fig. 2. The effects of collisions are shown in curve A and the effects of electron temperature are shown in curve B; the solid, black curve is the cold, collision-less case [Rawer and Suchy, 1967].

3.3 *Warm, isotropic plasmas*

Here $T \neq 0$, $B_0 = 0$, and $\varepsilon_{ij} = 0$ for $i \neq j$. The refractive index, given in Table II, never exceeds unity and the temperature effects only become significant for relativistic plasmas ($T \geqslant 10^{10}$ K) when Landau damping or non-collisional attenuation becomes important.

3.4 *Cold, isotropic plasmas*

Here $T \rightarrow 0$ and $B_0 = 0$, so that ε is a scalar constant, and the simplest, most commonly used case is obtained. The term "cold" or incompressible plasma is reserved for those plasmas in which the thermal motion of the electrons can be safely neglected. Thus, the working formulae do not contain the temperature explicitly.

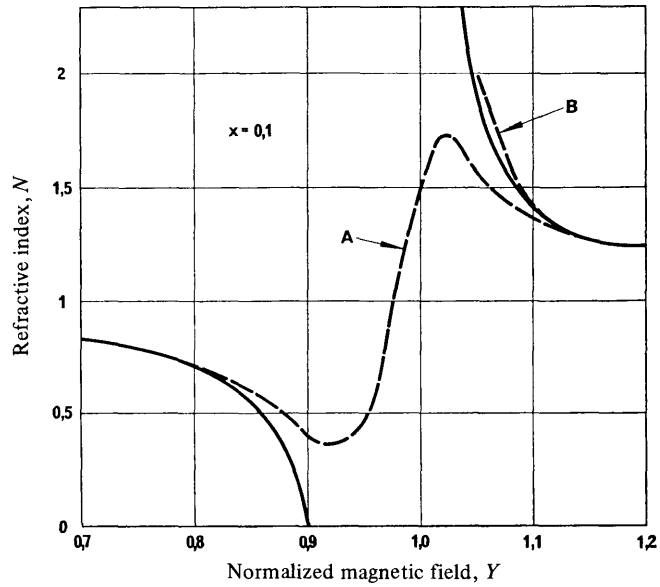


FIGURE 2 – *Variation in refractive index for a right-hand circularly polarized wave (propagation at an angle $\theta = 0°$ with respect to the magnetic field) for several cases*

1) the solid curve is for the cold, collision-less case
2) curve A shows the effect of collision ($kT = 0$, $Z = 0.03$)
3) curve B shows the effect of electron temperature ($kT = 100$ eV, $Z = 0$)

(However, the collision frequency is, in general, dependent on temperature; this is independent of the collective motions of the electrons.) In a cold, isotropic plasma, the propagating electromagnetic waves are TEM and the refractive index is given in Table II. There exist three different frequency regions in which the plasma behaves differently:

3.4.1 $\nu/\omega > 1$, the plasma acts like an imperfectly conducting medium;

3.4.2 $\nu/\omega < 1 < \omega_p/\omega$, the TEM waves are cut off, similarly to a waveguide beyond cut-off;

3.4.3 $\omega_p/\omega < 1$, the plasma behaves like a low-loss dielectric medium.

4. Impedance of aperture antennae in a plasma environment

A more detailed analysis is presented in this section on the effects of cold, isotropic plasmas on aperture antennae. The cold plasma approximation is justified, since the re-entry plasmas considered in this section have Debye lengths less than 1.0 mm and signal wavelengths greater than 3.0 cm. The isotropic plasma approximation is justified, since the Earth's magnetic field is of the order of 0.5 gauss or less. Warm plasma effects should be considered for shorter signal wavelengths and larger electron densities, such as those encountered on interplanetary missions. Non-isotropic plasma effects may be considered for less-dense plasmas and larger magnetic fields, such as those encountered by low velocity re-entry vehicles.

The derivation of the admittance expressions for various waveguide-fed aperture antennae can be found throughout the literature; however, a more general derivation can be obtained. The resulting aperture admittance of a waveguide terminated in an infinite flat ground plane can be conveniently expressed in the form:

$$y = g + jb$$

$$y = C \int_0^\infty \beta d\beta \left[E_{TE}(\beta)\, Y_{TE}(\beta) + E_{TM}(\beta)\, Y_{TM}(\beta) \right] \qquad (1)$$

where the subscripts $_{TE}$ and $_{TM}$ refer to that part of the solution which is derivable from a single transverse electric or transverse magnetic vector potential in the external region. $Y_{TE}(\beta)$ and $Y_{TM}(\beta)$, are the ratios of the solutions to a set of transformed wave equations [Swift and Evans, 1963] in the external region and their derivatives, both evaluated at the aperture ($z = 0$). Actually, $Y_{TE}(\beta)$ and $Y_{TM}(\beta)$, with $\beta = \sin\theta$, are the admittance of a plane wave incident at an angle of θ with the boundary $z = 0$. $E_{TE}(\beta)$ and $E_{TM}(\beta)$ are related to the Fourier transforms of the aperture electric fields, and C is a constant which normalizes the admittance to the dominant mode characteristic admittance of the particular feed waveguide whose cross section coincides with the aperture.

The various quantities in equation (1) are listed in Tables III and IV for several aperture geometries and external mediums of present interest. A particular solution is obtained by choosing the plane wave solutions for the external medium from Table IV and matching these with the appropriate aperture field transforms in Table III and then summing over all possible angles of incidence according to equation (1). The quantities N and k in Tables III and IV are the index of refraction of the external medium and the free-space wave number.

The numerical procedure for the evaluation of the admittance expression is straightforward, except for the case where the external medium is a non-lossy slab. In the limit of zero loss, poles may exist in the integrand for discrete values of β. The physical significance of these poles and the evaluation of the β integral near the poles is discussed in [Bailey and Swift, 1968; Croswell *et al.*, 1967]. The functions $F_1(\beta,0)$, $F'_1(\beta,0)$,$A_1(\beta,0)$, and $A'_1(\beta,0)$ in Table IV for the inhomogeneous layer can be evaluated by solving the wave equations numerically in a manner similar to that used in [Swift and Evans, 1963].

Fig. 3 shows a comparison between the measured admittance of a rectangular aperture under a shock ionized plasma [Taylor, 1968] and computations using the equations in Tables III and IV. The computations and measurements are for a standard X-band waveguide operating at a frequency of 10 GHz. The shock pressure was equal to 1.0 torr. The details of the experiment are discussed in [Croswell *et al.*, 1968] and [Taylor, 1968].

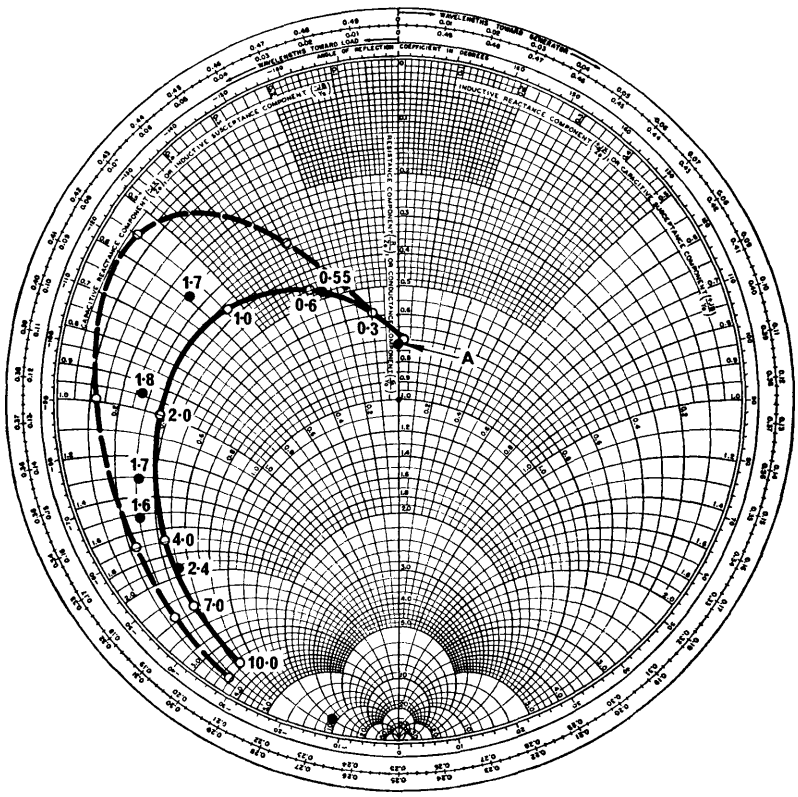


FIGURE 3 – *Comparison between the measured admittance of a rectangular aperture under a shock ionized plasma and computations using the equation in Tables III and IV. (The computations and measurements are for a standard X-band waveguide operating at a frequency of 10 GHz. The shock pressure was equal to 1.0 torr, see [Croswell et al., 1968; Taylor, 1968] for details).*

A: Free-space admittance

Computed ($v/\omega = 0.40$)
Computed ($v/\omega = 0.25$)
Measured

Fig. 4b shows the magnitude of reflection coefficient, $|\Gamma|$, Fig. 4c shows the conductance, g, and Fig. 4d shows the susceptance, b, for a circular aperture at 10 GHz under a plasma layer, whose electron density profile is illustrated by Fig. 4a. It has been determined numerically that the back wall of the plasma has no appreciable effect upon the antenna impedance when the plasma layer is thicker than about ⅓ wavelength. Thus, a density profile such as that of Fig. 4a is suitable for illustrating the effect of a low ionization boundary layer upon the impedance of an antenna (where the maximum ionization occurs outside the boundary layer). The computations were made for boundary layer thicknesses, δ, from 0 to 0.2 λ over a range of free stream electron densities of 2 decades above and below critical density.

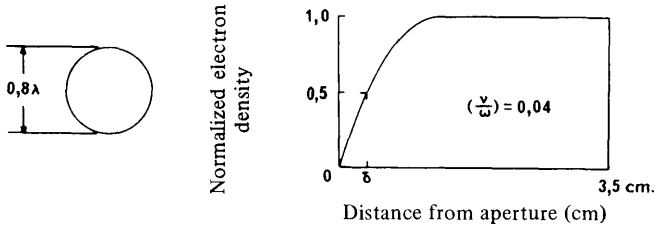


FIGURE 4a

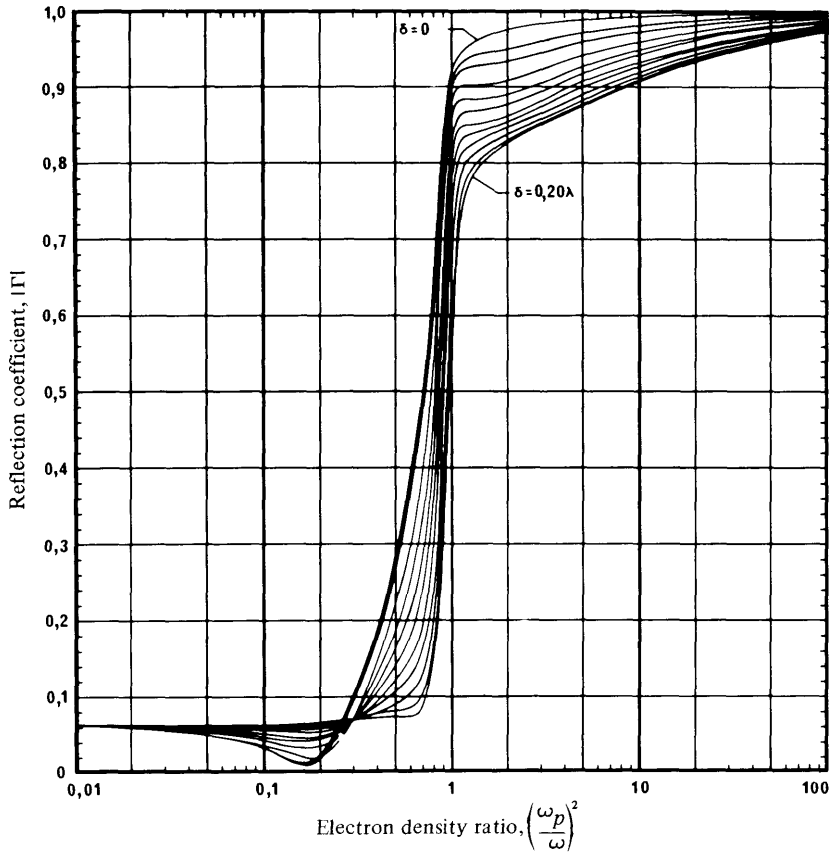


FIGURE 4b

FIGURE 4a and b – *Computed values of the magnitudes of the reflection coefficient, |Γ|, for the circular aperture with the electron density profile for various values of the distance δ to the half-peak density shown in Figure 4a (Frequency = 10 GHz)*

As was mentioned before, the primary effect of increasing the electron concentration of the plasma above critical density is a change in the phase of the antenna impedance, that is, the plasma adds inductive susceptance to the antenna. Varying the boundary layer thickness causes a change in the slope of the susceptance or phase curves. Near critical density ($\omega_p = \omega$) the conductance is reduced quite rapidly to a very low value and the magnitude of the reflection coefficient rises quite steeply to a high value as noted in Fig. 4b. In the limit of zero collisions, the reflection coefficient goes to unity for $\omega \leqslant \omega_p$, and so communications are cut off.

Only the circular aperture is used here for illustration; however, other broad band aperture antennae behave very similarly under a plasma, except for high electron densitites $[(\omega_p/\omega)^2 > 10]$ where an appreciable amount of energy may be trapped in the boundary layer. (See Figs. 8a and 8b, Report 222-3 (Geneva, 1974)).

A detailed study of the effects of plasmas upon the impedance of such a theoretical antenna model could be useful for inferring the properties of the ionized region around a re-entry vehicle.

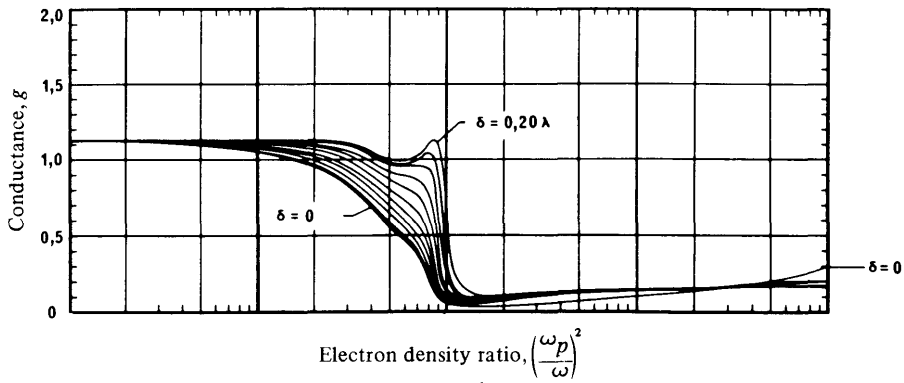


FIGURE 4c

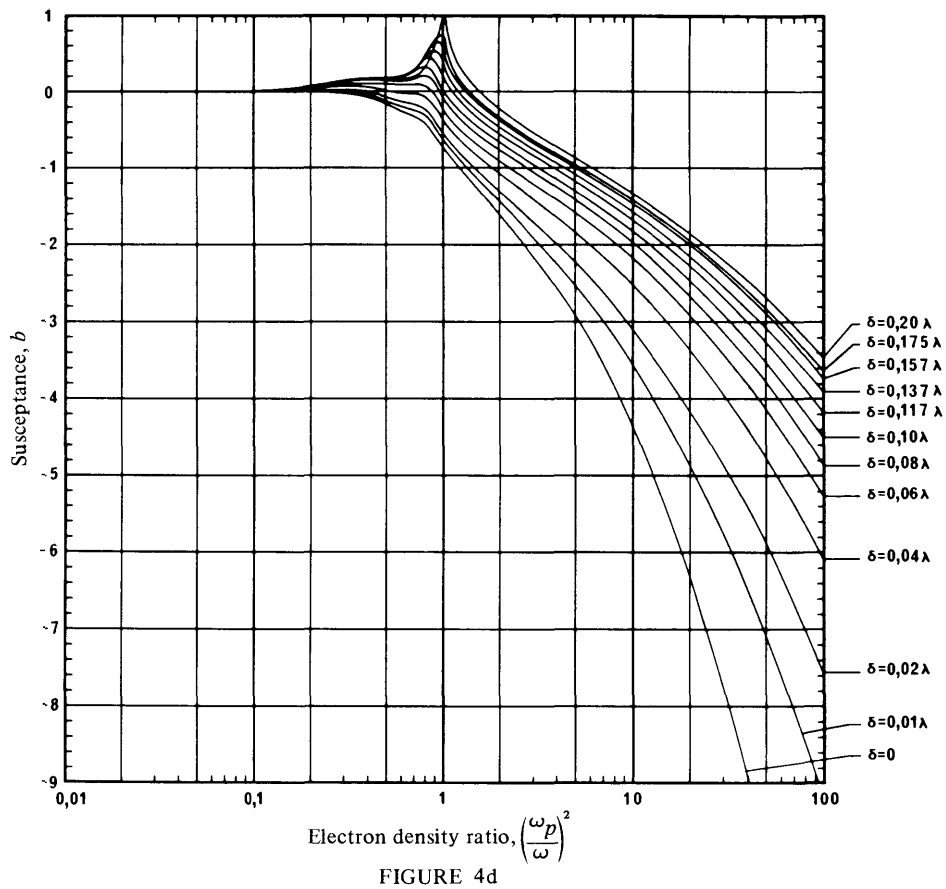


FIGURE 4d

FIGURES 4c and d – *Computed values of the magnitudes of the conductance, g, and the susceptance, b, for the circular aperture with the electron density profile for various values of the distance δ to the half-peak density shown in Figure 4a*
(Frequency = 10 GHz)

5. De-tuning effects of plasma upon resonant antennae

The plasma adds inductive susceptance to an antenna, thus an antenna which is highly resonant in air can be seriously de-tuned due to the existence of a plasma around the vehicle, and consequently, a drastic loss in signal strength will occur. If, however, the antenna can be re-tuned to the new resonant frequency after the addition of the plasma, the signal strength may be somewhat regained.

One resonant antenna of interest in atmospheric entry applications is a narrow longitudinal slot in the broad wall of a rectangular waveguide. The change in the ratio, L/λ, of the length of the slot to the resonant wavelength is shown in Fig. 9 of Report 222-3 (Geneva, 1974) as a function of the index of refraction, N, of the external medium.

This de-tuning phenomena of a plasma over such an antenna also suggests possible uses in atmospheric entry plasma diagnostics to predict such properties as plasma density, collision frequency, and plasma sheath thickness.

6. Antenna radiation patterns

The calculated equatorial plane patterns of an axial slot in an infinitely long circular cylinder covered with a homogeneous, isotropic, cold plasma sheath are shown in Figs. 5a, b and c [Swift *et al.*, 1969]. The predominant feature of these patterns is the nulling which occurs at the rear of the cylinder when $(\omega_p/\omega)^2 \approx 1.8$. This null is a remnant of the dipole resonance which normally occurs at $(\omega_p/\omega)^2 \approx 2.0$ in the scattering from meteor trails and is also called the main resonance in Tonks-Dattner experiments.

A general trend toward circularity and a reduction of the on-axis ($\varphi = 0°$) field strength is noted for $\omega_p > \omega$. The normalized on-axis ($\varphi = 0°$) field strength is plotted in Fig. 6 as a function of $(\omega_p/\omega)^2$ and ν/ω. The resonant dip near $\omega_p = \omega$ sharpens as the collision frequency decreases.

These predicted effects have been observed experimentally [Swift *et al.*, 1969] for a laboratory controlled plasma surrounding a finite length cylinder.

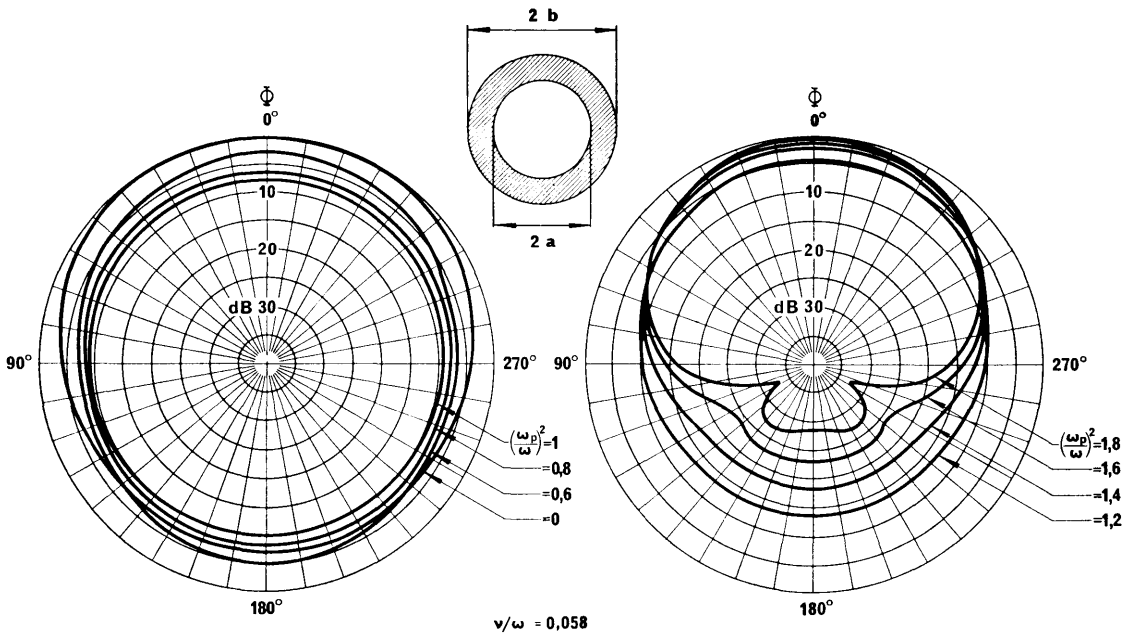


FIGURE 5a – *Calculated equatorial plane patterns of an axial slot in an infinitely long cylinder covered with a homogeneous, isotropic cold plasma sheath for various values of* ν/ω *and* $(\omega_p/\omega)^2$

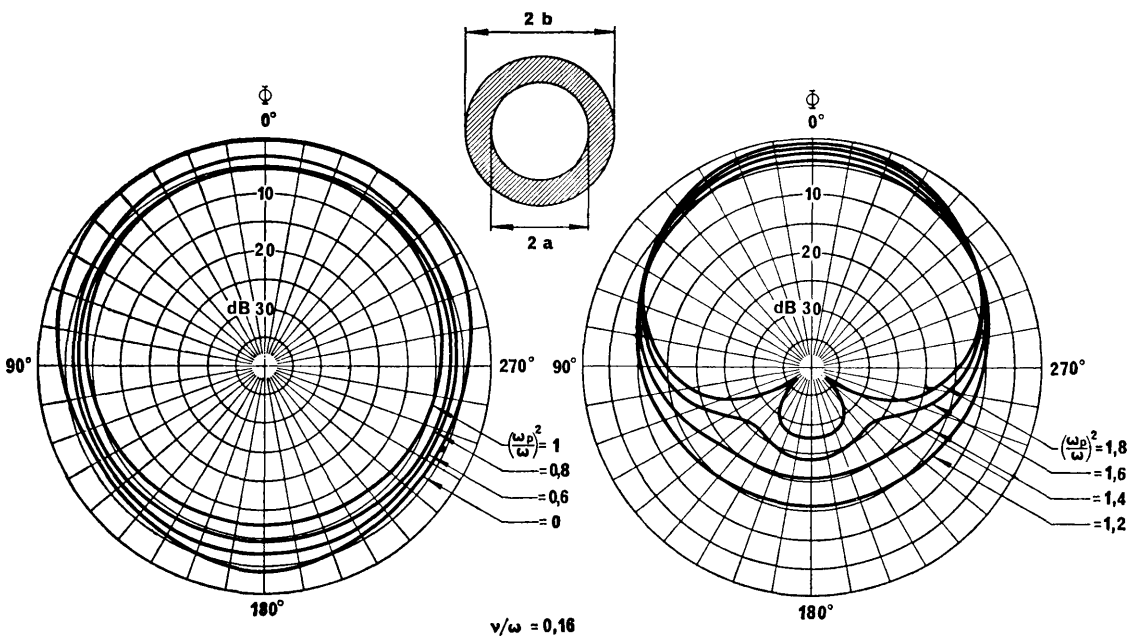


FIGURE 5b – *Calculated equatorial plane patterns of an axial slot in an infinitely long cylinder covered with a homogeneous, isotropic cold plasma sheath for various values of* ν/ω *and* $(\omega_p/\omega)^2$

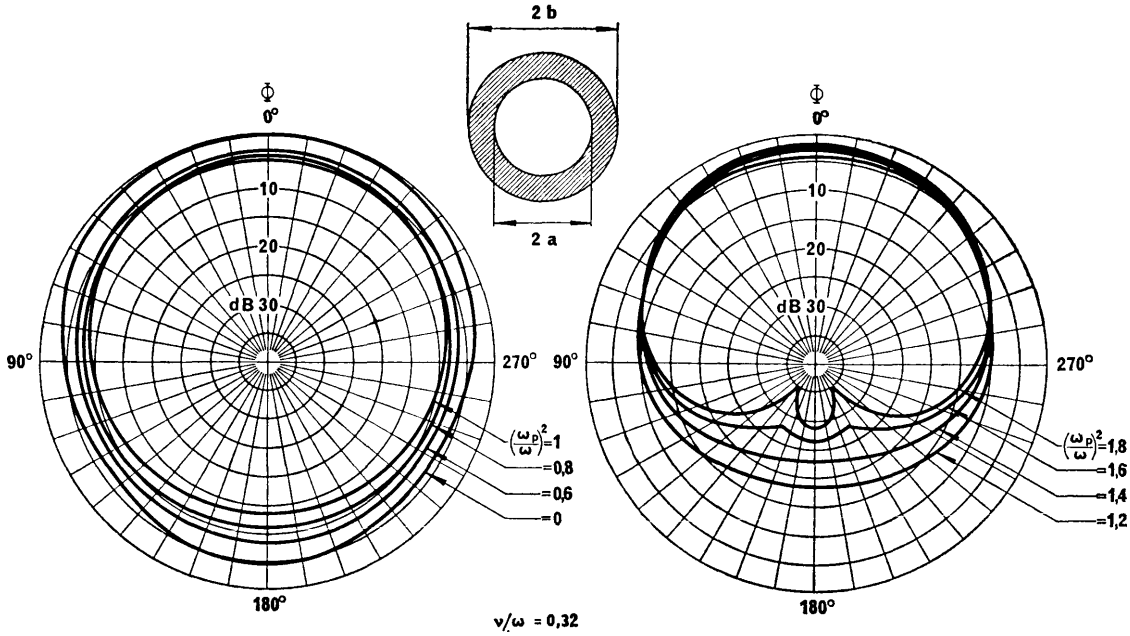


FIGURE 5c – *Calculated equatorial plane patterns of an axial slot in an infinitely long cylinder covered with a homogeneous, isotropic cold plasma sheath for various values of* ν/ω *and* $(\omega_p/\omega)^2$

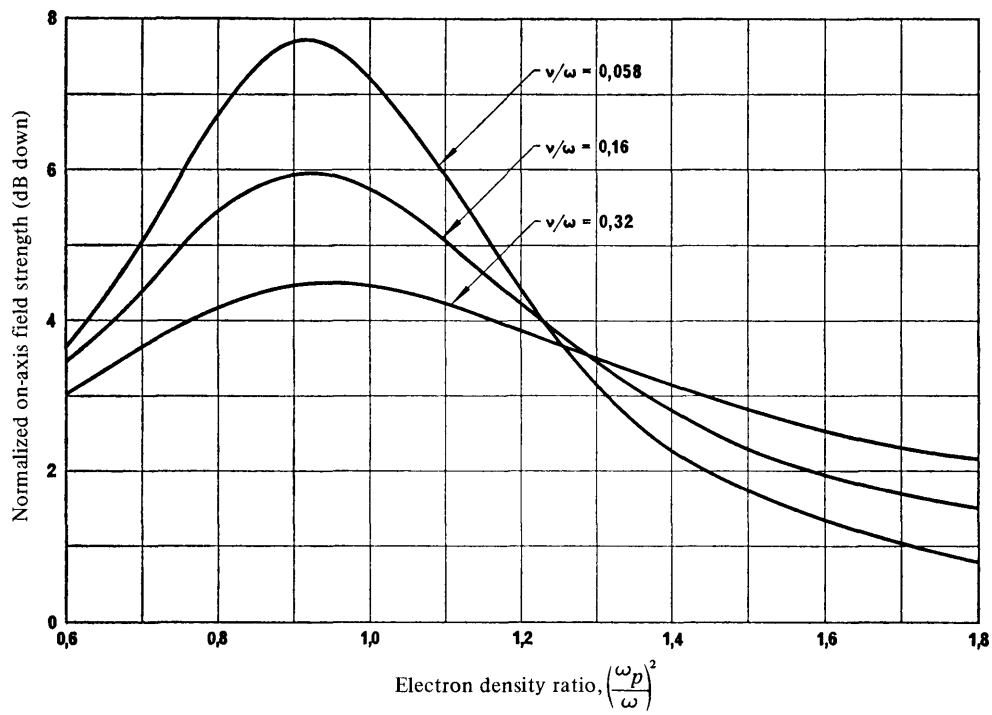


FIGURE 6 – *The normalized on-axis* ($\varphi = 0$) *field strength for an axial slot in an infinitely long cylinder covered with a homogeneous, isotropic cold plasma sheath. (See also Figs. 5a, b and c.)*

7. Concluding remarks on 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.

Recent 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 antennae 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 262-4). Possibly, combinations of these techniques may be used to reduce the plasma sheath effects.

8. Summary of rocket exhaust plasma effects upon electromagnetic propagation

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 ionised 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, for example, those of the "Blue Streak" vehicle [McD. Cummings and Wilson, 1967; Wilson, 1967].

Recent 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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TABLE I – *Plasmas parameters (mks units)*

n = electrons/m^3

$\mu_0 = 4\pi \times 10^{-7}$ henry/m $\qquad \varepsilon_0 = 8{\cdot}854 \times 10^{-12}$ farad/m

$m = 9{\cdot}1 \times 10^{-31}$ kg $\qquad e = 1{\cdot}6 \times 10^{-19}$ coulomb

$k = 1{\cdot}38 \times 10^{-23}$ joule/ K $= 8{\cdot}614 \times 10^{-5}$ eV/ K

1 eV = 11 609 K

Plasma frequency $= \omega_p = \sqrt{ne^2/m\varepsilon_0}$ radians/s

$f_p = \omega_p/2\pi = 8{\cdot}98\sqrt{n}$ Hz

Debye length $= l_D = \sqrt{\varepsilon_0 kT/ne^2} = 69\sqrt{T/n}$ m

R.m.s. thermal electron velocity $= v_T = \sqrt{kT/m} = 3{\cdot}89 \times 10^3\sqrt{T}$ m/s

$\omega_p l_D = v_T$

Cyclotron frequency $= f_B = eB_0/2\pi m = 28\ B_0$ GHz

Critical magnetic field $= B_c = \sqrt{4nT\mu_0 k} = 0{\cdot}63 \times 10^{-14}\sqrt{nT}$ gauss

Relativistic limit: $T = mc^2/k = 5{\cdot}93 \times 10^9$ K

Quantum limit: $kT = n\omega_p$, $T^2/n = 1{\cdot}86 \times 10^{-17}$

TABLE II – *Complex refractive index, N, for plasmas under four degrees of approximation*

1. Warm, non-isotropic plasma ($\theta = 0°$):

$$N\pm = \left\{ \frac{1 - \dfrac{X}{1 - jZ \pm Y}}{1 + \dfrac{X}{[1 - jZ \pm Y]^3}\left[\dfrac{kT}{mc^2}\right]} \right\}^{1/2}$$

2. Cold, non-isotropic plasma:

$$N\pm = \left\{ 1 - \left[\frac{X}{1 - jZ - \dfrac{Y^2 \sin^2\theta}{2(1 - X - jZ)} \pm \left[\dfrac{Y^4 \sin^4\theta}{4(1 - X - jZ)^2} + Y^2 \cos^2\theta \right]^{1/2}} \right] \right\}^{1/2}$$

3. Warm, isotropic plasma:

$$N = \left\{ \frac{1 - \dfrac{X}{1 - jZ}}{1 - \dfrac{X}{(1 - jZ)^3}\left[\dfrac{kT}{mc^2}\right]} \right\}^{1/2}$$

4. Cold, isotropic plasma:

$$N = \left[1 - \frac{X}{1 - jZ}\right]^{1/2}$$

$X = \omega_p^2/\omega^2$, $Y = \omega\beta/\omega$, $Z = \nu/\omega$

α = attenuation constant $= \omega\sqrt{\mu_0 \varepsilon_0} \cdot [\mathrm{Im}\,(N)]$

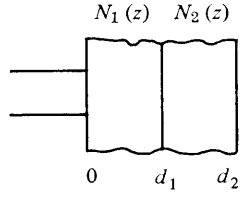
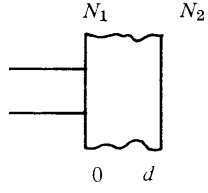
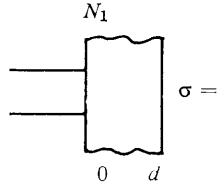
β = phase constant $= \omega\sqrt{\mu_0 \varepsilon_0} \cdot [\mathrm{Re}\,(N)]$

TABLE III – *(See equation (1))*

Waveguide aperture (excitation mode)	C	$E_{TE}(\beta)$	$E_{TM}(\beta)$
Parallel plate *(TEM)* a = height	$\frac{k_0 a}{\pi}$	0	$\frac{1}{\beta}\left[\frac{\sin\left(\frac{k_0 a\beta}{2}\right)}{\left(\frac{k_0 a\beta}{2}\right)}\right]^2$
Rectangular (TE_{01}) a = height b = width	$\frac{2(k_0 a)(k_0 b)}{\sqrt{1-\left(\frac{\pi}{k_0 b}\right)^2}}$	$\int_0^{2\pi} d\alpha\,[G(\alpha,\beta)\sin^2\alpha]$	$\int_0^{2\pi} d\alpha\,[G(\alpha,\beta)\cos^2\alpha]$
Coaxial *(TEM)* a = small radius b = large radius	$\frac{1}{ln\left(\frac{b}{a}\right)}$	0	$\left[\frac{J_0(k_0 a\beta)-J_0(k_0 b\beta)}{\beta}\right]^2$
Circular (TE_{11}) a = radius x_{11} = 1·841	$\frac{2}{(x_{11}^2-1)\sqrt{1-\left(\frac{x_{11}}{k_0 a}\right)^2}}$	$\left[\frac{x_{11}\left(\frac{x_{11}}{k_0 a}\right)\left[J_0(k_0 a\beta)-\frac{J_1(k_0 a\beta)}{k_0 a\beta}\right]}{\left(\frac{x_{11}}{k_0 a}\right)^2-\beta^2}\right]^2$	$\left[\frac{J_1(k_0 a\beta)}{\beta}\right]^2$

$$G(\alpha,\beta)=\left[\frac{\cos\left(\frac{k_0 b\beta\sin\alpha}{2}\right)}{\pi^2-(k_0 b\beta\sin\alpha)^2}\right]^2\left[\frac{\sin\left(\frac{k_0 a\beta\cos\alpha}{2}\right)}{\left(\frac{k_0 a\beta\cos\alpha}{2}\right)}\right]^2$$

TABLE IV

External medium	$Y_{TE}(\beta)$	$Y_{TM}(\beta)$
	$\dfrac{\mathrm{j}\,F_1'(\beta, o)}{k_0 F_1(\beta, o)}$	$\dfrac{k_0 N_1^2(o)\, A_1(\beta, o)}{\mathrm{j}\, A_1'(\beta, o)}$
	$\sqrt{N_1^2-\beta^2}\left[\dfrac{\sqrt{N_2^2-\beta^2}}{\sqrt{N_1^2-\beta^2}}+\mathrm{j}\tan\left(k_0 d\sqrt{N_1^2-\beta^2}\right)\right]$ $\left[1+\mathrm{j}\dfrac{\sqrt{N_2^2-\beta^2}}{\sqrt{N_1^2-\beta^2}}\tan\left(k_0 d\sqrt{N_1^2-\beta^2}\right)\right]$	$\dfrac{N_1^2}{\sqrt{N_1^2-\beta^2}}\left[\dfrac{1+\mathrm{j}\dfrac{N_1^2\sqrt{N_2^2-\beta^2}}{N_2^2\sqrt{N_1^2-\beta^2}}\tan\left(k_0 d\sqrt{N_1^2-\beta^2}\right)}{\dfrac{N_1^2\sqrt{N_2^2-\beta^2}}{N_2^2\sqrt{N_1^2-\beta^2}}+\mathrm{j}\tan\left(k_0 d\sqrt{N_1^2-\beta^2}\right)}\right]$
	$\sqrt{N_1^2-\beta^2}\left[\dfrac{1}{\mathrm{j}\tan\left(k_0 d\sqrt{N_1^2-\beta^2}\right)}\right]$	$\dfrac{N_1^2}{\sqrt{N_1^2-\beta^2}}\left[\dfrac{1}{\mathrm{j}\tan\left(k_0 d\sqrt{N_1^2-\beta^2}\right)}\right]$
	$\sqrt{N_1^2-\beta^2}$	$\dfrac{N_1^2}{\sqrt{N_1^2-\beta^2}}$

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 205-4 and 222-4).

REPORT 543 *

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

Comparison between predicted and measured field strengths at 2 GHz

(Study Programme 16A/2)

(1974)

1. Introduction

This Report describes and compares calculations and actual system tests used to determine power flux-density in the vicinity of a large (64 m) diameter reflector antenna with an input of 400 kW in the vicinity of 2 GHz. In this analysis, power flux-densities greater than 10 mW/cm^2 are examined in the greatest detail since they may be considered as being potentially dangerous to human beings exposed to the radiation [USA Standard, 1966]. Intermediate densities, from 1 to 10 mW/cm^2, are covered in lesser detail, since this category is considered safe for occasional exposure. Densities less than 1 mW/cm^2 are examined, although radiation in this category is considered safe for indefinite exposure. The material in this Report is taken largely from a report recently published in the United States [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].

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

2. System characteristics

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.

Fig. 1 gives the far-field E-plane and H-plane radiation patterns of the hybrid mode, corrugated, waveguide feedhorn used at 2.12 GHz. It has been possible to achieve the highly symmetrical beam shown in this figure because the feedhorn aperture distributions in both planes are equal, and are of low intensity near the waveguide boundaries. Ninety-three per cent of the radiated power has been subtended at 14.7° from the feedhorn boresight, which is the edge of the Cassegrain sub-reflector. The feedhorn axial gain is +21.8 dB with respect to isotropic.

Fig. 2 gives the far-field E-plane and H-plane radiation patterns of the complete feed system, i.e., the above feedhorn and the sub-reflector. The origin of these patterns is the focal point of the prime reflector. Fig. 2 shows that the feedhorn radiation has been primarily spread over a 60° zone, the edge of which represents the rim of the paraboloidal reflector. Fig. 2 also shows the reduced radiation in the 60° to 160° zone, and the feedhorn spillover past the edge of the sub-reflector in the 160° to 180° zone, as well as the back lobe due to feed system. Fig. 3 is helpful in visualizing the above zones.

At 61.4° from the feed system boresight, which is the edge of the paraboloid, 92.6% of the power has been subtended. From 61.4° to 90°, the rear spillover amounts to 0.4%. The forward spillover, from 90° to 180°, accounts for the remainder, 7%. Of this 7%, the bulk (5%) is contained within the 160° to 170° lobe. The total feed system axial gain is, for all practical purposes, +8.4 dB relative to isotropic *.

Three additional factors must be considered in accounting for the total power; scattering from the feed system supports (quadripod) and central blockage, leakage through the parabolic reflector, and the back lobe of the parabolic reflector. The total central power blockage due to the feedhorn cone is 3.0%. The area blocked by the quadripod is 6.3%. Accepting the quadripod blocking shadows on the 64 m aperture as having roughly the form of radial wedges, we obtain 6.3% power blocking. Recalling that we are blocking 6.3% of 93.0%, we finally obtain 5.9% loss for the quadripod and 8.9% total power scattered.

Excellent agreement between theory and experiment has been obtained for radio-frequency transmission through metal meshes such as are used for the outer 50% of the radius on the 64 m reflector. For the particular material used, the 2.1 GHz leakage for normal incidence is −42 dB. Non-normal incidence causes the leakage to tend towards −50 dB. An upper limit of 0.01% power leakage due to the mesh is reasonable. The front-to-back power ratio of the parabolic reflector has been estimated for the case of an isotropic feed as 58.5 dB [Kritikos, 1963]. In this case, the edge illumination is 6.4 dB below isotropic and the forward gain is about 4 dB better than produced by the isotropic feed; the front-to-back power ratio should be 60.9 dB. A reasonable estimate of the power lost due to the back lobe is approximately 10^{-4} %.

Table I summarizes the feed system and reflector in terms of the total power to be accounted for.

TABLE I *Total power description, 64 m hybrid mode feed system and reflector*

Radiation type	Percentage of total
Forward spillover	7·0
Scattered	8·9
Rear spillover	0·4
Reflector leakage	10^{-2}
Reflector back lobe	10^{-4}
Balance to main beam	83·7

* An anomaly of scattering computations of importance here is the axial (0 deg) "bright spot", seen in Fig. 2 which would lead to an axial gain figure of 9.7 dB. Whether the spot physically exists or not is unknown, but in either event is not of any consequence, since precisely zero power is contained in such a point. It is therefore entirely correct to ignore the bright spot and adopt an axial gain of +8.4 dB relative to isotropic.

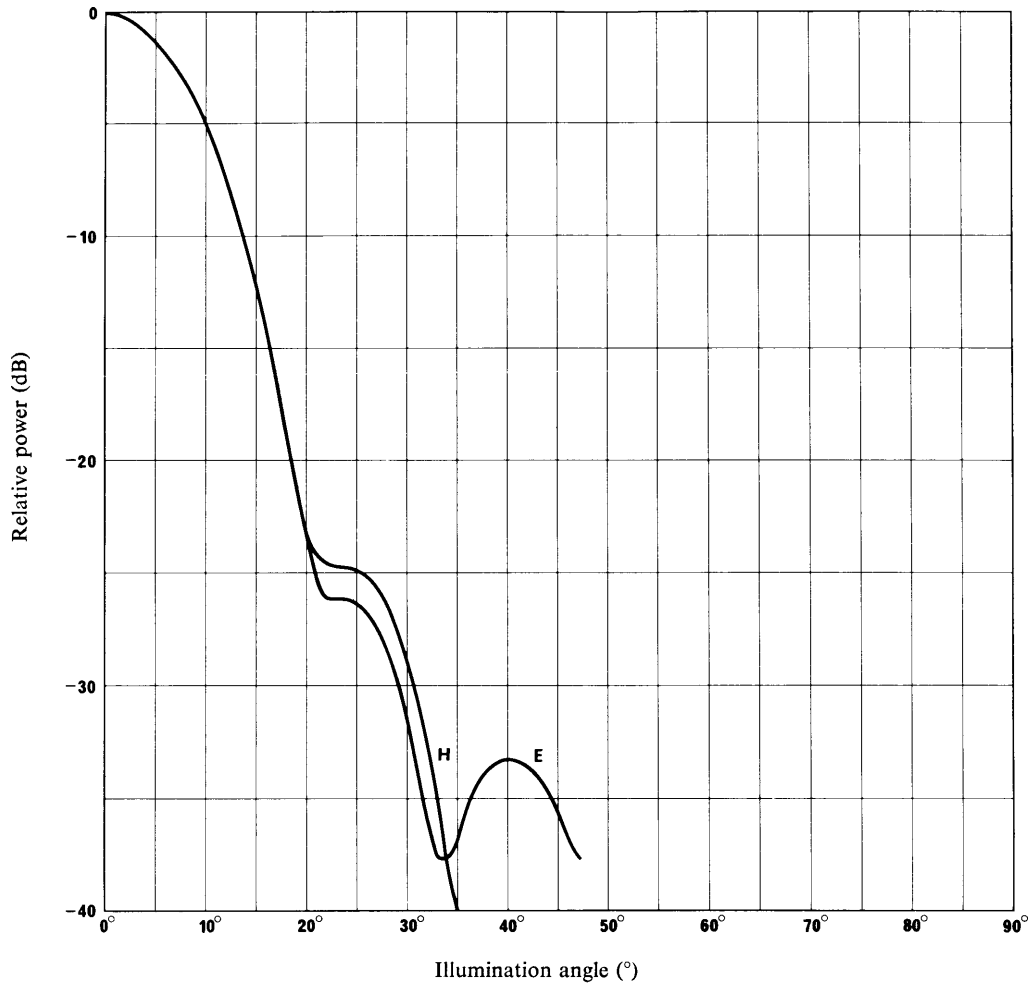


FIGURE 1 – *2120 MHz corrugated hybrid mode horn*

3. Power flux-density calculations

The power flux-density is $PG/4\pi r^2$, Where P is the power, G is the gain relative to isotropic and $(4\pi r^2)^{-1}$ is the inverse square law. It is implied in the use of this equation that we remain in the far zone (divergent rays) of the radiation considered. For example, the use of the above equation to predict power densities at distances less than $2D^2/\lambda$ from a constant phased aperture, where D is the aperture diameter, is incorrent. But, for the prediction of aperture illuminations (either of the sub-reflector by the feedhorn or of the paraboloid by the total feed system), or for the prediction of stray fields known to be divergent, the above applies.

The condition selected for calculation is shown in Fig. 3. With the system pointing at the lowest operational elevation angle of 6.0°, the main beam is in closest proximity to the ground and the forward and rear spillovers as well as the scattered power are intercepted by the ground. From the H-plane pattern is Fig. 2 and taking the ranges from Fig. 3, we can obtain Table II, a straightforward series of singular field calculations. By the expression "singular field" it is meant that we postpone considerations of possible power additions due to multiple sources, and possible reflections. Further, Table II does not take into consideration the scattered, leakage and back lobe components.

Table II shows that on the basis of singular fields, power flux-densities greater than 1 mW/cm^2 exist only on the aperture.

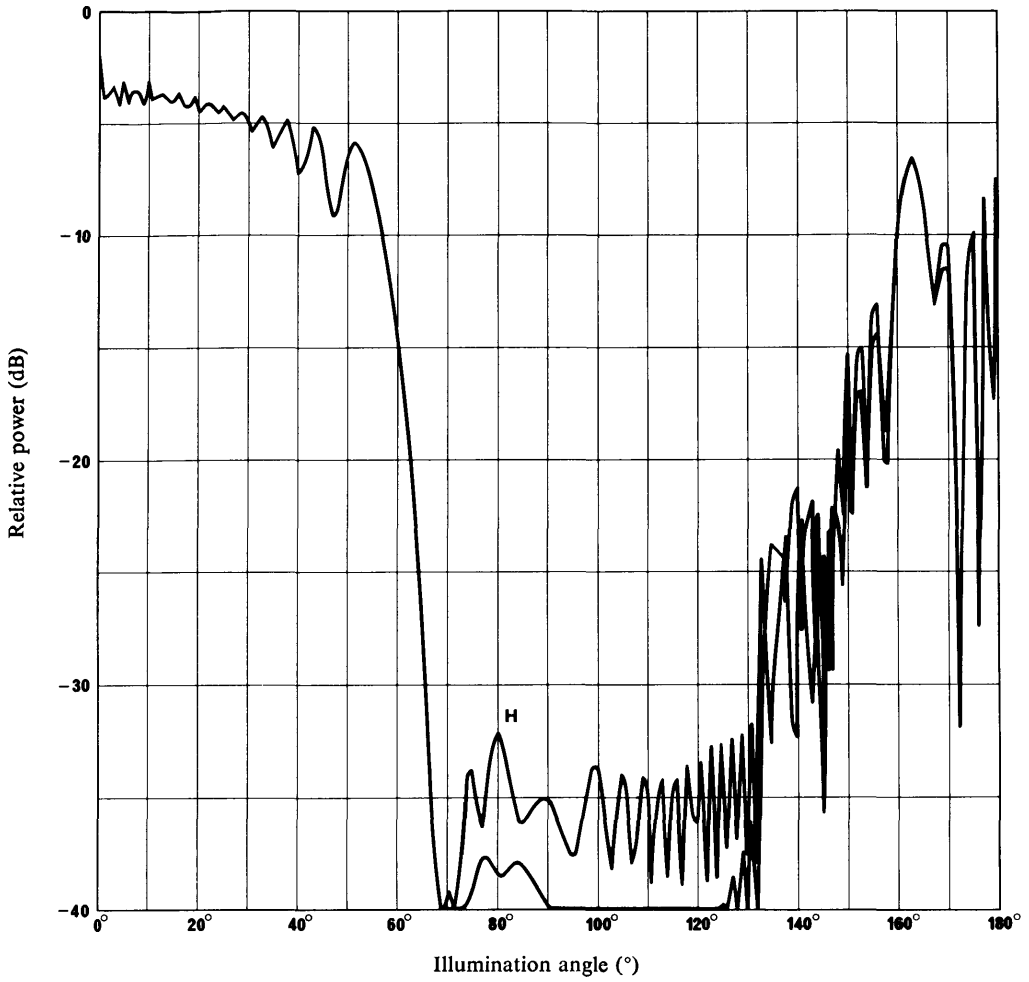


FIGURE 2 – *Scatter pattern*

4. Main beam characteristics

Fig. 4 is an example of the 64 m system far-field pattern at 2.3 GHz, showing the half-power beamwidth of 0.14° that is normally considered for such an aperture. At ranges which are less than $2D^2/\lambda$ (58 km), but greater than $D^2/2\lambda$ (14.5 km), the observed patterns are in a transition zone between the far-field pattern and the aperture distribution. At ranges of less than $D^2/2\lambda$, a parallel or tubular beam exists which exhibits no divergence and therefore no "space loss". The significance of the tubular beam is that, for practical purposes, one should imagine the aperture distribution being repeated in space, beginning at the aperture and extending to about $D^2/2\lambda$. Of course, neither range mentioned above represents a sharp demarcation in beam type, but here we may assume that this is so for simplicity. In so doing, useful and consistent results will be achieved.

The peak power flux-density at 14.5 km is approximately 32 mW/cm^2, and at 58 km, 1 mW/cm^2. It must be emphasized that the 32 mW/cm^2 density in fact exists, beginning at the aperture and extending outward to 14.5 km. This tubular beam is 64 m in diameter with approximately 0.5 mW/cm^2 density at the edges, and an estimated 12 dB/radius decay beyond the beam edge as listed in Table III.

It is worthwhile noting that a second order tubular beam theory predicts a power flux-density increase of 2 dB at a range of one half of the 14.5 km value above mentioned [Bickmore and Hansen, 1959]. The most intense power flux-density for the system considered here would thus be 48 mW/cm^2 at a range of 7 km.

It is noteworthy that for a given power output, the smaller systems produce higher power flux-densities in the tubular beam.

Tubular beaming has been observed with the 64 m system, albeit at short ($0.05\ D^2/2\lambda$) range, as shown in Fig. 5. The observed angular width of the beam ($\approx 5°$) is that of a 64 m arc at a distance of 0.7 km.

Energy transport by means of tubular beam transmission has been studied and verified by experiment, where high efficiency (≈ 0.8) transfer is realized up to the $D^2/2\lambda$ range. The 64 m/400 kW system is an efficient power transmission means, up to a range of 15 km, and its calculated power flux-densities are in the danger category (Table III).

TABLE II – *Calculated singular power flux-densities* 64 m reflector, 6.0° elevation angle, 400 kW*

Angle Ψ (deg)	Gain, G, relative to isotropic (dB)	Range, r, to intercept (m)	Type of intercept	$PG/4\pi r^2$ (mW/cm^2)	Notes
0	+ 8·4	27·0	Paraboloid	30	27 m is the focal length of paraboloid
10	+ 8·4	27·2		29·5	
19	+ 7·9	27·6		25·7	
29	+ 7·1	28·9		19·5	
38	+ 6·7	30·3		16·2	Mesh reflector portion
46	+ 3·5	31·9		7·1	
54	+ 4·9	34·0		8·5	
61	− 5·8	36·4		0·63	
61·4	− 6·4	36·5		0·55	Edge of reflector
61·4	− 6·4	41·5	Ground	0·41	First ray to ground
62	− 7·5	41·3		0·32	
64	−13·1	40·8		0·09	
66	−19·3	40·4		0·02	
68	−25·6	39·9		0·005	
75	−22·1	38·9		0·001	
80	−20·6	38·6		0·018	Shortest ray to ground
90	−23·6	38·8		0·009	
100	−22·1	40·1		0·012	
120	−24·6	47·6		0·012	
140	− 9·7	69·0		0·071	
150	− 3·8	94·8		0·15	
160	+ 2·3	157		0·22	
162	+ 4·9	184		0·29	Forward spillover peak
163	+ 5·2	201		0·26	
164	+ 4·4	218		0·18	
165	+ 3·0	241		0·11	
175	+ 1·8	∞	Sky	—	
180	+11·6	∞		—	

* Aperture distribution, forward and rear spillovers only.

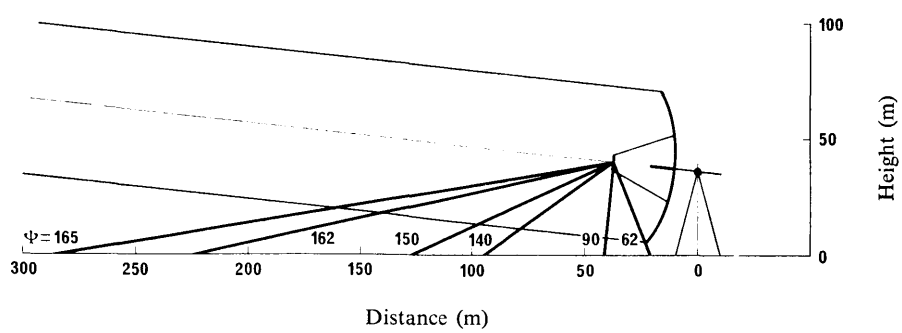
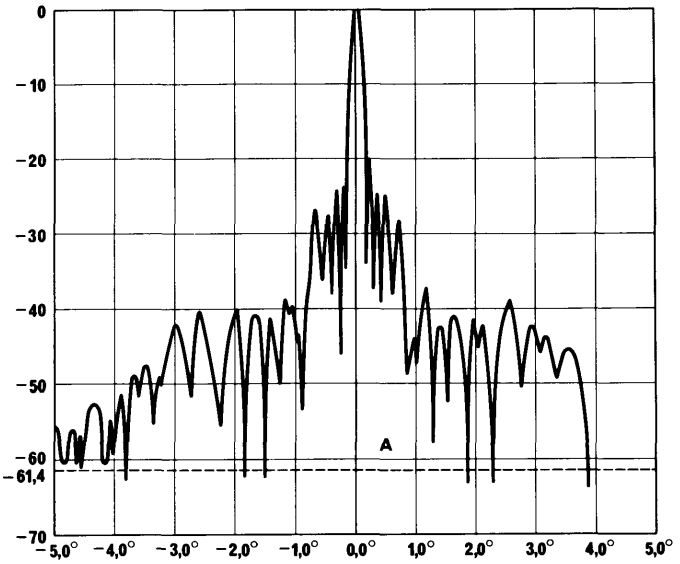


FIGURE 3 – *64 m antenna system power flux-density study (see Table IV)*



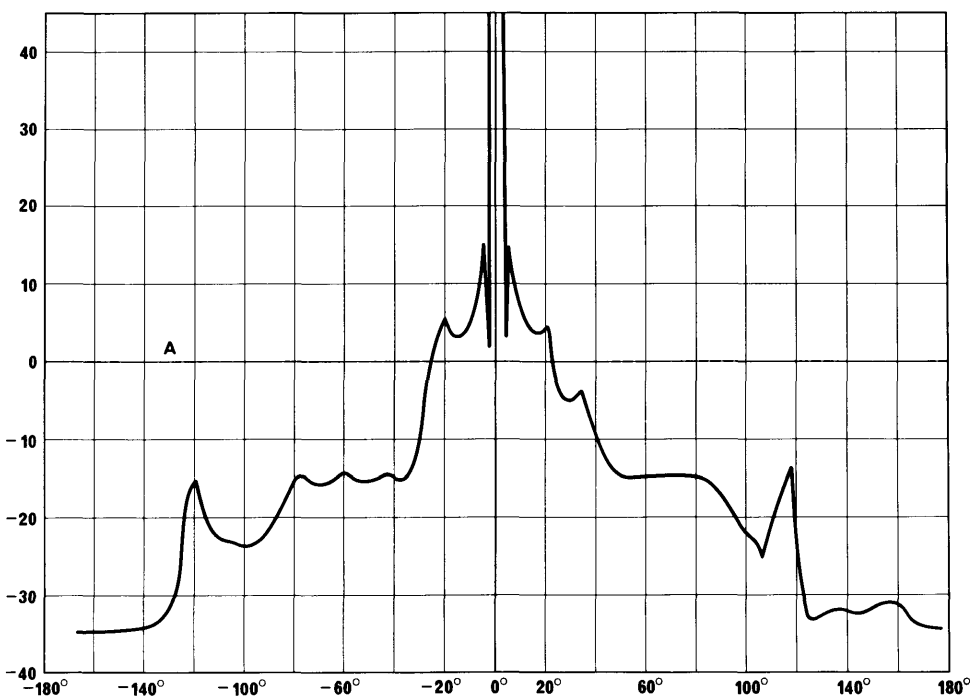
Angle off boresight (degrees)

FIGURE 4 – *Measured azimuth pattern of the 64 m advanced antenna system at Goldstone, California 2295 MHz, 400 000 km range*

A : Isotropic antenna

Radius (m)	Power flux-density (mW/cm^2)
0	30·2
4·7	29·5
9·1	25·7
14	19·5
19	16·2
23	7·1
28	8·5
31	0·63
32	0·55 (beam edge)
48	0·14
64	0·035 (−12 dB/radius)

TABLE III – *Calculated tubular beam power flux-densities 64 m reflector, 400 kW*



Angle off boresight (degrees)

FIGURE 5 – *Measured azimuth pattern of the 64 m antenna system at Goldstone, California 2115 MHz, 700 m range*

A : Isotropic antenna

5. Stray radiation, forward zone, 6° elevation

Table II gives the singular field power flux-densities along the boresight direction of the reflector, at ground level, arising from the forward and rear spillover components. We will next consider the scattered components and also discuss the possible multiple sources and reflections.

The model for quadripod scattering (5.9%) or −12.3 dB supposes the total power directed equally in all directions with the exception of the shielding provided by the 64 m reflector, leading to an average gain +1.3 dB relative to isotropic. The resultant radiation level (−11.0 dBi*) may be compared with the −15 dBi plateau seen in Fig. 5. This plateau is considered to extend from boresight ± 100° approximately, and crudely verifies the simple model. Accepting this radiation as arising from a complex line source along the reflector z axis, which is 35 m above ground, the power flux-density due to quadripod scatter is estimated as 0.2 mW/cm^2 on the ground, immediately below the quadripod.

In the model, the central blockage (scattering 3%, or −15.2 dB total power) is assumed to direct this energy fraction into the forward hemisphere with a gain of +3 dBi. The source is taken to be in the region of the feedhorn, again 35 m above ground. The resultant radiation level (−12.2 dBi) is similar to the quadripod level; the power flux-density due to central blockage scatter is estimated as 0.16 mW/cm^2 on the ground, immediately below the feedcones.

From Table II we have 0.4 mW/cm^2 due to direct spillover on the ground, immediately below the antenna, and from scattering we have 0.2 and 0.16 mW/cm^2. Adding the three nearly equal signals coherently, we obtain possible maxima of 2.2 mW/cm^2. An intensity maximum of this kind, due to multiple sources, will be found on a spot basis only. Minima will also be found due to destructive interference, again on a spot basis.

A second region of interest in the reflector boresight direction on the ground is the feedhorn forward spillover maximum of 0.29 mW/cm^2, roughly 200 m from the other sources. The scattered sources contribute 0.016 and 0.013 mW/cm^2 at 200 m on the ground. A fourth source, the decay of the tubular beam in this region, contributes 0.07 mW/cm^2. Again, taking the peak or spot maxima for this region on the ground we obtain 1.1 mW/cm^2.

Ground (or other) reflections can be relied upon for doubling the field amplitude or the 6 dB spot power maximum provided the angle of incidence is grazing. For normal incidence, the ground is taken as absorbing. Therefore, it appears that this region on the ground, in front of the 64 m reflector, and extending perhaps 250 m from the azimuth axis, contains the calculated spot maximum power flux-densities of the order of 2.5 to 4 mW/cm^2. Uniform power flux-densities in this category are considered safe for incidental or occasional exposure.

6. Stray radiation, rear zone

We have two indices of back radiation mentioned earlier: mesh leakage and the predicted front-to-back ratio. With a maximum power flux-density of 20 mW/cm^2 on the mesh (Table II) and a leakage of −42 dB, the maximum fields immediately behind the reflector will be 0.0013 mW/cm^2, due to mesh leakage.

It appears proper to treat the back lobe as another tubular (non-divergent) beam, insofar as within reasonable observing distances it has not yet formed in the far-field sense. The non-divergent beam exhibits no space loss, so we may consider the aperture power flux-density maximum (32 mW/cm^2) as being down in level to the order of 60 dB; the resultant 0.000032 mW/cm^2 due to the near field or tubular back lobe is indistinguishable in the presence of the mesh leakage above. Calculated power flux-densities in the rear zone are considered safe for indefinite exposure.

7. 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 IV (the entries in Table IV indicating the points at which measurements were made; see Fig. 3). The primary purpose of Table IV 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 found. The back radiation is seen to be very small.

* Decibels relative to isotropic.

We consider the 64 m/400 kW system 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. We have the calculated tubular beam maximum agreeing with the measurement at 700 m 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, that is, 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. Results of sufficient accuracy are quickly obtained and the interested reader is presented with a clear impression. A survey party using the hand-held equipment, mentioned in the measurement paragraphs above, would observe a received power of about 25 watts at 7 km; 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; 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 S-band. 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, we have calculated spot power flux-densities, but 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.

TABLE IV – *Selected power flux-densities, 64 m/400 kW Goldstone system (see Fig. 3)*

Measurement point	Power flux-density		Remarks
	Measured values (mW/cm^2)	Calculated values (mW/cm^2)	
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.

The greatest hazard is thus the tubular beam itself. Because acceptable siting of large microwave ground antennae 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 antennae, 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 3.

* 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 was evident here; the dish collected approximately 5 kW with resultant loss of feed and cabling due to thermal damage.

8. 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 familiarized with 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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REPORT 682 *

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

(Study Programme 16A/2)

(1978)

1. Introduction

This Report is concerned with §§ 1 and 2 of Question 52/1 (former Question 21/4) and § 8.2 of Report 385-1 and specifically analyses 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 antennae 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.

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

3. Probability of a hazarduous 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.

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), 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.

ANNEX I

1. Introduction

In this Annex the potential hazard from the beam of a deep-space 64 m antenna system is assessed. The number and types of aircraft flying in proximity to a typical deep-space complex such as Goldstone Lake, California, and their mode of operation were determined from the best available sources of data. The information used to evaluate the possibility of hazards to aircraft is predicated on this data. **

A 64 m parabolic antenna used in conjunction with a 400 kW CW transmitter has been chosen for this example. *** This type of radiator will generate a near-field pattern whose boresight power flux density remains above 10 mW/cm^2 out to approximatly 25 km from the antenna. The power flux density does not drop below 1 mW/cm^2 until a distance of about 74 km is reached.

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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.

** Only light aircraft are considered in this example. In the USA, commercial aircraft are rigidly controlled during flight and must follow precise routes and altitudes. General (light) aircraft fly under the Federal Aviation Administration Visual Flight Rules (VFR) and this traffic is not controlled, per se, by air traffic controllers. Although light aircraft are expected to abide by certain regulations, they are not strictly controlled and wide deviations from flight paths are possible. The operating ceiling for general aviation in the United States is approximately 3700 m above sea level. The normal preference of pilots of these planes is to fly in the vicinity of 150 to 900 m above the highest known terrain in mountainous regions; this altitude range is also preferred over smooth terrain.

*** This power output and antenna system typifies that used at the United States deep-space complex.

2. Development of probability figures

2.1 *Probability of intrusion into restricted zone*

Typical statistics on flight plans of light aircraft indicate that about 100 000 aircraft flights per year are made in the vicinity of the U.S. deep-space complex restricted zone. During the 1973 to 1974 calendar period, four intrusions into the restricted area were recorded. Assuming that only one in every hundred cases were observed, a worst-case estimate would indicate that about 400 intrusions per year occurred. Assuming there are 400 intrusions into the restricted area annually, the consequent probability of any single flight intruding is 400/100 000 or 4×10^{-3}.

2.2 *Probability of entering butterfly*

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

The actual physical area of the butterfly contained between $+30°$ and $-30°$ declination and with a minimum elevation of 10° varies with altitude. The actual available flying area contained within the restricted zones is similarly altitude dependent. However, at altitudes below 5000 feet (1525 m) this area is also very heavily terrain dependent.

Fig. 1 shows this ratio of areas as a function of altitude.

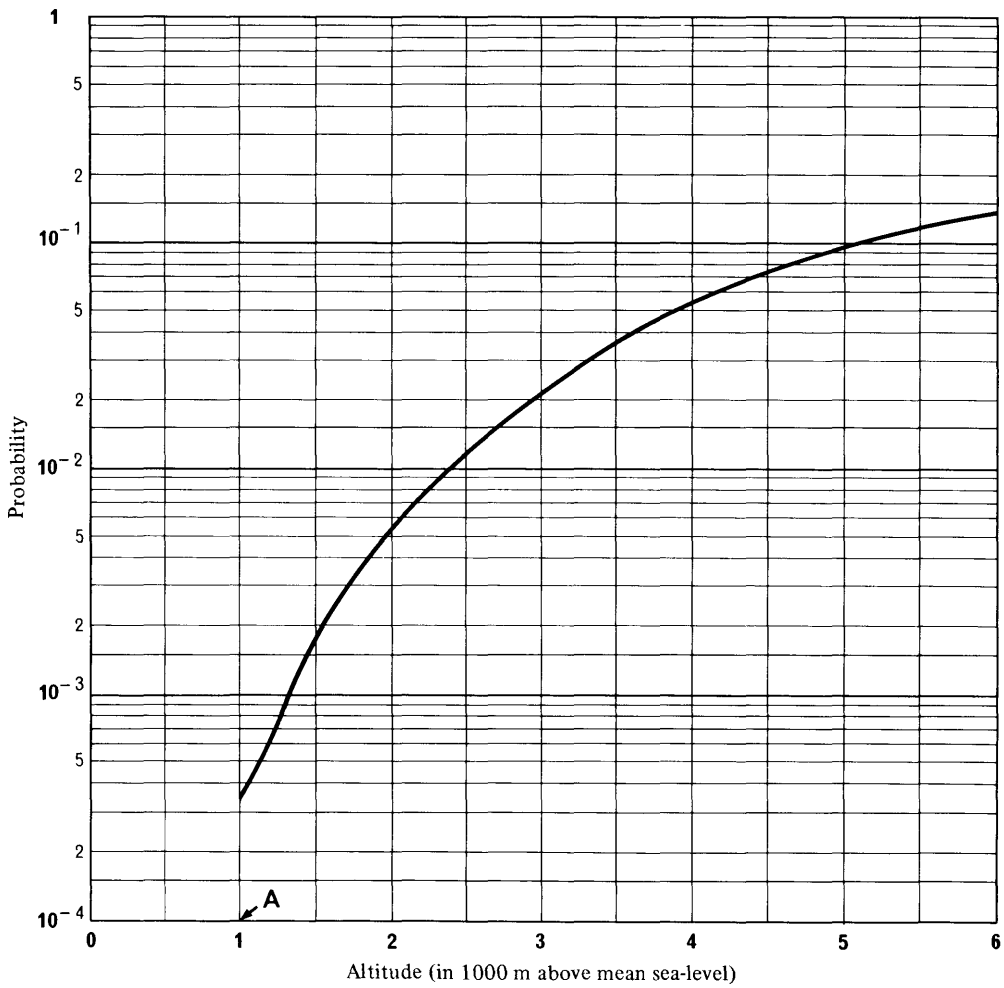

FIGURE 1 – *Probability of aircraft in restricted zone entering butterfly region*

A: Altitude of deep-space site

This approach is actually a worst-case model. For example, if a pilot took off from Los Angeles flying towards Las Vegas, the most probable way he would enter the Goldstone Lake restricted zone would be by a faulty setting of his inertial compass, which would, depending on the extent of the mistake made by the pilot, cause the aircraft to penetrate accordingly into the restricted zone. Basically, since for altitudes below 18 000 feet (5486 m) the butterfly contour exists deep within the interior of the restricted zones, the probability of a pilot

entering the butterfly is a function of the magnitude of the error made (i.e. the larger the mistake the more he would penetrate into the restricted zone). Therefore, if we assume that the probability of entering a particular restricted zone is in proportion to the ratio of the areas, we have at the same time assumed that all pilot mistakes are equally likely. This is obviously not completely true, but does however lead to a worst-case example.

2.3 *Probability of entering hazardous region*

Given that an aircraft enters the butterfly region, the probability of its actually intercepting the radar beam can be established by assuming that this region at a given altitude is divided into a number of segments, each being the same size as the worst-case hazardous area of the radar beam at that altitude, and determining how many of these regions the aircraft will intercept in a random flight across the butterfly. For example, at an altitude of 10 000 feet (3048 m) the Goldstone butterfly encompasses approximately 204 km^2, and the maximum hazardous region surrounding the beam as it penetrates the 10 000 feet level is appproximately 6.2×10^{-3} km^2. This means that the butterfly area should be divided into approximately 33 000 individual regions, one of which contains the beam. Each of these regions will be approximately 79 m on a side. The aircraft flying from one extreme of the butterfly to the other, would cover approximately 23 km in its travels and, in a worst-case, would intercept approximately 580 of these regions. Since the probability of any single region being hazardous is one over the total number of regions (or approximately 3×10^{-5}) and the aircraft will intercept about 580 of these regions, the probability of its traversing the one hot region is 1.8×10^{-2} or one chance in about 400.

This again is the worst-case estimate, because the aircraft could in fact traverse the butterfly by crossing a minimum of 290 regions. However, on a random basis, travelling the 23 km distance within the butterfly, it could also intercept upwards of twice this number.

Fig. 2 shows the probability, as a function of altitude, of an aircraft wandering into the beam once it is in the butterfly.

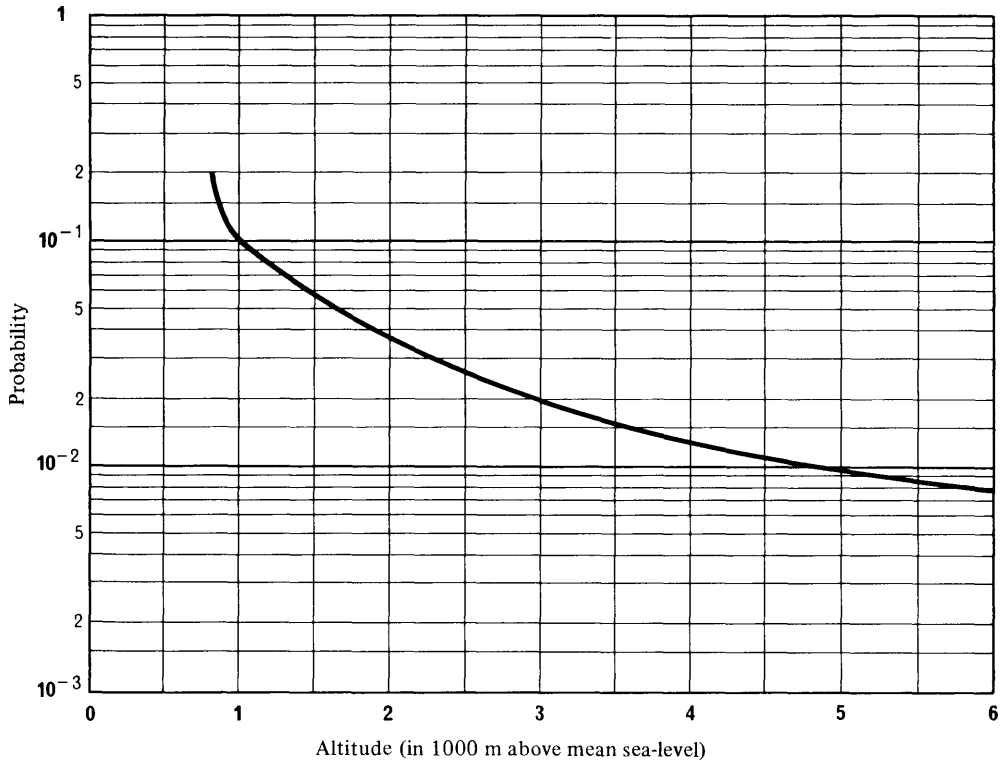

FIGURE 2 – *Probability, as a function of altitude, of aircraft in butterfly zone entering the beam*

2.4 *Altitude weighting parameters*

Because of the altitude dependence of the various probabilities considered in this model, the altitude variation of the general aviation aircraft population in the vicinity of the deep-space complex must be considered.

Most general aviation pilots apparently prefer to fly between 150 and 900 m above the highest terrain along their intended flight path. This means that in the example area most of the general aviation traffic should occur between about 1700 and 2600 m above the mean sea-level (MSL).

The majority of small aircraft, because of cost reasons, are single engined craft without superchargers. Because of the reduced engine power available at higher altitudes these aircraft have a maximum service altitude of around 3700 to 4000 m MSL. The only small aircraft flying above this altitude are the high-performance single engine or multi-engine aircraft which constitute a relatively small percentage of all general aviation aircraft. Finally, United States regulations limit general aviation traffic to below about 5500 m MSL.

These facts dictate that the distribution of general aviation aircraft should have the following characteristics:

- no aircraft below about 900 m MSL because of topographic considerations;
- a maximum between about 1500 and 2600m MSL;
- a tail existing to about 5500 m MSL.

Fig. 3 illustrates this type of distribution.

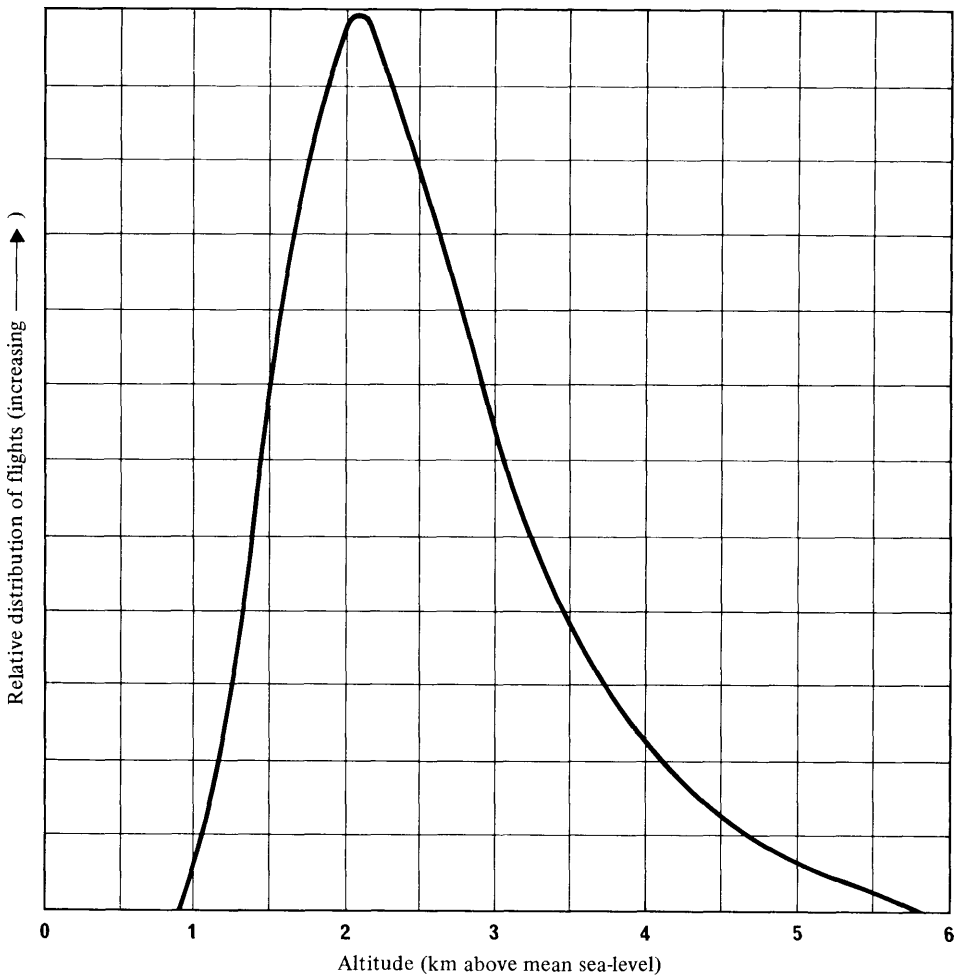

FIGURE 3 – *Expected distribution of detecting general aviation aircraft as a function of altitude*

The method undertaken in this analysis is to quantize this distribution and use a point-by-point analysis of the probability curves. This was accomplished by obtaining the relative value of the aircraft population versus altitude at 16 points (every 300 m in altitude beginning at 900 m MSL) and normalizing the values so that their sum is equal to one. These values are then multiplied by the probability that an aircraft in the restricted zone will enter the butterfly, and the probability that an aircraft in the butterfly will enter the antenna beam. The overall probability that an aircraft within the restricted zone will enter the beam is the sum of these weighted probabilities.

3. Results of probability assessment

Combining the individual conditional probabilities and summing up all the altitude weighting parameters yields a probability of 1.2×10^{-6} for the aircraft entering the hazardous region of the beam of the example site. This analysis assumes that the deep-space earth station is used continuously; it also assumes worst-case approaches to the development of the individual conditional probabilities wherever possible, and again is actually intended only to develop an order of magnitude of the chance of a plane entering the hazardous region.

The chance of an aircraft accidentally wandering into the deep-space beam is extremely small and if, indeed, 400 aircraft per year do wander into the restricted areas surrounding the example site it could be expected that approximately one aircraft every eight years or so would enter the beam.

4. Effect of passage through the beam

The maximum hazardous region for the beam (for the 10 mW/cm^2 level) is approximately 88 m wide. Again this is under worst-case conditions and, as a general rule, the maximum distance across the hazardous area of the beam will be less.

A typical minimum air speed for a small plane is about 110 km/h. This would imply that the maximum exposure time, while in level flight, would be less than eight seconds. The Surgeon General of the United States has stipulated that a 10 mW/cm^2 power density is hazardous if a person is exposed to it for six minutes or more. The maximum power flux contained within the deep-space radar beam is approximately 50 mW/cm^2. Since the radiation hazards levels set forth by the Surgeon General's office are concerned solely with the thermal heating effect on the human body, using a linear relationship, a person should be able to withstand the 50 mW/cm^2 for the order of 72 seconds without any significant harm. The probability of his being exposed to the maximum hazardous region of the radar beam for greater than 72 seconds approaches zero.

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SECTION 2B: SPACE RESEARCH

Recommendations and Reports

REPORT 548-1

TELECOMMUNICATION REQUIREMENTS FOR MANNED AND UNMANNED NEAR-EARTH SPACE RESEARCH

(Questions 1-1/2 and 22/2; Study Programme 22B/2)

(1974 - 1978)

1. Introduction

This Report presents a summary of the technical characteristics and system parameters of telecommunication systems in near-Earth space research services. The discussions provide a foundation for establishing the radio-frequency spectrum requirements for space research services and for frequency sharing between space research services and various terrestrial services.

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. 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;
- solar and stellar astronomy;
- atmospheric physics;
- radio propagation;
- geodesy;
- biology;
- earth exploration and meteorology (experimental only).

The purpose, duration, orbit and spacecraft physical characteristics of the various space research missions differ widely from one mission to another. However, sufficient experience has been gained to determine general descriptions of certain aspects of any given mission, such as mission durations, number of simultaneous spacecraft required by the mission, critical communication periods and types of orbit.

2.1 *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. Typical mission durations may last from a few months to several years for unmanned missions, and several days to a few 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 at regular intervals.

2.2 *Multiple spacecraft*

Certain space research missions require more than one spacecraft. An example of unmanned space research using multiple spacecraft is in satellite geodesy. In its simplest form, satellite geodesy operates as follows: as many satellites as possible are tracked from the Earth's surface with the utmost accuracy. From these observations, deviations of the satellite orbits from the ideal Keplerian motions are computed. With further corrections for solar pressure, atmospheric drag, the attractions of Sun and Moon, and other forces, partial information about the shape and mass properties of the Earth can be obtained.

2.3 *Critical communication periods*

During each space research mission there are certain periods which are critical to the success of the mission. Failure of reliable communication during these critical periods may cause anything from a minor difficulty to the total failure of the mission. Critical periods for near-Earth missions generally occur during those times where the satellite is within viewing range of a tracking site.

2.4 *Orbit types*

Most orbits may be classified in one of three general categories:

- low,
- geosynchronous,
- highly elliptical.

2.4.1 *Low orbit*

The class of low orbits may be based on the following definition:

Low orbit (of a satellite):

a satellite orbit in which the apogee is significantly nearer the Earth than is the geostationary satellite orbit.

2.4.2 *Geosynchronous satellite orbit*

The altitude for the geosynchronous satellite orbit is about 35 800 km. A characteristic of this type of orbit is that the satellite is continuously visible to its associated earth station. It is generally required that continuous data transfer occur to and from the spacecraft, which results in difficulties for time-sharing with non-geosynchronous spacecraft.

2.4.3 *Highly elliptical orbit*

A characteristic of this type of orbit is that the percentage of time the satellite is visible to its associated earth station is high. Nearly continuous data transfer to and from the spacecraft is generally required, which also results in restricted time-sharing possibilities.

3. Communication requirements

There are four basic telecommunication systems that are required by nearly all spacecraft:

- telemetering maintenance system for transmitting to the earth station the data obtained from the sensor systems in the spacecraft or from its human occupants;
- a mission telemetry system capable of transmitting mission gathered data, including sensor data in unmanned missions, and sensor, television and voice communications in manned missions;
- a tracking system to provide the information regarding the position and velocity of the spacecraft necessary for computing its orbit;
- a telecommand system to enable guidance and control of the spacecraft from the ground.

Because of severe limitations on size and weight, many spacecraft use combined systems similar to those illustrated in Fig. 1. Such systems have the advantage of allowing one receiver and one transmitter to perform several functions simultaneously, thus providing for efficient spectrum usage.

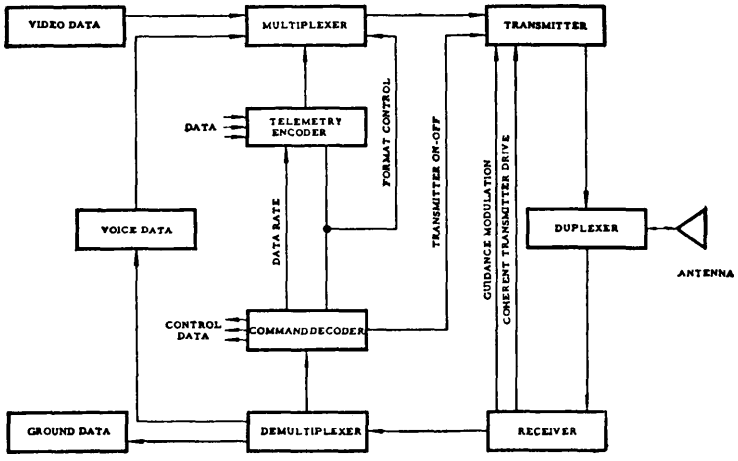

FIGURE 1 – *Typical block diagram of a system of integrated tracking, telemetering and telecommand for a spacecraft*

More detailed information regarding the technical characteristics of telecommunication links between earth stations and spacecraft, pertinent to the determination of suitable operating frequencies and bandwidth, is given in the following sections of this Report. Additional technical information, pertinent to telecommunication links between earth stations and spacecraft, is available [Edelson, 1972; Filipowsky and Muehldorf, 1965; Golomb, 1964; Balakrishnan, 1963].

All the telecommunication functions may be accomplished by radio links directly between the spacecraft and earth station; or by relay satellites to relay the data from the earth station to the space-research spacecraft; or from the spacecraft to the earth station (see Report 537-1).

It must be kept in mind that the overriding requirement of manned space flight is safety of the astronauts. Since satisfactory communications have a direct bearing on their safety, it is essential that only the most reliable and efficient communications techniques be utilized and that sufficient protection against interference be afforded (see Recommendations 363-1 and 364-3 and Reports 222-4, 396-3 and 456-2).

In manned space-flight research, 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, and these channels must be afforded maximum protection from interference.

3.1 *Maintenance telemetering*

3.1.1 *Modulation techniques*

In a general way, the modulation forms employed for telemetering can be classified in three major categories:

- time-division multiplex (TDM),
- frequency-division multiplex (FDM),
- code-division multiplex (CDM).

The performances of various specific modulation systems have been described in considerable detail [Edelson, 1972; Schwartz *et al.*, 1966; I.R.I.G., 1960; Cahn, 1959; Viterbi, 1960; Nichols and Rauch, 1957; Baghdady, 1961]. In general, time-division multiplex systems make more efficient use of the transmitted energy for highly accurate measurements. For less accurate measurements, frequency-division multiplex systems are simpler and will, therefore, remain desirable for certain applications.

Although both frequency and time-division multiplex systems have been used for sharing one communication channel among many engineering measurements, modern systems are converging on the time-multiplex technique. This is a result of the ease with which the complex time-multiplexer may be implemented with digital logical circuits for measurements in digital form. Code-division multiplex systems are particularly useful in the tracking and data relay satellite system where pseudo noise codes are sometimes necessary to combat interference and multipath problems.

The radiated energy per bit of information in the presence of noise may be reduced by increasing the occupancy of the radio-frequency spectrum. Conversely, bandwidth occupancy may be contracted by expending more energy per bit of information. Limitations in the power capabilities of spacecraft will thus tend to make modulation system design lean toward a smaller amount of energy per bit of information at the expense of bandwidth. Frequency- or phase-modulation systems are attractive because they can exchange bandwidth for transmitter power fairly easily. Pulse-code modulation systems also accomplish this exchange by proper selection of the code structure. It can be safely predicted that extensive use will be made in the immediate future of suitable orthogonal coding techniques in space telemetering.

Systems for the United States and European Space Agency spacecraft have converged on digital (PCM) transmission because it leads to simplified design of spacecraft, to simpler ground data handling, and to improved communication efficiency.

3.1.2 *Frequency considerations*

The most technically suitable frequencies for space research Earth satellite telemetry ranges from about 100 MHz to about 30 GHz, depending primarily on the specific applications and mission requirements.

3.1.3 *Bandwidth*

Channel bandwidth requirements for space research near-Earth satellite systems (both manned and unmanned) will vary greatly from mission to mission. Also, a large number of simultaneous missions require a number of discrete channels. In the data relay satellite system, very large bandwidths will be required for the relay satellite and the earth stations because of the summing of data from a number of space research satellites (including space laboratories). Table I indicates typical bandwidths for single links that may be required for telemetering in various sections of the radio-frequency spectrum.

3.2 *Mission telemetering*

Mission telemetering is defined as the transmission of information other than that included under the usual definitions of maintenance telemetering, tracking, and telecommand.

3.2.1 *Voice communication*

The requirements for the transmission of voice, to and from a manned spacecraft, differ from more conventional mobile voice links in the high degree of reliability required during critical periods and the necessity for communications with a given spacecraft from points widely separated on the surface of the Earth.

For normal speech transmission, an information bandwidth of 3 kHz and a speech-to-noise ratio of 20 dB is recommended.

3.2.1.1 *Speech compression techniques*

There is some promise that future requirements for power and bandwidth for voice transmission from spacecraft might be reduced by the use of the techniques of speech bandwidth compression. The results obtained to date, with experimental voice-compression systems, suggest that a word intelligibility of about 80% can be achieved with analogue bands of 200 to 800 Hz or with digital transmission rates of 1200 to 2000 bit/s.

3.2.1.2 *Power and spectrum conservation by peak-clipping techniques*

Peaks, some 15 dB above the average speech power, can be expected for about 0.1% of the time; smaller peaks occur more frequently. The peak factor (ratio of peak to average power) can be reduced by clipping the peaks above a specified level (followed by low-pass filtering), thereby permitting higher average modulation and a higher average received signal. Clipping of peaks above 7 or 8 dB permits a 5 to 1 reduction in transmitter power compared with that required for essentially unclipped speech, at a moderate sacrifice of speech quality and appears to be a reasonable compromise between quality and power.

3.2.1.3 *Modulation techniques*

In spacecraft-to-Earth voice links, emphasis is placed on minimizing the transmitter power requirements of the spacecraft. This is an important consideration, both from the standpoint of primary power and of peak-power rating of the radio transmitting equipment. From the viewpoint of primary power in the spacecraft, average transmitter power may be of more importance than peak power, and average power will be substantially lower than peak power for double and single sideband transmitters.

3.2.1.4 *Frequency considerations*

In most circumstances, it appears that the optimum frequency ranges for other emissions from earth stations to spacecraft will also be the best for voice links. However, there are special situations where frequencies in the HF range are needed to extend the range of the voice link beyond line-of-sight distance. Frequencies higher than 10 GHz appear to be useful for voice communications with a manned spacecraft in conditions of blackout during atmospheric re-entry (see § 3.6).

3.2.1.5 *Bandwidth*

Bandwidth requirements vary widely for different modulation schemes and required speech quality. They vary from a few kilohertz for single sideband and amplitude modulation to 45 kHz for pulse-code modulation and quadrant phase-shift keying (PCM/QPSK).

3.2.2 *Television*

3.2.2.1 *Modulation*

In terrestrial television broadcasting, vestigial sideband transmission is used to conserve spectrum. For space applications, the modulation method must be chosen primarily on the basis of minimizing weight and complexity. Given the video bandwidth and the wanted signal-to-noise ratio, the designer may use a minimum radio-frequency bandwidth system, such as vestigial sideband transmission and a corresponding transmitter power output, or a wider band system such as frequency modulation, frequency modulation with feedback, or pulse-code modulation, and a smaller power output.

3.2.2.2 *Frequency*

For normal conditions, it appears that frequencies between 1 GHz and 15 GHz will be suitable for television between earth stations and spacecraft, the centre of the range usually being the most suitable.

3.2.2.3 *Bandwidth*

The video bandwidth of a television system can be expressed as:

$$\text{bandwidth} = 0.35\, mL^2FR\,(1-V)/(1-H) \quad \text{Hz} \qquad (1)$$

where,

L: number of lines per frame,

F: number of frames per second,

R: width-to-height ratio of picture,

V: fraction of total vertical sweep-time, during which the trace is blank,

H: = fraction of total horizontal sweep-time, during which the trace is blank,

m: = ratio of horizontal-to-vertical resolution.

The values of R, V and H of the above equation will remain approximately the same for all applications. The important parameters are, therefore, L and F. The choice of the value of L is a matter of the degree of resolution required for the mission.

Present-day television systems for spacecraft, planned or in use, have from 200 to 1000 lines per picture. With new pick-up devices under development, and the higher powers which will be available in future spacecraft, it is expected that the number of lines will be increased substantially.

In some applications, the time needed to read-out each frame for transmission to the Earth may differ by orders of magnitude from the time used initially to view each frame. For example, in a recent series of meteorological satellites, each picture is taken with an exposure time of 1.5 ms, while the time taken to transmit the picture is 2 s. For applications where a given number of pictures are taken to be played back later when the satellite is in view of a suitable earth station, the time needed to read-out each frame is chosen to permit the number of pictures stored to be scanned during the time that the satellite is visible to the earth station.

3.3 *Telecommand systems*

A telecommand system is necessary to control functions within the spacecraft (manned or unmanned) from the earth station. It may use its own radio-frequency link or be combined in an integrated system, in which the radio-frequency link is shared with voice, ground data and tracking signals. Commands, transmitted to the spacecraft when it is within radio visibility of an earth station or a space station (in the case of tracking and data relay satellite systems), can either be executed immediately as real-time commands, or stored in a memory to be extracted later and executed as stored-programme commands.

3.3.1 *Modulation*

The telecommand signals are coded to provide a capacity for a number of discrete commands and to protect the spacecraft from spurious signals. Commands may be transmitted either by the use of various combinations of sub-carriers modulating the main carrier, or in the form of a serially pulse-coded transmission.

Tone-code commands are used extensively for small near-Earth satellites. For other systems, it is usually convenient to use binary-coded command words with modulation schemes using frequency-shift keying or phase-shift keying.

The problem of interference to telecommand receivers in spacecraft is difficult in that the "wanted signal" is not always present, and the interfering signal must not trigger the telecommand receiver even in the complete absence of the "wanted signal". Also, interfering signals can often enter the system from many directions because telecommand systems tend to use broad beamwidth antennae on the spacecraft to ensure that command reception is nearly independent of spacecraft attitude. A favourable factor is the rejection of signals which are not properly coded.

Typical information rates of a command code range from as low as 1 to 10 bit/s to more than 1000 bit/s for some of the more complex near-Earth satellites. The inclusion of a simple parity bit or the use of the complement of the command words are simple single-error detection methods. More elaborate multi-error correcting codes are also used.

3.3.2 *Frequency considerations*

In general, telecommand reception is required to be independent of spacecraft attitude. Thus, broad-beamwidth on spacecraft antennae is generally required. Usually, omnidirectional antennae are easier to design below 1 GHz. However, ominidirectional patterns can be achieved at frequencies as high as 10 GHz (see § 5.2). Thus, frequencies from 100 MHz to 10 GHz can be used for command applications.

3.3.3 *Bandwidth*

A bandwidth of approximately 50 kHz is usually sufficient for each telecommand link.

3.4 *Tracking systems*

Reliable radio tracking of spacecraft is one of the basic requirements of any experimental space programme. In addition to providing information necessary to determine the location in space of the spacecraft at any instant (past, present, and future), tracking is also necessary for evaluation of launch performance, for vernier corrections to trajectories, for determining precise timing for critical manœuvres such as retro-rocket firing, and for pointing highly directional ground-receiving antennae. Three basic tracking schemes are discussed briefly below.

3.4.1 *Interferometer tracking*

The interferometer operates on the following principle: if plane wavefronts are intercepted and detected at two antennae separated by a baseline, L, and a phase difference, φ, is measured between them, the direction of the satellite, α, subject to atmospheric and ionospheric corrections, is given by

$$\alpha = \cos^{-1} \frac{\varphi \lambda}{2\pi L} \qquad (2)$$

where λ is the wavelength of the satellite beacon signal (see Fig. 2).

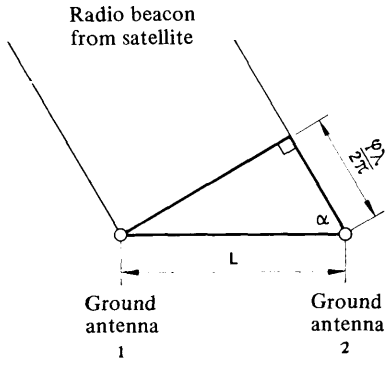

FIGURE 2 – *Interferometer system*

An interferometric system such as that described above provides only angular-bearing information, and several observations must be made over an appreciable period of time before the orbit of a satellite can be computed. When more precise data are required in a shorter time; for example, in the case of manned space experiments, more elaborate tracking systems are needed.

The interferometer system lacks precision on highly eccentric orbits where small angular displacements as seen from the Earth may correspond to large segments of the orbital trajectory. It is also of little use in tracking geostationary satellites. Nonetheless, the interferometer is simple, fairly accurate, and relatively inexpensive, and thus is still desirable for certain space-research missions, especially if only a satellite beacon is available.

3.4.2 *Range and range-rate tracking*

The range and range-rate system measures by comparing the phase of a signal before transmission and after return from the spacecraft transponder beacon (esentially, this is a time measurement). Range-rate is measured by Doppler techniques.

3.4.2.1 *Non-coherent system*

In a typical non-coherent sidetone range and range-rate tracking system, the earth station transmitter is phase-modulated by coherent sidetones. The satellite receives this signal and frequency-translates it to an intermediate frequency using an on-board crystal oscillator. This same oscillator serves as a source of transmitter frequency for the satellite transmitter. The frequency-translated signal is used to phase-modulate the satellite transmitter. The earth station uses this composite signal to extract the two-way Doppler and transmission path delay to determine range-rate and range. For the satellite, the non-coherent or crystal-controlled transponder represents the simplest electronic solution.

3.4.2.2 *Two-way coherent Doppler system*

In a typical two-day coherent Doppler system, the earth-station carrier may be phase-modulated by a specific ranging code. The satellite will phase-lock to the carrier and the satellite phase-locked oscillator is then used to generate a transmitter carrier which is coherent with the received signal. A satellite-generated ranging code, synchronous to the received ranging code, is used to modulate the satellite transmitter. This signal is radiated by the satellite to the earth station. The earth station phase-locks the carrier and thus extracts two-way Doppler for range-rate. By locking the code, total path delay can be extracted for range determination. Phase coherence is maintained at both the satellite transponder and the earth station. This somewhat increases the equipment complexity, but improves tracking accuracy.

3.4.3 *Radar*

Primary radars are rarely used in tracking for scientific purposes, except during launch phases, when on-board equipment may be shut down for environmental reasons. Rather than rely on weak echoes, scientific satellites almost inevitably carry beacons or transponders. There is no alternative to the use of radar echoes when the satellite is not transmitting, apart from limited use of optical tracking.

3.4.4 *Frequency considerations*

The optimum frequency range for the interferometer system is determined from consideration of the necessity for a good omnidirectional antenna on the spacecraft, transmitter efficiency in the spacecraft and a sufficiently wide beamwidth for the earth antenna. Consideration of such factors usually favours a frequency below 1 GHz. More elaborate interferometer systems have been built for frequencies above 6 GHz.

For range and range-rate systems which must operate during all weather conditions, the principal limitations imposed by tropospheric attenuation and ionospheric refraction [Barton and Sherman, 1960], (Report 205-4), define a useful frequency range of 1 to 8 GHz.Consideration of the design of antenna diplexers and the frequency multiplying circuitry in the spacecraft dictate that the "up frequency", transmitted from the Earth, be spaced between 6% and 10% from the "down frequency" transmitted from the spacecraft.

For tracking by primary radar systems, atmospheric attenuation usually limits the frequencies to less than 6 GHz.

3.4.5 *Bandwidth*

A bandwidth of several hundred hertz to several kilohertz is generally required for the interferometer system to allow for oscillator instability and Doppler shift. The high precision two-way coherent range and range-rate system requires a bandwidth from 1 MHz to 100 MHz, depending upon the accuracy required. In the radar tracking system, a bandwidth of 1 to 10 MHz will, in general, be sufficient.

3.5 *Storage and processing of data aboard the spacecraft*

The use of on-board data storage and processing techniques provides a possibility for significant reduction in bandwidths required for the information to be transmitted and for the transmitter power.

Data storage can provide a step-down conversion between data acquisition and data transmission rates to reduce transmission bandwidth. This technique is particularly effective when the source produces information at a high rate, but for short periods of time. Also, the use of on-board data storage permits several spacecraft to share common earth-station facilities, since the information stored by the spacecraft may be transmitted only when commanded by a ground station.

On-board data processing has not, as yet, been extensively used because the weight, power and complexity of the equipment required has been incompatible with the requirements of the spacecraft. Wider use of this technique in the future depends greatly on component reliability and miniaturization.

3.6 *Launch and re-entry communication*

The primary problem associated with launch and re-entry communication is the "communication blackout" which in many cases results in a complete loss, or at least a severe decrease, in the strength of signals between the spacecraft and the ground. Experience indicates that frequencies of 10 GHz and higher are required for launch and re-entry communications (Report 222-4), [Pylak and Churchill, 1971].

4. Spectrum requirements

On the basis of propagation data (see, for example, Section C of Vol. V) and the communication requirements outlined above, it is possible to specify those ranges in the spectrum for which allocations are required for various links between earth stations and research spacecraft.

4.1 *Location in spectrum*

Below 100 MHz, ionospheric effects are so great and the galactic noise is so high that the use of these frequencies is of limited value. For frequencies above about 15 GHz, scatter and absorption by cloud and precipitation increase to such a point that a large margin for weather effects must be provided, even though the background noise is low in this region of the spectrum. Under present and near future technology, it is difficult to use the spectrum above 30 GHz.

4.1.1 *Below 1 GHz*

Frequencies below 1 GHz, particularly in the range of 100 MHz to 500 MHz, are well suited for transmission from near-Earth spacecraft. Frequencies in the region of 100 MHz to 300 MHz are desirable for use by existing tracking networks and the extensive VHF networks which have been established for reception of telemetered data.

The use of frequencies in the region of 100 MHz to 500 MHz is especially attractive for spacecraft and earth stations which have very broad or omnidirectional antenna patterns. Such patterns are normally required for spin-stabilized or unstabilized spacecraft, for satellites providing narrow bandwidth relay links for several low orbit satellites, and for simple earth stations without facilities for antenna tracking. In the frequency band of 100 MHz to 1 GHz, atmospheric absorption is low and the weather has very little effect. Atmospheric noise is insignificant; but the background noise is relatively high, so the use of low-noise receivers does not give significant improvement in performance.

4.1.2 *Between 1 and 6 GHz*

The radio-frequency spectrum of 1 to 6 GHz is the region which is in the heaviest demand for links between earth stations and research spacecraft. In this range galactic noise density is low; atmospheric absorption is low; low-noise parametric and maser pre-amplifiers are feasible; practical directional

spacecraft antennae have gains compatible with the capabilities for attitude stabilization and beam-steering; and both surface and pointing accuracy requirements for large earth station antennae can be met. However, weather conditions begin to affect communications in this band, especially at the high frequency end. Nonetheless, the required margin for weather effects is small and nearly weather independent communication is expected.

4.1.3 *Between 6 GHz and 10 GHz*

Frequencies in the range of 6 to 10 GHz will be required to accommodate very wide-band (10 to 100 MHz) precision tracking and communication systems. Some re-entry links may use frequencies in this range. Low-noise parametric and maser pre-amplifiers are feasible in this region and galactic noise is even lower than that below 6 GHz; however, atmospheric absorption is somewhat higher and atmospheric noise will be correspondingly higher. This frequency range may prove useful for links between spacecraft, because these paths do not necessarily pass through the atmosphere.

4.1.4 *Between 10 GHz and 30 GHz*

Technical developments are making the use of frequencies in this region much more attractive, although the bands closest to 10 GHz are more desirable. The re-entry "black-out" problem often requires the use of frequencies in this range. Galactic noise is very low and parametric and maser pre-amplifiers are feasible. However, atmospheric absorption and atmospheric noise can be very high and very sensitive to weather changes. Thus considerably higher margins for weather effects must be considered. Ranging accuracies of one metre or better require such large bandwidths that available bands can be found only in this area. The transmission of coded digital video data will require large bandwidths, as will the rapid transmission of large quantities of data. Another use of these frequencies will be for links between spacecraft. Frequencies above 10 GHz will be very useful when missions have flexible schedules.

4.2 *Bandwidth*

Channel bandwidth requirements for near-Earth space-research satellite systems, both manned and unmanned, will vary greatly from mission to mission. Also, a large number of simultaneous unmanned missions would require a number of discrete channels for both directions of transmission. Table II indicates typical bandwidths that may be required in various sections of the radio-frequency spectrum. In the case of data relay satellites serving a number of missions, it may be necessary to consider time-sharing, multiplexing or wider bandwidths. In the Earth-to-space direction, larger bandwidths will be required for precision ranging and television data transmission to manned spacecraft, e.g., space laboratories.

5. Technical characteristics of typical space research equipment

5.1 *Transmitters in spacecraft*

The development of solid-state transmitters is advancing very rapidly. Moderate power can be generated by amplification techniques up to about 2 GHz and, at frequencies above this, efficient methods of parametric frequency-multiplication may be used. Other advanced techniques such as Impatt diodes and Gunn-effect devices are under development above 5 GHz. Some laboratory development models reach a power output of 10 W with an efficiency of about 5% at 15 GHz. Table III shows the powers and the efficiency of conversion from d.c. to radio frequencies achievable with solid-state devices (some of these are experimental).

Solid-state transmitters are inherently well suited to relatively wideband applications. Owing to the small size of solid-state devices, the low voltages involved (which render pressurization unnecessary), and the simplicity of the problem of heat transfer, the weight of this type of transmitter can be much less than its vacuum tube counterpart.

The higher powers necessary for present and future space missions, especially at the higher frequencies, can be obtained with various types of vacuum tube, such as high transconductance triodes, tetrodes, beam power-tubes, klystron oscillators, klystron amplifiers, backward-wave oscillators, voltage-tuned magnetrons and travelling-wave tubes.

Triodes, tetrodes and beam power-tubes are most efficiently used in medium bandwidth systems in the UHF region and below. Powers in excess of 150 W are possible in push-pull configurations with conversion efficiencies of approximately 15% from d.c. to radio frequencies.

High-level output above the UHF region is best obtained with voltage-tuned magnetrons, klystron oscillators, klystron amplifiers and travelling-wave tubes.

5.2 *Antennae for spacecraft*

For many applications, essentially omnidirectional antennae are required for spacecraft. Such antennae can usually be designed much more readily at frequencies below 1 GHz than above. However, some antennae designed for spacecraft produce omnidirectional radiation pattern characteristics at frequencies as high as 10 GHz, with a loss of efficiency not exceeding a few decibels.

Considerations of pointing accuracy and surface precision for a directional antenna are essentially the same on a spacecraft as at an earth station. However, some of the problems encountered with high-gain antennae on the Earth will be absent in space. For example, the mechanical design of an antenna might be simpler, since it will not involve loadings due to gravity, wind and ice; on the other hand, problems of erecting antennae with suitable surface accuracy and protection against micrometeorites and temperature gradients induced by solar radiation will be important. Omnidirectional or broad-beam antennae are usually desirable for spacecraft, to minimize the requirements for stabilization and attitude control, or to provide continuous wide-angle coverage. Conversely, for communication at great distances, for wide bandwidth links between spacecraft and earth stations, or for wide bandwidth links between spacecraft, high-gain antennae are essential. Precision in attitude control, and the other factors mentioned above, will limit the antenna beamwidth on the spacecraft. For a gain degradation of 1 dB due to pointing errors of $\pm$ 0.2°, $\pm$ 1° and $\pm$ 3°, the minimum beamwidths at the 3 dB points are approximately 0.8°, 4°, and 12° respectively. Table IV shows the corresponding frequencies for various antenna diameters.

5.3 *Receivers for spacecraft*

On the spacecraft, a low-noise receiver would be desirable, but this might not be worth a large weight penalty, since a more powerful transmitter at the earth station could compensate for lower receiver sensitivity. If a narrow-beam antenna is used on a spacecraft, it would "see" the earth-station transmitter against a background at 300 K, the temperature of the surface of the Earth, so there would be no advantage in a much lower receiver temperature. The noise temperatures of typical spacecraft receivers range from 600 K to 3000 K.

5.4 *Earth station antennae*

The type of antenna at an earth station, used for space research, tracking and data acquisition, depends to a large degree on the particular mission requirements and spacecraft performance including orbital characteristics. It can, therefore, be expected that earth-station antennae will have a number of configurations for experimental telecommunication links between earth stations and spacecraft.

5.4.1 *Fixed-beam, low-to-medium gain antennae at earth stations for automatic tracking*

Many scientific near-Earth satellites will operate at frequencies below 1 GHz and at altitudes where angular rates are high. For these applications, a number of fixed fan-beam antennae or low-to-medium gain, automatic-tracking, parabolic reflectors or arrays will be used.

5.4.2 *High-gain antennae at earth stations for automatic tracking*

For near-Earth satellites with high-information rates, earth station antennae with gains and effective apertures as large as practicable will be required. The antenna gains and effective areas of earth station antennae are limited by the low mobility of massive structures for tracking spacecraft, by manufacturing tolerances, and by meteorological conditions.

5.4.2.1 *Tracking*

Tracking errors of antennae which use automatic tracking circuitry to control the pointing of the main beam must be less than one tenth of the minimum beamwidth. This limitation is closely related to the tracking rates involved; for spacecraft in near-Earth orbits, angular rates can be as high as several degrees per second, but may be as low as sidereal rates (0.004 deg/s), or even essentially zero, as is the case for geostationary satellites.

5.4.2.2 *Surface tolerance*

The accuracy of the surface contour which can be fabricated and maintained with loads due to gravity, heat, wind and ice, decreases as the size of the antenna increases. Current manufacturing practices result in an r.m.s. deviation from a true paraboloid of approximately 10^{-5} times the antenna diameter.

5.4.2.3 *Meteorological conditions*

Insufficient information regarding the phase instability of the Earth's atmosphere during periods of adverse meteorological conditions, is available at present to predict accurately the degradation in gain which can be expected with large paraboloidal antennae. Present estimates indicate that the combination of limitations on structural tolerance and the inhomogeneities of the Earth's atmosphere will probably limit the realizable gain of large aperture antennae to about 70 dB.

5.5 *Receivers at earth stations*

The smallest signal that a radio receiver can detect is limited by the ambient noise generated in the receiver and that contributed by external sources. At the earth-station receiver, the noise is kept as low as possible, to minimize the power requirements of the spacecraft transmitter. Except for possible man-made interference, the

major contribution to the total system noise is the antenna background noise, which is a function of the operating frequency, angle of elevation of the antenna, existing meteorological conditions and ground thermal radiation into the antenna side and back lobes. Sky background noise arising from galaxy and sun bursts decreases with increasing frequency (approximately as $f^{-2.5}$), while noise due to the Earth's atmosphere increases above 1 GHz. Atmospheric noise due to heavy rainfall becomes significant at about 4 GHz and increases with frequency to a value of 100 K or more at about 15 GHz. Using narrow-beam antennae at the earth station down to angles of elevation of 5°, under adverse weather conditions, the minimum overall operating noise temperature which can be expected is 30 to 40 K at approximately 2.5 GHz.

5.6 *Transmitters at earth stations*

The provision of transmitter powers and stabilities required in the foreseeable future at earth stations, for telecommunication links between earth stations and spacecraft, should not present any serious technical problems. It may sometimes be necessary to programme the Doppler frequency-shift into the earth station transmitter to reduce the bandwidth or the complexity of the spaceborne receivers and antennae. An earth station e.i.r.p. of 1 mW or more (see Table V) will be needed in the frequency range under consideration, and should be realizable. It should be noted that these high powers will be used with high-gain antennae with beamwidths of less than 1° and angles of elevation greater than 5°. However, the amount of radiated power of specific emitters may have to be limited occasionally because of the geographical location, antenna characteristics and distance of earth stations from other users sharing the same frequency.

6. Sharing considerations

6.1 *General*

Radio frequencies from 100 MHz up to 30 GHz, sometimes with an extra channel in the HF region, have been shown to be suitable for various telecommunication links used in space research. The spectrum suitable for space research has already been allocated to one or more terrestrial services. Frequency sharing between space research and terrestrial services is inevitable. A careful sharing analysis based on typical characteristics of the space research service and terrestrial services must be performed to guarantee satisfactory performances for both the space research and the terrestrial services.

For space research missions, loss of more than 5 min of communication during a critical period would seriously affect a manned research mission and loss of more than 15 min could result in failure of the mission.

It is necessary to distinguish between the effects of interference which is "noise-like", i.e., which has approximately the same spectral characteristics as the noise in the system and that concentrated in narrow frequency bands, or "CW-type". For a given total interference power at the input to the receiver, CW interference can be the more harmful to Doppler, narrow-band telemetry, telecommand, synchronization of television, and certain types of range modulation, the bandwidths of which are typically of the order of 1 to 100 Hz. Because signals sweep through a considerable frequency range by Doppler frequency-shift and carrier instabilities, an interfering carrier would successively harm each sub-carrier or sideband (disrupting the corresponding telemetry channel or range tone), as the Doppler frequency-shift changes.

Noise-like interference can conveniently be considered and specified in terms of its power density, but for interference of CW-type, the power level of every major component is significant and the effects of these components upon the wanted signal must be estimated.

PCM/PSK/PM systems are favoured for space research by the United States and by the European Space Agency. The carrier and sub-carriers are generally demodulated with phase-locked loops. The experimental investigation of interference effects in phase-locked loops is discussed in Report 544.

In general, the effects of interference are difficult to evaluate analytically. Some interference studies have been performed in the past on space research services. In particular, the effects of interference on research spacecraft telemetering (especially binary bit detectors) are discussed in Report 545.

6.2 *Protection from interference*

The degree of protection from interference required by any receiving system depends upon the sensitivity of the system to interference and the consequences of degraded reception upon the overall operations.

Interference which is considerably less than the background noise level is of no consequence. The permissible ratio of interference-to-background noise is determined by the design margins customarily used in the particular communications link. In any spacecraft, there is a great incentive to minimize design margins because of the severe penalties in weight and cost of producing electrical power. It is possible to work with design margins as low as 3 to 6 dB, if the utmost care is exercised in equipment design. Design of a communication link may become much more difficult when man-made interference increases the total noise level by more than 1 dB. Complete disruption of communications and tracking could occur if the interference level were two or three times that of the background noise.

6.3 *Interference probability*

In general, the interference level is a statistical quantity that depends upon trans-horizon propagation and fluctuating weather conditions, the changing gain in the link between the interfering station and the receiving station due to relative motions of the antennae, etc.

The possibility of a terrestrial station interfering with an earth station is dependent upon propagation conditions. Propagation data are usually presented in the form of a percentage of time that certain conditions are exceeded and it is difficult to calculate a value for a given period of time, such as five continuous minutes, from such data. Propagation conditions are such that the least transmission loss between two stations will generally persist for much longer time periods than five minutes. Therefore, to provide protection which will prevent interference of longer than five minutes per day, it is necessary not only to consider the worst hour in a year, but also, the worst five minutes within that hour. This is approximately 0.001% of a year, and propagation data for time periods so short are not readily available. However, one analysis has shown that the value of transmission loss for 0.001% is approximately 20 dB less than the value for 0.01% of the time.

6.4 *Interference to space station receivers*

The factors that make space stations vulnerable to terrestrial interference are:

- space stations are in the direct line-of-sight from large areas of the Earth;
- antennae on space stations are necessarily pointed directly at the Earth and potential interfering sources, except when intermediate relay satellites are used.

Other factors that influence vulnerability to terrestrial interference are:

- the operating noise temperature of the receiver in the space station is usually limited (600 K or -201 dB(W/Hz)) by the necessity of viewing the warm Earth;
- the detection-bandwidth on the space station is greater (1 kHz), due to the need for rapid, automatic acquisition of signals from the Earth;
- the angular motion of the space station across the sky keeps the space station from staying very long within the (fixed) main beam of an interfering station (angular motions are 0.25°/min, or faster). Typical beams are 1° wide;
- the high velocity of the space station keeps it from staying within 1000 km of any one station for longer than 5 min.

The vulnerability of the command-receiver can be reduced by raising its threshold of sensitivity, permitting satisfactory operation under interference levels greater than the noise temperature of the receiver.

The appropriate criterion for protection of the space station is therefore:

For frequencies greater than 300 MHz, the total time shall not exceed five minutes per day (see § 6.3), during which the power flux-density of noise-like interference, or the total power of CW-type interference in any single band and in all sets of bands 1 kHz wide, is greater than -171 dB(W/kHz) at the input terminals of the receiver in the space station for manned research missions. In the case of other near-Earth research missions the limit is -161 dB(W/kHz) not exceeding 0.1% of the time. For frequencies less than 300 MHz, the permissible interference may be increased at the rate of 20 dB per decreasing frequency decade.

Interference of this type is random in nature and exact probabilities are very difficult to calculate. However, if line-of-sight radio-relay systems are considered, the limitations of $+13$ dBW transmitter power and $+55$ dBW e.i.r.p. should permit sharing. Trans-horizon radio-relay systems in general, necessarily use much higher transmitter powers and antenna gains and, if the number of such stations in a particular frequency band continues to increase, this may result in an unacceptably high probability of interference if bands are to be shared.

A summary of basic data for interference to space station receivers is included in Part 2 of Table V.

6.5 *Interference to earth station receivers*

The factor which makes earth stations more vulnerable than space stations is:

- the operating noise temperature of the receiver in the earth station is usually low (15 K to 3000 K) making it more susceptible to interference.

The factors which make earth stations less vulnerable than space stations are:

- except for initial acquisition the earth station antenna seldom operates with an elevation angle of less than 10°;
- earth stations are usually situated with some degree of natural site shielding.

The appropriate criterion for protection of the earth station is therefore:

For frequencies greater than 1 GHz, the total time during which the power flux-density of noise-like interference or the total power of CW-type interference in any single band and in all sets of bands 1 Hz wide is greater than -220 dB(W/Hz) and shall not exceed five minutes per day for manned research missions (0.1% of the time being a condition permissible for other near-Earth research missions). For frequencies below 1 GHz, permissible interference may be increased at the rate of 20 dB per decreasing frequency decade.

Available propagation data indicate that earth station receivers in the space research service may share frequency bands with line-of-sight radio-relay systems provided that applicable sharing criteria are observed. Sharing with trans-horizon radio-relay systems can be accomplished only where adequate terrain shielding and/or geographical separation is possible.

A summary of basic data for interference to earth stations is included in Part 1 of Table V.

6.6 *Interference to terrestrial receivers from spacecraft transmitters*

The factors that make the terrestrial receivers vulnerable are:

- terrestrial stations are in the direct line-of-sight for all spacecraft above the horizon;
- except when intermediate relay satellites are used, antennae on space stations are necessarily pointed directly at the Earth and at all terrestrial stations contained within the area of coverage.

The factors that make the terrestrial receivers less vulnerable are:

- the operating noise temperature of the terrestrial receivers is usually high;
- the angular motion of non-geosynchronous space stations across the sky keeps them from staying very long with the main beam of the terrestrial receiving antenna;
- the high velocity of the space station keeps it from staying within 1000 km of any one station for longer than 5 min.

In frequency bands shared between space research systems and terrestrial fixed systems, the power flux-density produced at the surface of the Earth by emissions from a space station should not exceed the limits agreed upon for sharing between the fixed satellite service and line-of-sight radio-relay systems. This is technically acceptable also to the space research service (trans-horizon radio systems would not be adequately protected by this limit and may require up to 40 dB extra protection).

6.7 *Interference to terrestrial receivers from earth station transmitters*

After a review of all factors known at the present time it is considered that, by selecting antenna radiation patterns and local site configurations, mission objectives can be met by an earth station e.i.r.p. limit in the horizontal plane of not more than +55 dBW in any 4 kHz band, and an earth station antenna elevation angle above the horizontal plane of not less than 5 degrees. Consideration of frequency sharing and co-ordination distances should be based on these factors. Sharing with line-of-sight radio-relay systems is feasible on this basis, but sharing with trans-horizon radio-relay systems will be more difficult and can be accomplished only where adequate terrain shielding or geographical separation is possible.

6.8 *Co-ordination distance procedures*

Procedures for determining co-ordination distances and areas are set forth in Appendix 28 of the ITU Radio Regulations and applicable Recommendations of the CCIR.

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Table I – *Bandwidths and frequencies for transmissions for typical research spacecraft*

Frequency range (GHz)	Type of signal	Radio-frequency bandwidth per link
Less than 1	Voice Telemetering Wideband data	3 to 45 kHz 10 to 100 kHz 50 to 500 kHz
1 to 6	Voice Telemetering Wideband data and television	3 to 45 kHz 500 to 800 kHz 500 kHz to 4 MHz
6 to 10	Voice Telemetering Wideband data and television	3 to 45 kHz 500 kHz to 4 MHz 4 to 20 MHz
10 to 30	Voice Telemetering Wideband data and television	3 to 45 kHz 1 MHz to 20 MHz Up to 300 MHz

TABLE II – *Typical channel bandwidths and frequencies per mission*

Frequency band (GHz)	Space-to-Earth		Earth-to-space	
	Unmanned	Manned	Unmanned	Manned
Less than 1	30 to 200 kHz	30 to 200 kHz	20 to 50 kHz	30 to 200 kHz
1 to 6	500 kHz to 4 MHz	500 kHz to 6 MHz	100 kHz to 3 MHz	500 kHz to 6 MHz
6 to 10	1 to 10 MHz	1 to 20 MHz	500 kHz to 6 MHz	1 to 20 MHz
10 to 30	Up to 300 MHz	Up to 300 MHz	Up to 300 MHz	Up to 300 MHz

TABLE III – *Powers and efficiencies of conversion from d.c. to radio frequencies achievable with solid state devices*

Frequency (MHz)	Power output (W)	Efficiency (%)
100	150	60
400	75	40
1 000	35	35
2 000	35	30
5 000	8	15
10 000	32 (1)	10
15 000	10 (1)	5

(1) Impatt diodes.

TABLE IV – *Relation between antenna diameter, beamwidth and frequency*

Beamwidth (degrees) (2)	Antenna diameter (m)			
	0·3	0·9	3	9
	Frequency (GHz)			
0·8	87·5 (1)	29·2 (1)	8·75	2·92
4	17·0 (1)	5·7	1·70	0·57
12	5·7	2·0	0·57	0·2

(1) The upper frequency limits may be determined by atmospheric absorption rather than by minimum usable beamwidths.

(2) These beamwidths require the pointing accuracies given in § 5.2.

TABLE V – *Summary of basic data for earth satellite interference probability and coordination distance calculations for frequencies between 1 and 15 GHz*

	Unmanned	Manned		Unmanned	Manned
1. *Earth station: receiving*			2. *Spacecraft receiver*		
Minimum elevation angle of the receiving antenna (degrees) . .	3	3	Gain of the receiving antenna (in the direction of the Earth) (dB) Max.	+60	+60
Main-beam antenna gain (dB) Max.	70	70	Gain of the receiving antenna (in the direction of the Earth) (dB) Min	−10	−10
Main-beam antenna gain (dB) Min.	10	40	Modulation type	amplitude and/or angle	amplitude and/or angle
Modulation type	amplitude and/or angle	amplitude and/or angle	System noise temperature (K) Max.	3000	3000
System noise temperature (K) Max.	3000	60	System noise temperature (K) Min.	600	600
System noise temperature (K) Min.	30	15	Nominal receiver bandwidth Max.	6 MHz	20 MHz
Nominal receiver bandwidth Max.	10 MHz	20 MHz	Nominal receiver bandwidth Min.	20 kHz	30 kHz
Nominal receiver bandwidth Min.	30 kHz	30 kHz	Interference level at the receiver input (dB(W/kHz)), which is not to be exceeded for more than:		
Interference level at the receiver input (dB(W/Hz)), which is not to be exceeded for more than:			0·1% of the time	−161	
0·1% of the time	−220		0·001% of the time (1) . . .		−171
0·001% of the time (1) . . .		−220	N/I (2) for 0·1% of the time (dB)	−10	
N/I (2) for 0·1% of the time (dB)	6		N/I for 0·001% of the time (dB)		0
N/I for 0·001% of the time (dB)		6			
3. *Earth station: transmitting*			4. *Spacecraft transmitter*		
Minimum elevation angle of the transmitting antenna (degrees)	5	5	Main-beam antenna gain (in the direction of the Earth) (dB) Max.	+60	+60
Main-beam antenna gain (dB) Max.	70	70	Main-beam antenna gain (in the direction of the Earth) (dB) Min.	−10	−10
Main-beam antenna gain (dB) Min.	10	40	Transmitter power (W) Max.	40	50
Transmitter power Max.	6 kW	6 kW	Transmitter power (W) Min.	0·25	1
Transmitter power Min.	100 W	100 W	Modulation type	amplitude and/or angle	amplitude and/or angle
Modulation type	amplitude and/or angle	amplitude and/or angle	Nominal frequency bandwidth Max.	10 MHz	20 MHz
Nominal frequency bandwidth Max.	6 MHz	20 MHz	Nominal frequency bandwidth Min.	30 kHz	30 kHz
Nominal frequency bandwidth Min.	20 kHz	30 kHz	Ranges from the surface of the Earth (km) Max.	4×10^5	4×10^5
			Ranges from the surface of the Earth (km) Min.	10^2	10^2

(1) It is considered that the 5-minutes criterion (in any day of the year chosen at random) in Recommendation 364-3 should be regarded as 0.001 % of the time when making use of relevant propagation data.

(2) N/I: Noise to interference ratio.

REPORT 536-1

TELECOMMUNICATION REQUIREMENTS FOR MANNED AND UNMANNED DEEP-SPACE RESEARCH

(Question 21/2)

(1974 - 1978)

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 via spacecraft, and the technical methods and parameters of systems used in connection with such missions [Edelson, 1972].

A set of deep-space research missions considered probable during the 1977 to 2000 time period is shown in Table I. (This set is part of a larger group being studied in the US.)

Considerations regarding preferred frequency bands for deep-space research can be found in Report 683. Interference, protection criteria and sharing are discussed in Report 685.

2. Telecommunication requirements

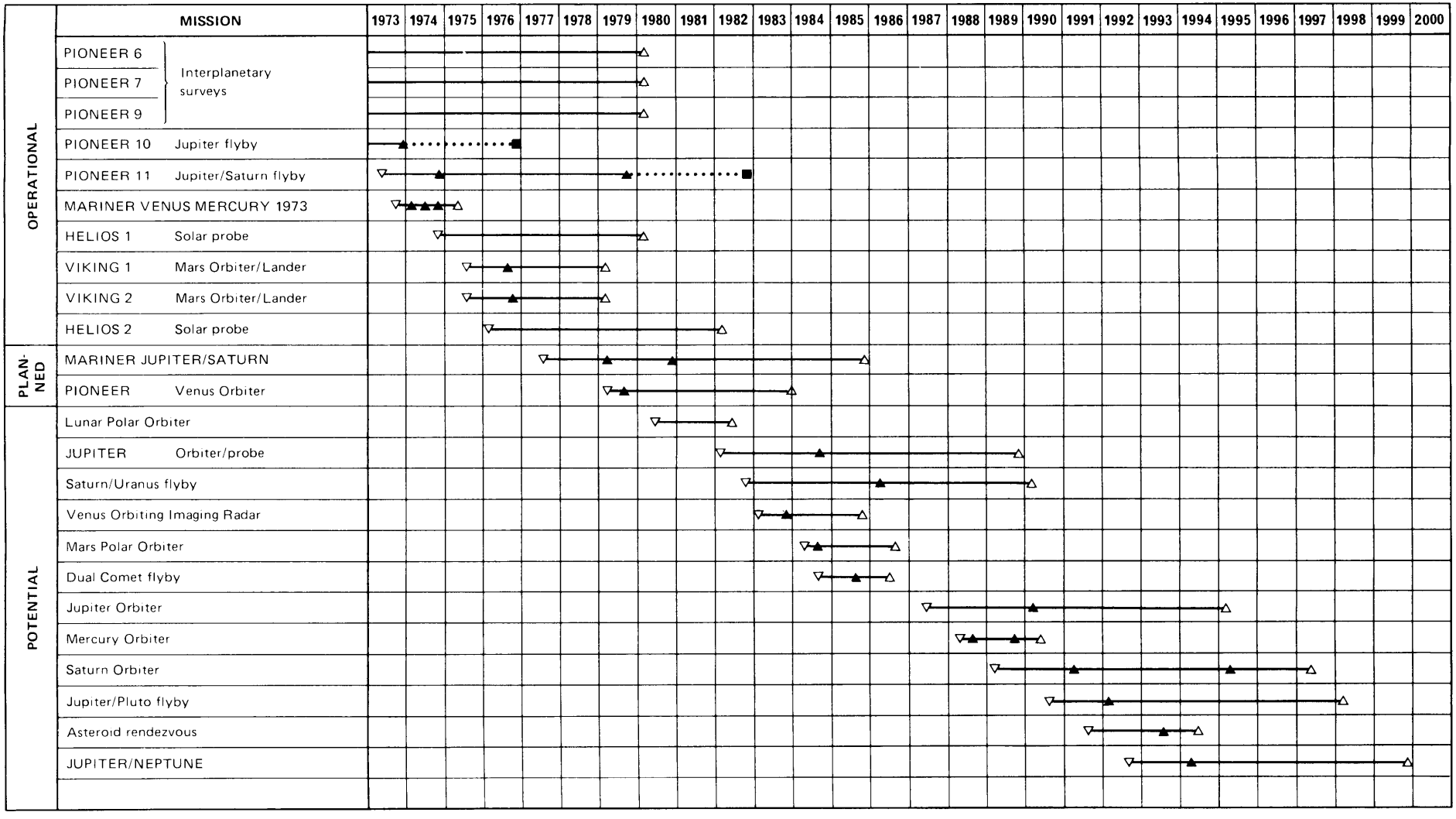
Deep-space missions require highly reliable communications. As shown in Table I, this must be accomplished over long periods of time and great distances. The need for high e.i.r.p. and very sensitive receivers is because of the large communication distance.

TABLE I – *Characteristics of potential US missions planned by 1977*

Mission	Launch year	Duration (years)	Maximum communication distance (× 10^6 km)
Jupiter Saturn Flyby	1977	4	2962
Venus Orbiter	1978	6	259
Lunar Polar Orbiter	1980	2	0.41
Jupiter Orbiter/Probec	1982	8	917
Saturn/Uranus Flyby	1982	7	3023
Venus Orbiter Imaging Radar	1983	2-1/2	260
Mars Polar Orbiter	1984	2-1/2	396
Dual Comet Flyby	1984	1-1/2	157
Jupiter Orbiter	1987	7-1/2	964
Mercury Orbiter	1988	5	259
Saturn Orbiter	1989	8	1580
Jupiter/Pluto Flyby	1990	7-1/2	4499
Asteroid Rendezvous	1991	2-1/2	528
Jupiter/Neptune	1992	7	4620

Continuous usage of deep-space communication bands is a consequence of the several missions now in existence and others being planned. Fig. 1 shows how the long duration of missions to the outer planets results in the need for communication with several deep-space missions at any given time. Each spacecraft must have the for communication with at least one earth station at all times, particularly during mission critical times such as orbit correction manœuvre, planetary flyby, orbit insertion, or emergencies such as equipment malfunction. Unplanned loss of communication may result in poor mission performance and even mission failure.

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.



▽ : Launch date

▲ : Arrival date

△ : End of data date

■ : End of mission not known

FIGURE 1

Durations of US deep-space missions

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 MARINER Jupiter Saturn (MJS) spacecraft to be launched in 1977 will have data rates of 40 and 1200 bit/s.

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 Mars lander (VIKING) consists of two facsimile cameras; non-imaging science experiments are biological, meteorological, seismological, molecular and mineral analysis. Data rates and acceptable error rates may be quite different for the two types of data.

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.

A figure of merit used to show telemetering capability is shown in Fig. 2.

The figure of merit is the product of telemetering data rate and the square of communication distance. It was calculated for four missions: MARINER Mars 1964, MARINER Mars 1969, VIKING Orbiter 1975, and MARINER Jupiter/Saturn 1977. Each represents an important step in telemetering development. If the 1977 figure of merit is applied to the proposed 1983 Venus Orbiting Imaging Radar (VOIR) mission with a communication distance of 2.60×10^8 km, a data rate of 1.5 Mbit/s might be anticipated. The imaging radar experiment will need a rate of approximately 3 Mbit/s, so an improvement in figure of merit is required.

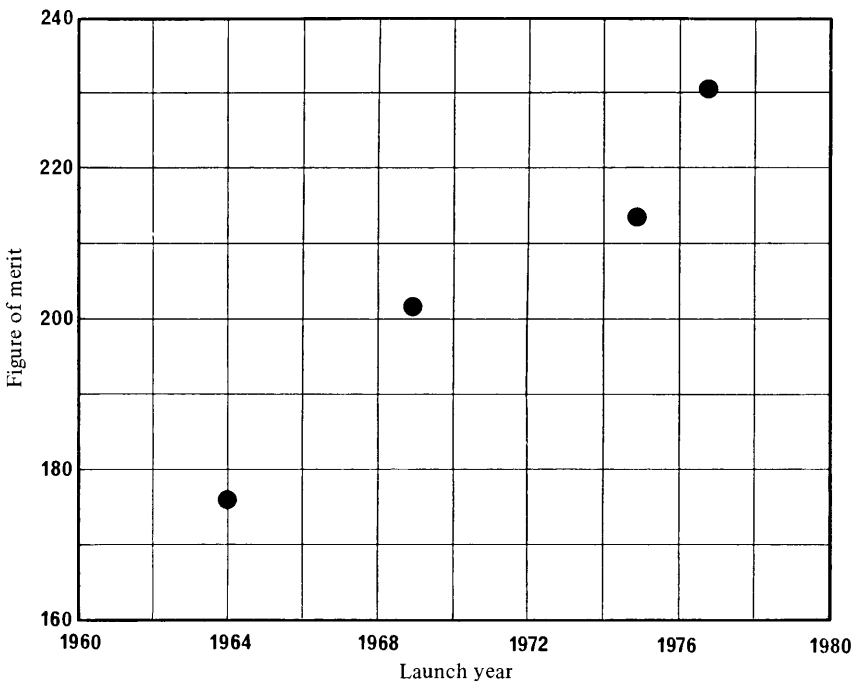


FIGURE 2 – *Telemetering figure of merit versus launch year*

figure of merit = 10 log (data rate × distance^2)

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]. 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 rate not greater tnan 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]. Table II lists accuracy specifications for the VIKING Mars Orbiter/lander and MARINER Jupiter/Saturn (MJS) flyby missions. Future requirements for longer or more difficult missions require more accurate navigation and tracking [Melbourne, 1976].

TABLE II – *Navigation and tracking accuracy specifications*

Mission	Required navigation accuracy (km)	Doppler frequency measurement accuracy (Hz)	Range measurement accuracy (m)	Earth station location estimate accuracy (m)
Viking Mars Orbiter/lander	300 (at Mars)	± 0.003	± 20	± 20
Mariner Jupiter/ Saturn Flyby	400 (at Jupiter)	± 0.001	± 4	± 2
	1300 (at Saturn)	± 0.001	± 4	± 2

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 *et al.*, 1972]. Amplitude, phase, frequency, polarization and delay measurements provide the needed information. The opportunity to make these measurements depends upon the availability of appropriate allocations. Within the 2 to 20 GHz range, 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 III. At each complex there is one 64 m diameter antenna, two or more 26 m antennae, 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 III – *Location of DSN earth station complexes*

Location	Latitude	Longitude	Height above mean sea level
Goldstone, Ca. (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 IV *(a)* to *(d)* list major characteristics of the earth stations. Tables IV*(a)* and *(b)* show current implementation, while Tables IV*(c)* and *(d)* show planned performance improvements and additions. For current 26 m stations, increase in antenna size to 34 m and the addition of 8 GHz receive capability is planned to be complete at one station in each complex by 1980. The 64 m antennae are expected to be increased to 70 m by 1984. Transmit capability near 15 GHz may be in operation by 1990.

The system noise temperatures listed in Table IV 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 curve B of Fig. 3. 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 IV a – *Current characteristics of earth stations with 26 m antennae*

Frequency (GHz)	Antenna gain (dBi)	Antenna beam-width (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)	Receiving system noise temperature (K) (1)	Receiving system noise spectral density (dB(W/Hz)) (1)
2.1 (Earth-to-space)	53	0.368	43	96	–	–
2.3 (Space-to-Earth)	54	0.328	–	–	33	–213

(1) Clear weather, 30° elevation angle, diplex mode for simultaneous reception and transmission.

TABLE IV b – *Current characteristics of earth stations with 64 m antennae*

Frequency (GHz)	Antenna gain (dBi)	Antena beam-width (degrees)	Transmitter power (dBW) (1)	e.i.r.p. (dBW)	Receiving system noise temperature (K) (2)	Receiving system noise spectral density (dB(W/Hz)) (2)
2.1 (Earth-to-space)	61	0.146	50 56	111 117	–	–
2.3 (Space-to-Earth)	62	0.131	–	–	16	–217
8.4 (Space-to-Earth)	72	0.041	–	–	23	–215

(1) + 56 dBW transmitter power use during spacecraft emergencies only.

(2) Clear weather, 30° elevation angle, receive-only mode.

TABLE IV c – *Expected characteristics of earth stations including planned increase in antenna size from 26 m to 34 m*

Frequency (GHz)	Antenna gain (dBi)	Antenna beam-width (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)	Receiving system noise temperature (K) (1)	Receiving system noise spectral density (dB(W/Hz)) (1)
2.1 (Earth-to-space)	55	0.292	43	98	–	–
2.3 (Space-to-Earth)	56	0.260			22	–215
7.2 (Earth-to-space)	66	0.082	43	109		
8.4 (Space-to-Earth)	67	0.073	–	–	25	–215
15 (Example)	72	0.041	To be determined	To be deter-mined	35	–213
30 (Example)	76	0.026	To be determined	To be deter-mined	To be determined	To be determined

(1) Clear weather, 30° elevation angle, receive-only mode.

TABLE IV d – *Expected characteristics of earth stations including planned increase antenna size from 64 m to 70 m*

Frequency (GHz)	Antenna gain (dBi)	Antenna beam-width (degrees)	Transmitter power (dBW) (1)	e.i.r.p. (dBW)	Receiving system noise temperature (K) (2)	Receiving system noise spectral density (dB(W/Hz)) (2)
2.1 (Earth-to-space)	62	0.131	50 56	112 118	–	–
2.3 (Space-to-Earth)	63	0.116	–	–	16	–217
7.2 (Earth-to-space)	72	0.041	50 56	122 128	–	–
8.4 (Space-to-Earth)	73	0.037	–	–	23	–215
15 (Example)	76	0.026	To be determined	To be deter-mined	33	–213
30 (Example)	73	0.037	To be determined	To be deter-mined	To be determined	To be determined

(1) + 56 dBW transmitter power for use during spacecraft emergencies only.

(2) Clear weather, 30° elevation angle, receive-only mode.

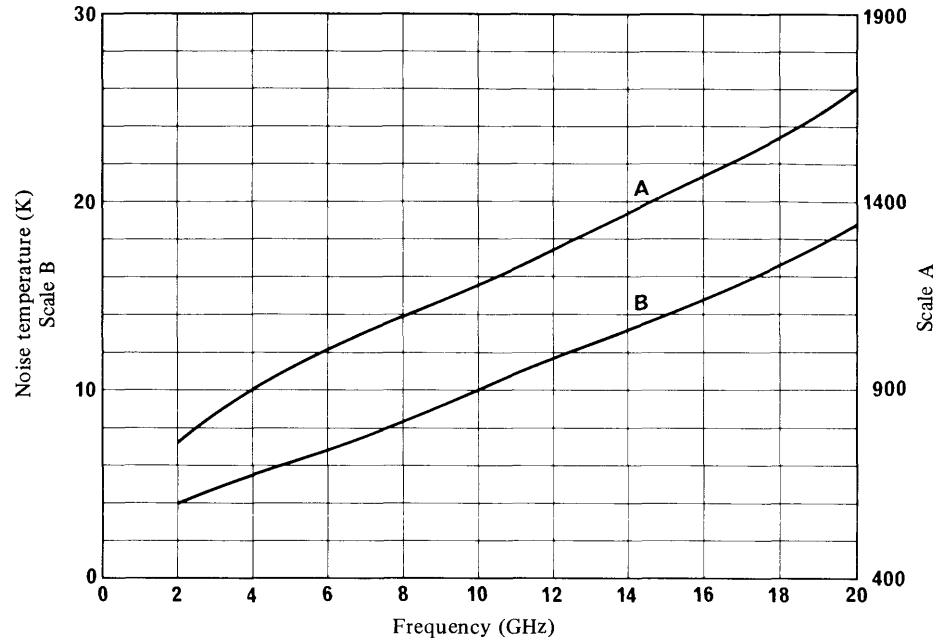


FIGURE 3 – *Noise temperature of receiving equipment including antenna losses*

A : space station B : Earth station

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 V lists major characteristics of space stations designed for the 1977 mission to Jupiter and Saturn.

The noise temperature of the space station receiver is shown by curve A in Fig. 3. The curve is based on the noise temperature of the HELIOS spacecraft of the Federal Republic of Germany, (600 K at 2.3 GHz), and estimates of possible implementation at the higher frequencies.

At the present time, the power of the space station transmitter is limited by primary power available on the spacecraft, and not by transmitter technology, for the 2 to 20 GHz frequency range.

TABLE V – *Characteristics of 1977 US space station design (Mariner Jupiter Saturn-MJS)*

Space-to-Earth frequency GHz	Antenna size (m)	Antenna gain (dBi)	Antenna beamwidth (degrees)	Transmitter power (dBW)	e.i.r.p. (dBW)
2.3	3.7	37	2.3	13.6	51
8.4	3.7	48	0.64	13.2	61

Earth-to-space frequency GHz	Antenna size (m)	Antenna gain (dBi)	Beamwidth (degrees)	Receiver noise temperature (K)	Receiver noise spectral density (dB(W/Hz))
2.1	3.7	36	2.6	1540	–197

4. Deep-space telecommunication methods

Telemetering and telecommand functions for deep-space telecommunications are typically accomplished by transmission of phase modulated carriers (Viterbi, 1966]. 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.

R.F. 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 increase 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]. 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 MARINER Jupiter Saturn (MJS) mission, with a maximum bit error rate 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 (Section 2.3.2), a code frequency of at least 30 MHz is required.

4.6 *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 subcarrier frequency plus the fifth harmonic of the clock rate (1/2 the bit rate). With present techniques, the subcarrier frequency must be high enough to provide 1.5 subcarrier cycles per data bit. The total bandwidth required is therefore:

$$BW = 2\,[(BR \times 1\,½ \times 5) + 5 \times ½\,BR] \quad (1)$$
$$= 20\,BR$$

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 4 shows a curve representative of telemetering spectra.

As telemetering data rates increase, the need for a subcarrier to move the data sidebands away from the carrier tracking loop becomes less important. 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. When an instrument like this is used for the study of other planets, the telemetering bandwidth required will be far beyond that available in current deep-space allocations.

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 Figure 5. 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. Transmission in relatively wide band allocations in the 10 to 20 GHz portion of the spectrum will be necessary to meet the ranging accuracy required for radio science.

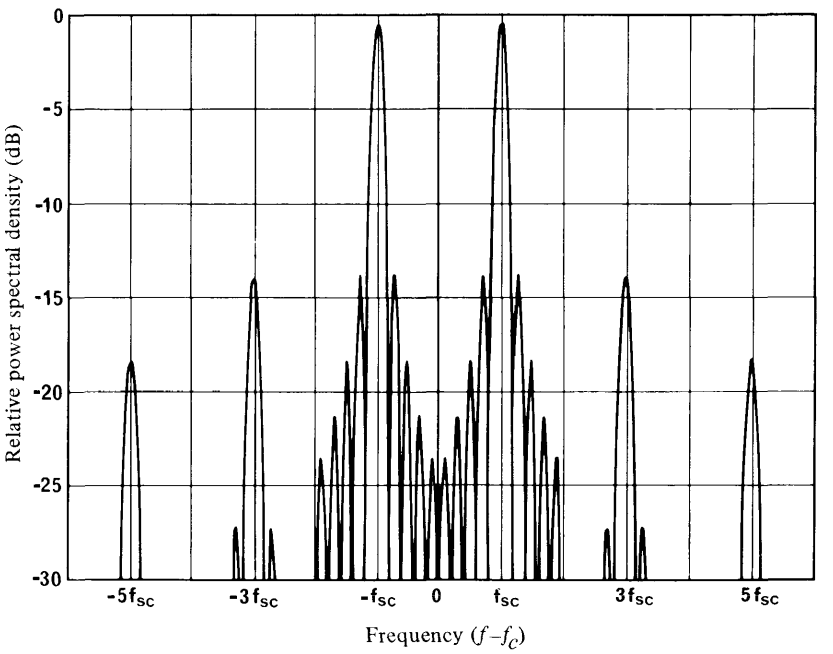


FIGURE 4 – *Telemetering power density spectrum (Space-to-Earth)*

$f - f_c$: Frequency relative to carrier

f_c : Carrier frequency

f_{sc} : Subcarrier frequency

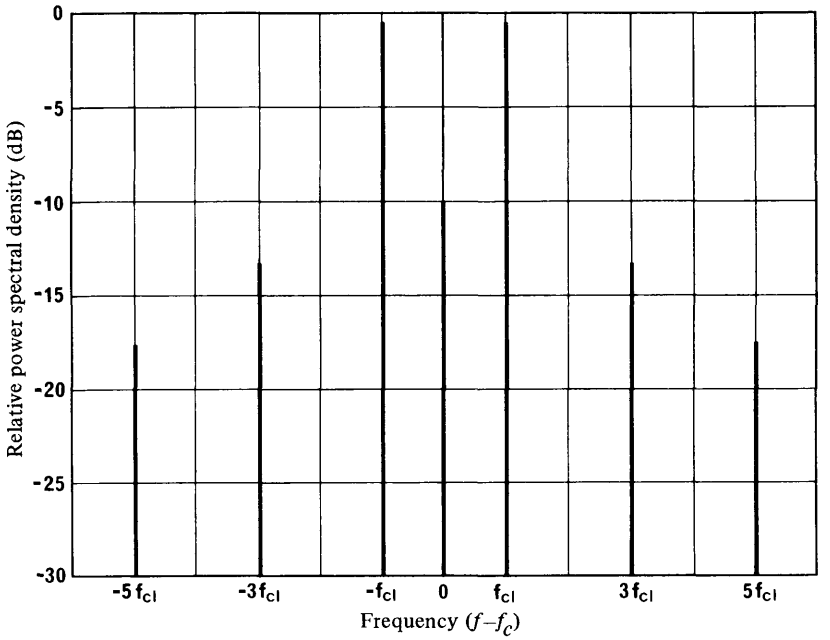


FIGURE 5 – *Ranging power density spectrum (Earth-to-Space)*

$f - f_c$: Frequency relative to carrier

f_c : Carrier frequency

f_{cl} : Ranging clock frequency

Link bandwidth requirements for deep-space research are based on needed bit rates for the various functions shown in Table VI.

TABLE VI – *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

Table VII lists the bandwidth required for these bit rates, assuming the use of techniques to minimize the width of the transmitted spectrum.

TABLE VII – *Required bandwidths for deep-space missions*

Direction and function	Link		
	Weather independent	Normal	High rate data
Earth-to-space			
Channel bandwidth (MHz)	4	40	400
Telecommand (kHz)	1 to 5	1 to 5	1 to 5
Computer programming (kHz)	5 to 250	5 to 500	1 to 1000
Voice (kHz)	50 to 200	50 to 200	50 to 200
Video (MHz)	1 to 4	1 to 24	6 to 50
Ranging (MHz)	4	40	400
Space-to-Earth			
Channel bandwidth (MHz)	4	40	400
Maintenance telemetering (kHz)	1 to 5	1 to 5	1 to 10
Scientific data (kHz)	0.008 to 115	1 to 500	50 to 10^4
Voice (kHz)	50 to 200	50 to 200	50 to 200
Video (MHz)	0.2 to 0.8	2 to 8	6 to 24
Ranging (MHz)	4	40	400

Some deep-space missions use two or more spacecraft. Table VIII shows the total required bandwidth for expected deep-space missions.

TABLE VIII – *Deep-space research bandwidth requirements and frequency bands, current and planned*

Period of use and type of link	Total required bandwidth (MHz)	Suitable space research frequency bands (MHz)
Weather independent 1970 →	10	2100 to 2120 Earth-to-space 2290 to 2300 space-to-Earth
Normal 1970 →	100	7145 to 7235 Earth-to-space 8400 to 8500 space-to-Earth
High rate data 1980 → (development starting in 1970s)	1000	Various bands above 10 000

4.7 *Antenna gain and pointing*

For the parabolic antennae 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 antennae, is manufacturing precision.

For earth station antennae, surface deformation is caused by wind and thermal effects. As elevation angle is varied, gravity introduces additional distortion of the surface.

For space station antennae, size is limited by space available in the launch vehicle, and by the state of the art in the construction of unfurlable antennae. Thermal effects cause distortion in space station antenna surfaces.

The maximum usable gain of antennae 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 beamdwidth and the maximum usable gain.

Table IX shows typical limits on antenna performance. Figure 6 shows the gain of the 64 m earth station antennae as a function of frequency and elevation angle.

TABLE IX – *Current limitations on accuracy and maximum antenna gain*

Limiting parameter	Space station antennae		Earth station antennae	
	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	± 0.15° (3σ)	55 dB(2)	± 0.016° (3σ)	75 dB(2)

(1) Gain at other frequencies will be lower.

(2) Gain of antenna with half power beam width equal to 2 × pointing accuracy (3σ). Beam of higher gain antenna will be too narrow.

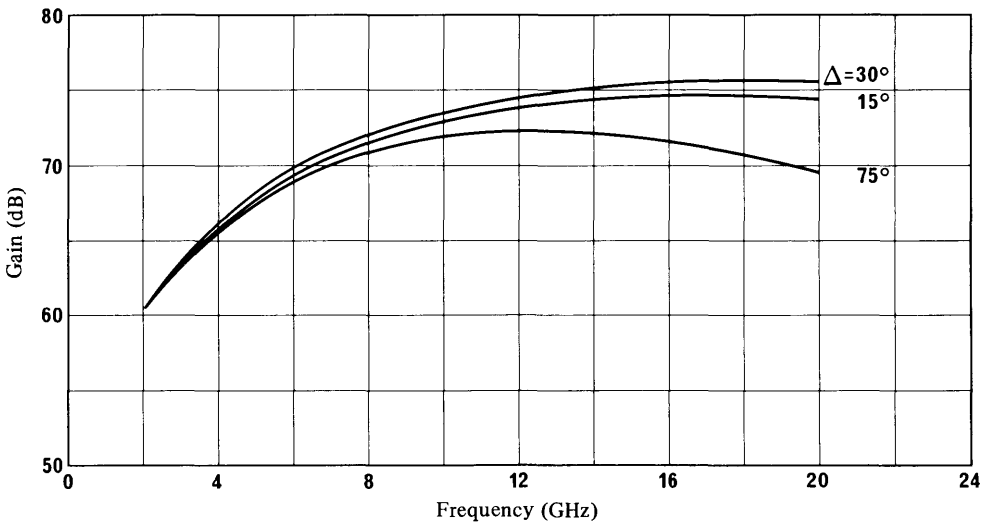


FIGURE 6 – *Gain of 64 m Earth station antenna*

Parameter Δ: elevation angle of Earth station antenna

4.8 *Additional radio navigation 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 [CCIR, 1974-78].

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].

5. Performance analysis and design margins

Table X 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.

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CCIR Documents

[1974-78]: 2/168 (United States of America).

TABLE X – *Performance budget. Spacecraft-to-Earth from Jupiter*

Mission: MARINER 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 antennae, (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)	2.3
Threshold data power, (dBW)	−162.2
Performance margin, (dB)	3.5

REPORT 683

PREFERRED FREQUENCY BANDS FOR DEEP-SPACE RESEARCH USING MANNED AND UNMANNED SPACECRAFT

(Study Programme 22A/2)

(1978)

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 536-1 contains a detailed discussion of the telecommunications requirements for deep-space research that were used in determining the preferred frequency bands.

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 orbitor 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.

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 536-1.

3. Equipment factors

Earth stations include large steerable parabolic antennae, high power transmitters and sensitive receivers. All of these are very expensive and infrequently constructed. For this reason, analysis of link performance versus frequency considers the earth station antennae 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 antennae. 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 rate, 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. Allocations in the 10 to 20 GHz range are needed for future missions requiring optimum link performance for very high telemetering rates and wideband ranging.

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 for these pairs are shown in Tables III and IV.

The existing 2110 to 2120 MHz and 2290 to 2300 MHz allocated pair meets 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 existing 7145 to 7235 MHz and 8400 to 8500 MHz allocated pair, provides increased link performance using the spacecraft high gain antenna. The 8 GHz allocation is not optimum, but provides acceptable performance. The 100 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.

A new pair of bands between 10 and 20 GHz will be needed for clear weather use by future missions. These bands should be approximately 500 MHz wide to 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.

TABLE III – *Preferred frequencies and their uses*

Region of preferred frequency	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 antennae. 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 multi-frequency 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 multi-frequency 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*

Region of preferred frequency (GHz) (1)	Current allocation (GHz)
1 to 2 Earth-to-space	2110 to 2120 Earth-to-space
1 to 2 space-to-Earth	2290 to 2300 space-to-Earth
7 to 9 Earth-to-space	7145 to 7235 Earth-to-space
4 to 6 space-to-Earth	8400 to 8500 space-to-Earth
12 to 20 Earth-to-space	none
10 to 14 space-to-Earth	none

(1) Frequencies near 30 GHz, and perhaps higher, will also be needed in the future for space-to-space communication.

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 Report 564-1 of Volume V, and Report 263-4, 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.

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:

$$P_r - N_0 = P_t + G_t - L_p - L_a - L_{Ra} + G_r - 10 \log (kT_T) \quad \text{(dB)} \quad (1)$$

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: path loss between isotropic antennae (dB)
L_a: transmission loss through the atmosphere including water vapour (dB)
L_{Ra}: transmission loss through rain (dB)
G_r: receiving antenna gain (dBi)
k: 1.38×10^{-23} (Joule/K)
T_T: total noise temperature (K)

$$T_T = T_a + T_{Ra} + T_g + T_r \quad \text{(K)} \qquad (2)$$

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 Report 721.

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.

Fig. 1 presents curves of attenuation between space and Earth as a function of frequency and elevation of the earth station antenna. The figure was derived from data in Reports 205-4, 563-1, 564-1 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 4, and include the attenuation of the atmosphere.

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. Report 205 – 4 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.

Fig. 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.

3.3 *Tropospheric scintillation and refraction*

Reports 564-1 and 718 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°. These effects have not been included in the analysis of preferred frequencies.

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 263-4.

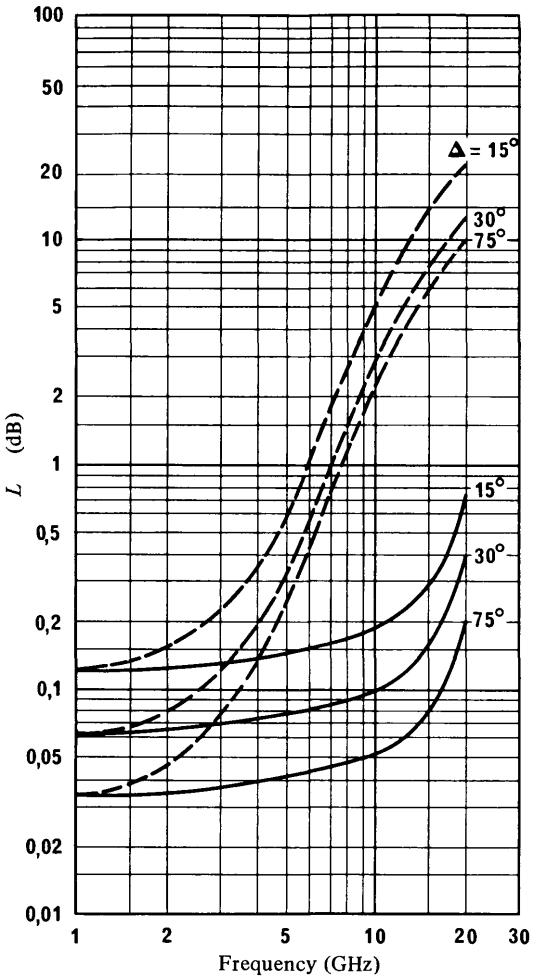

FIGURE 1 – *Attenuation L by atmosphere and rain*

clear weather, atmosphere only

rain and atmosphere; 32 mm/h

Parameter Δ: elevation of earth station antenna

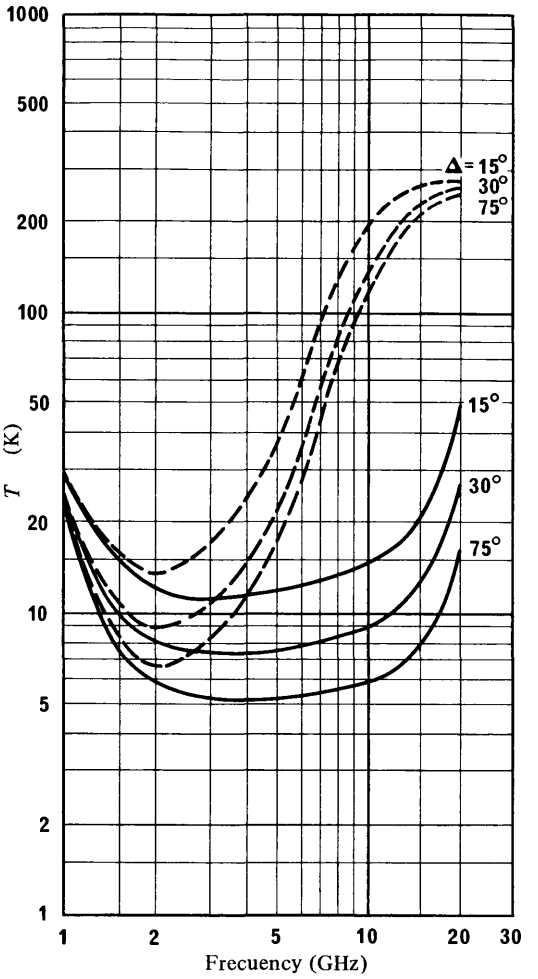

FIGURE 2 – *Sky noise temperature, T*

clear weather, atmosphere only

rain and atmosphere; 32 mm/h

Parameter Δ: elevation of earth station antenna

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 has been shown to be the following [Trask and Efron, 1966]:

$$\Delta t = \frac{40.3}{cf^2} \int N \mathrm{d}s \qquad \text{seconds} \tag{4}$$

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 delay through the ionosphere ranges from 0.25 μs at 1 GHz to 62 nS at 20 GHz. Further discussion will be found in Report 263-4.

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 approximation formula:

$$N = 10^{12}\left(\frac{70}{r^6} + \frac{0.6}{r^2}\right) \quad (5)$$

where,

N: electron density in electrons/metre^3,

r: distance from Sun surface in Sun radii.

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.

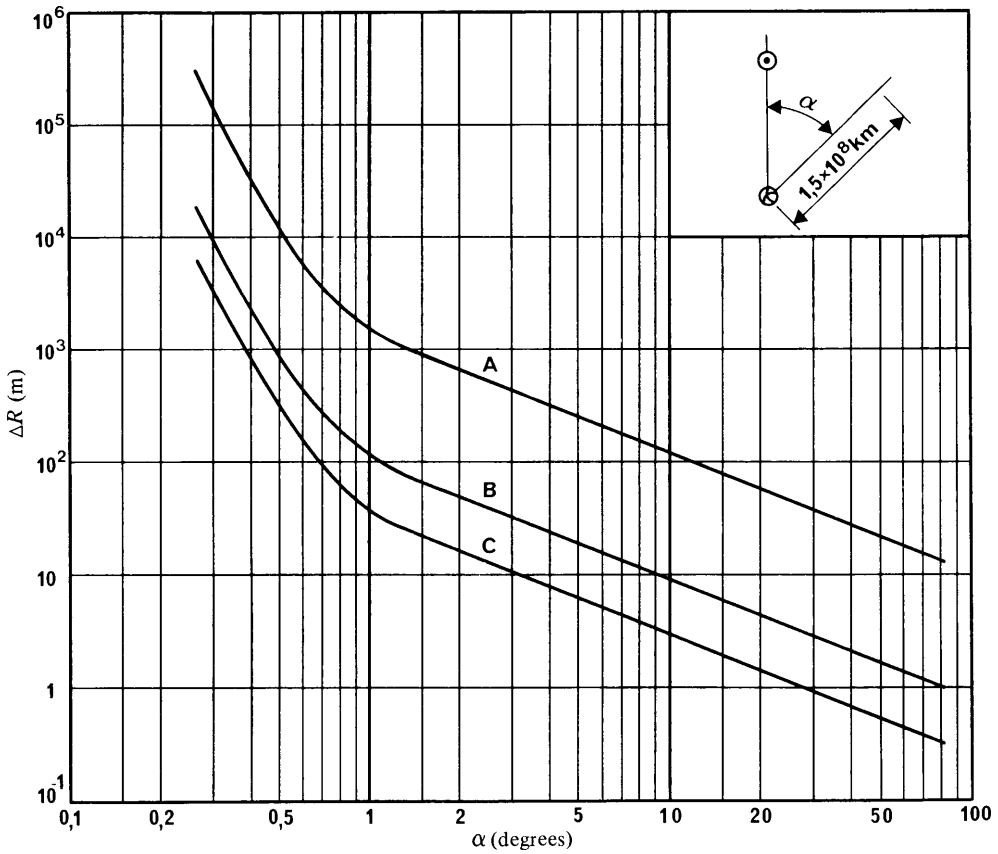

FIGURE 3 – *Approximate error ΔR, in indicated range caused by charged particles, as a function of angle from limb of Sun α*

A: 2.295 GHz
B: 8.450 GHz
C: 15.0 GHz

⊙ : Sun
⊕ : Earth

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 536-1.

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.

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 for 1977 implementation is considered to follow the curve in Fig. 3 of Report 536-1.

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 for 1977 implementation the noise temperatures are as shown in Fig. 2 of Report 536-1.

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 536-1, 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, antennae characteristics and transmitter power would not significantly change the shape of the curves.

Figs. 4 to 7 show curves for clear and rainy weather, and for earth station antenna elevation angles of 15° (near horizon), 30° and 75°. Figs. 4a, 5a, 6a and 7a reflect the implementation limitations typical of 1977 earth and deep space stations. Gravity induced structural distortions on large earth station antennae reduce gain to an extent dependent on elevation angle. This effect is included in the figures for 1977, and is the cause of the crossing of several curves.

Figs. 4b, 5b, 6b and 7b assume the use of perfect antennae 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.

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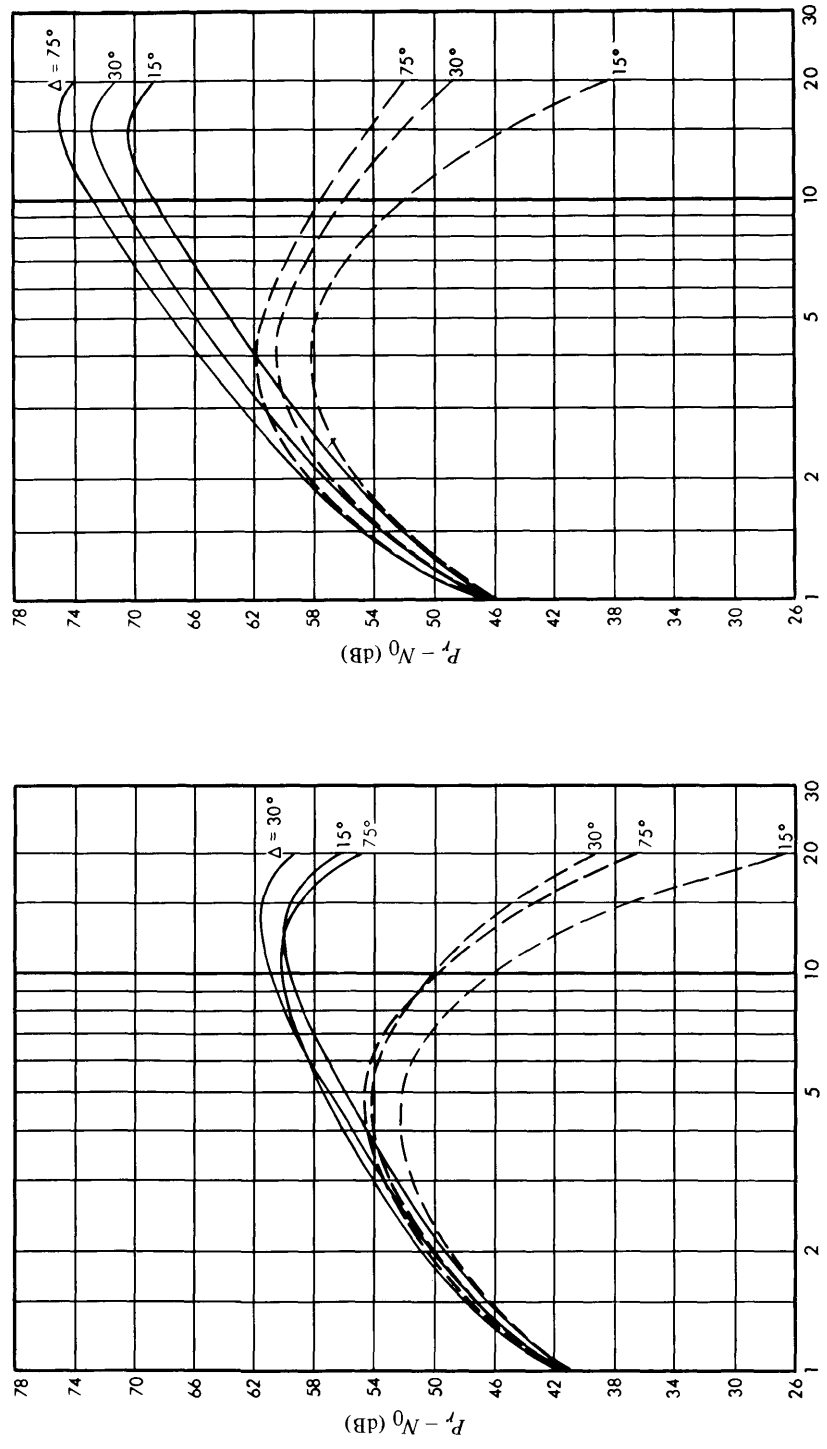


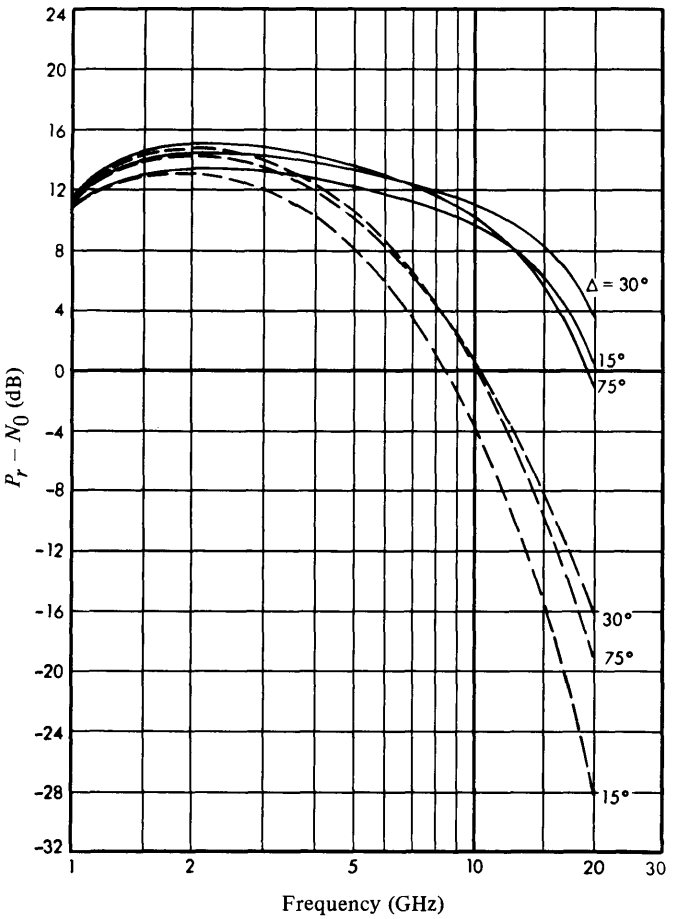
FIGURE 4 – *Space to Earth link performance ($P_r - N_0$)*

Two fixed diameter antenna

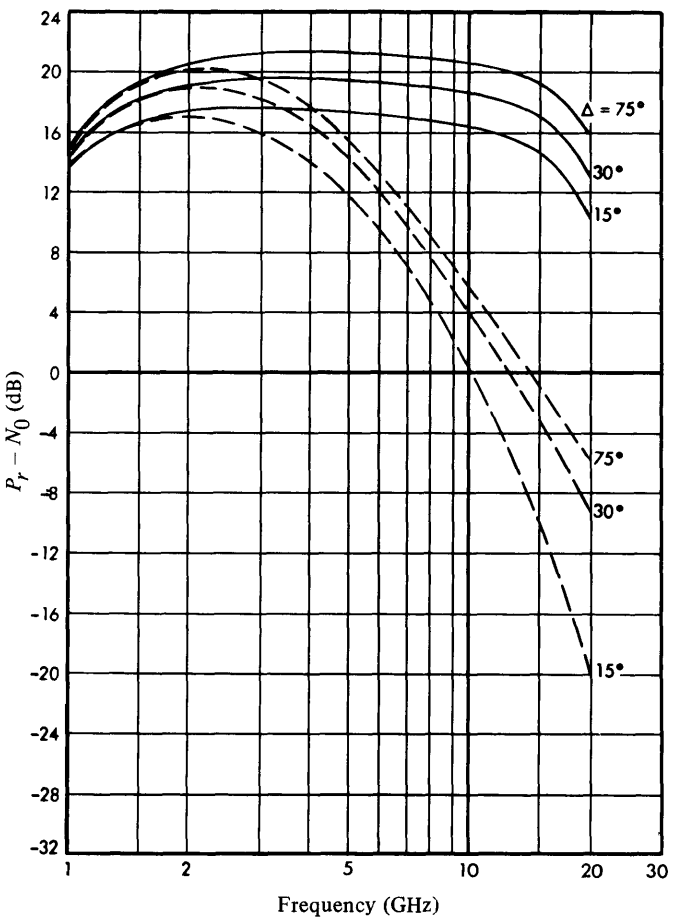
——— clear weather, atmosphere only

– – – – – rain and atmosphere

Parameter Δ : elevation angle of earth station antenna



(a) 1977 implementation



(b) Future limits from natural phenomena only

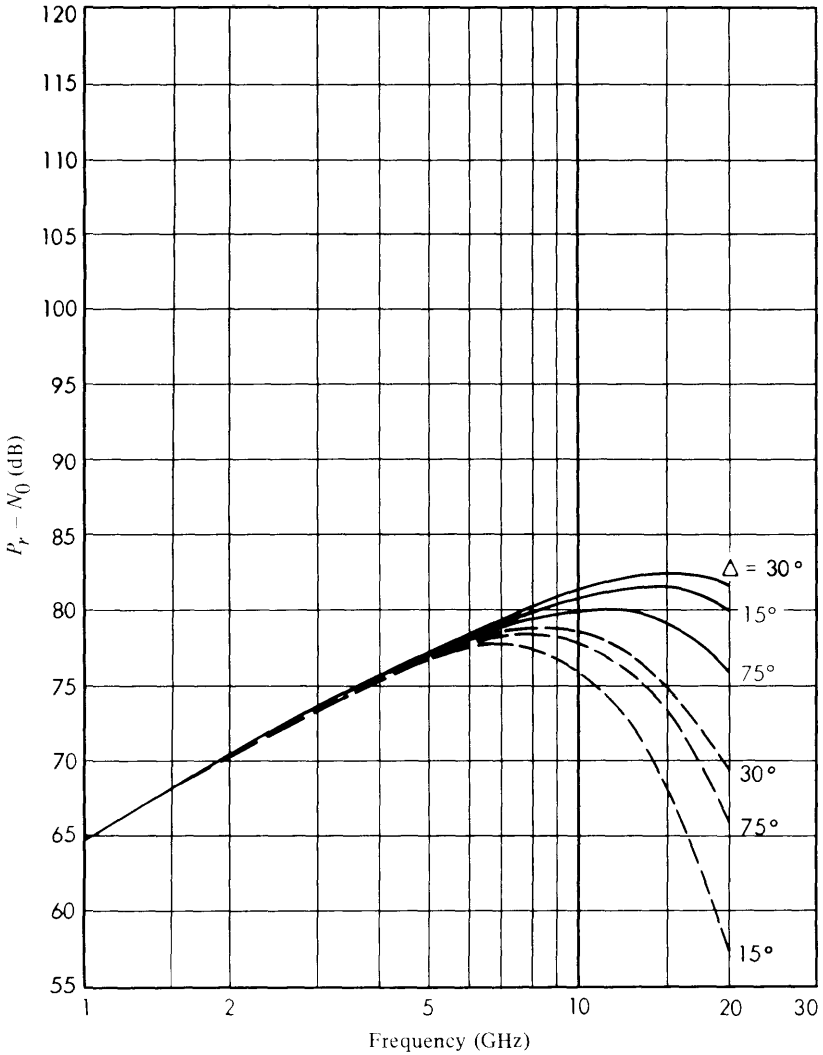
FIGURE 5 – *Space to Earth link performance ($P_r - N_0$)*

Fixed beamwidth station antenna, fixed diameter earth station antenna

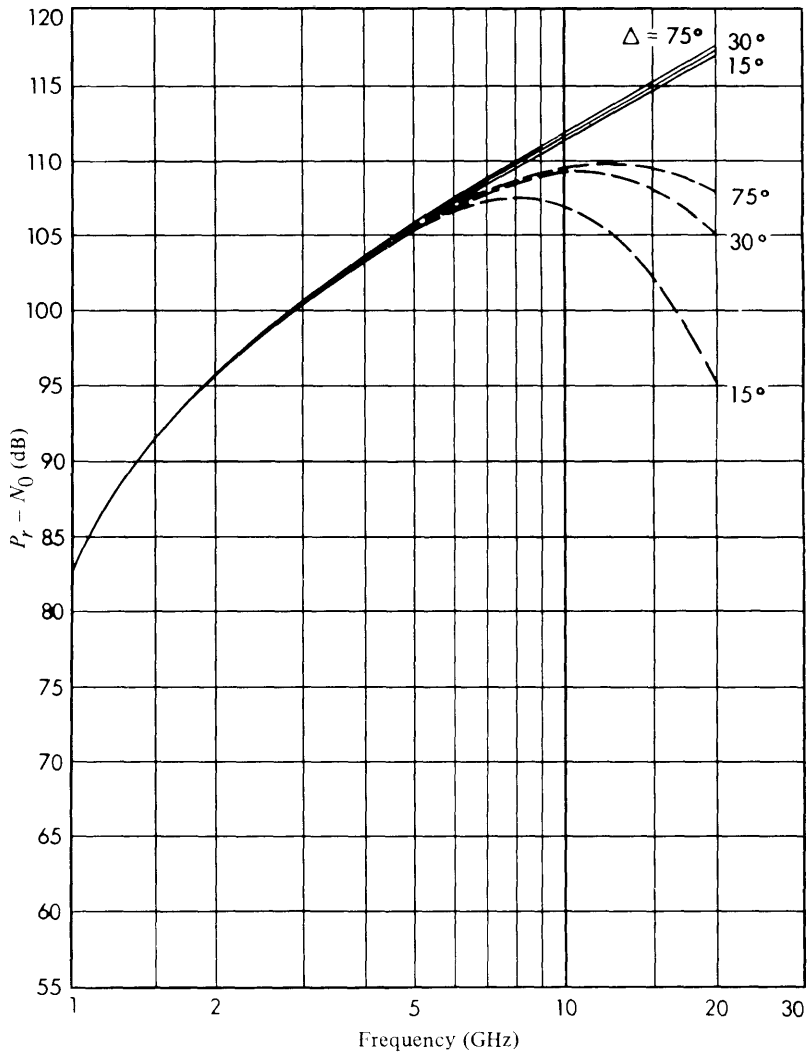
——— clear weather, atmosphere only

– – – – – rain and atmosphere

Parameter Δ: elevation angle of earth station antenna



(a) 1977 implementation



(b) Future limits from natural phenomena only

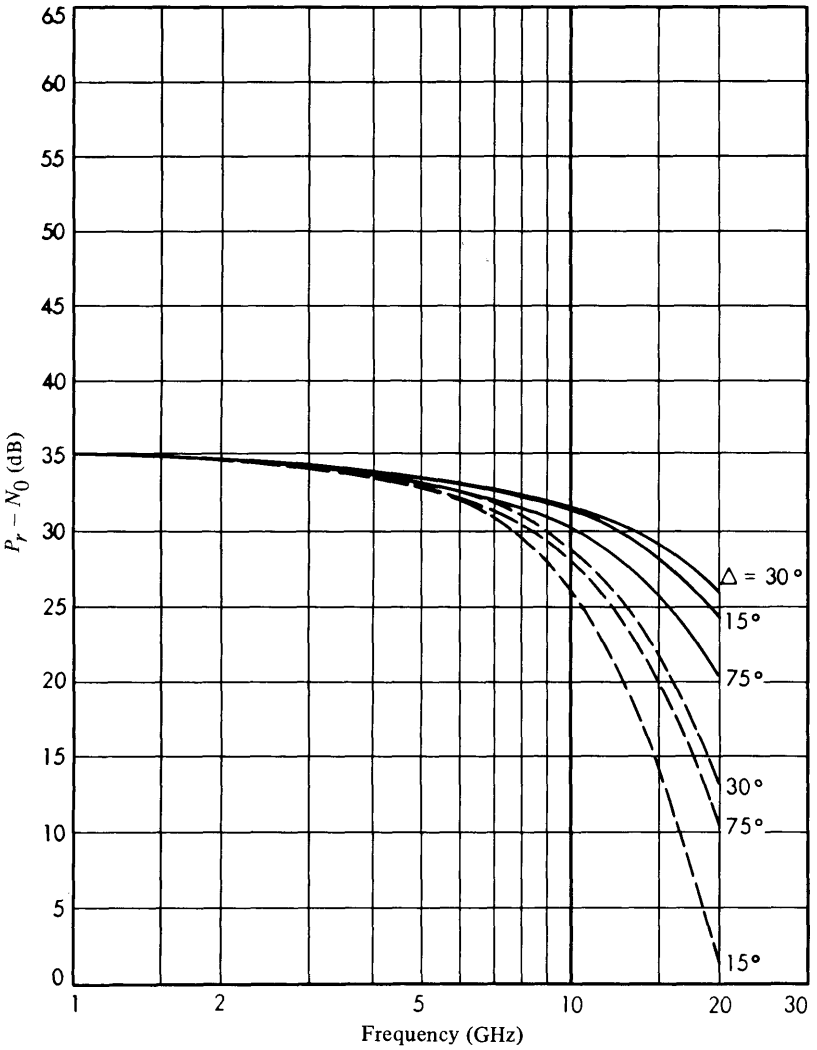
FIGURE 6 – *Earth-to-space link performance ($P_r - N_0$)*

Two fixed diameter antenna

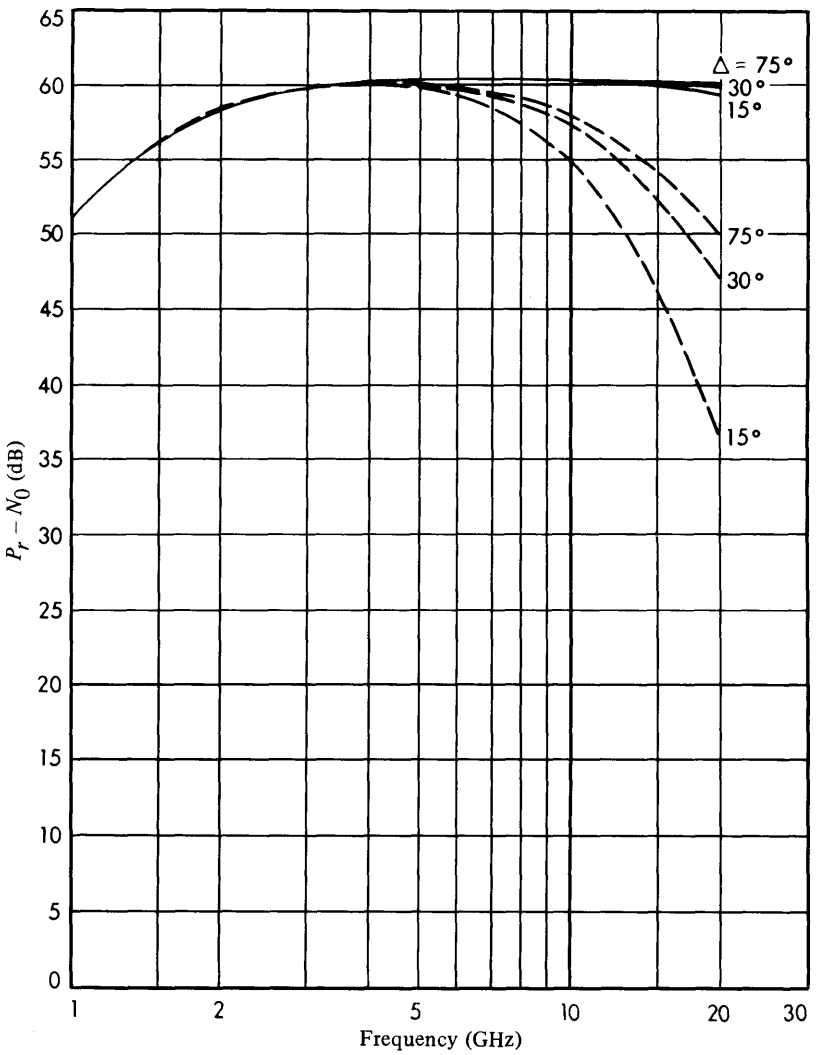
——— clear weather, atmosphere only

– – – – rain and atmosphere

Parameter Δ : elevation angle of earth station antenna



(a) 1977 implementation



(b) Future limits from 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

RECOMMENDATION 365-3 *

FREQUENCIES, BANDWIDTHS AND PROTECTION CRITERIA FOR MANNED AND UNMANNED DEEP-SPACE RESEARCH

(Question 1-1/2)

(1963 - 1966 - 1974 - 1978)

The CCIR,

CONSIDERING

(a) that suitable operating frequencies, required radio-frequency bandwidths, and limiting interference criteria for deep-space manned and unmanned research telecommunication links are determined by the technical considerations set forth in Reports 536-1, 683 and 685.

(b) that cosmic noise and man-made noise militate against the use of frequencies lower than 100 MHz and that atmospheric noise and absorption allow the use of only particular frequency bands at frequencies much higher than 10 GHz;

(c) that some high precision tracking techniques required for guidance of spacecraft to the Moon and the planets and for manoeuvres in their vicinity result in a preference for several widely separated frequencies above 1 GHz;

(d) that two-way communication is required for all deep-space missions, and is vital for manned deep-space missions;

(e) that manned deep-space missions require in particular two-way voice and also television as aids to command and control, guidance navigation and other telecommunication functions;

(f) that for most deep-space missions the typical operating noise temperature of earth station receivers, operating at frequencies in the 2 GHz region will be 16 K, equivalent to -217 dB(W/Hz), in the 8 GHz region will be 23 K, equivalent to -215 dB(W/Hz), and in the 15 GHz region will be 33 K, equivalent to -213 dB(W/Hz), with design margins of less than 6 dB; 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;

(g) that the typical operating input noise temperature of a receiver in a deep-space station operating at frequencies in the 2 GHz region will be 600 K, equivalent to -201 dB(W/Hz), in the 7 GHz region will be 800 K, equivalent to -200 dB(W/Hz), and in the 15 GHz region will be 1100 K, equivalent to -198 dB(W/Hz), with design margins of less than 6 dB; and that for reception at frequencies less than 300 MHz, cosmic noise increases the system noise temperature approximately as the inverse of the square of the frequency;

(h) that, at frequencies higher than 4 GHz, water vapour in the atmosphere can produce significant degradation in the quality of deep-space communications;

(j) that typical deep-space systems will use directional antennae both on the Earth and on the spacecraft. These antennae will have a surface precision of between 0.24 mm and 5 mm r.m.s., regardless of diameter, so that frequencies between 1 and 20 GHz will generally be more suitable for efficient transmission;

(k) that Doppler shifts can be of the order of 1×10^{-4} of the carrier frequency;

(l) that interruptions in communications which aggregate to more than five minutes on any one day without prior planning, could seriously affect the success of the mission;

(m) that real-time television from the lunar surface is practical with frame rates, resolutions, and qualities comparable to terrestrial television, and that photographic facsimile from the nearer planets is similarly practical;

(n) that it is practical and desirable to effect telemetering, data transmission, and tracking functions on the same space-to-Earth link, and telecommand and tracking functions on the same Earth-to-space link;

(o) that to effect precision tracking, a pair of coherently-related Earth-to-space and space-to-Earth frequencies with a separation of at least 7% of the higher frequency in any one band (e.g. pairs near 2 GHz, 8 GHz and the region of 15 GHz) is required, and that for more accurate correction for effects of charged particles on space propagation delays, simultaneous use of space-Earth links with coherent frequencies in two or more of these bands is required;

(p) that to enable precision tracking corrections and to allow both low-rate weather-immune emergency communications, and high-rate primary communications, both Earth-to-space and space-to-Earth communications are desirable on two or more widely separated frequency bands (e.g. 2 GHz, 8 GHz and near 15 GHz);

(q) that the angular spacings of the Moon and the planets are often such that the same frequency may be used for probes at different celestial coordinates, but that different spacecraft in the vicinity of the same coordinates or in the antenna beamwidth may require different frequencies;

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* This Recommendation is brought to the attention of Study Groups 1, 4, 7, 8, 9, 10 and 11.

(r) that geographical separations which permit sharing between terrestrial services and deep-space research operations are typically several hundreds of kilometres, and may be greater than 500 km in the absence of terrain shielding; that separations of this magnitude are not readily obtainable in many parts of the world; and that the spacecraft are visible over large areas of the Earth;

(s) that considerable difficulties can be expected when sharing frequencies between deep-space research operations and other services, due to the technical problems of furnishing the required protection against both terrestrial and near-Earth satellite transmissions,

UNANIMOUSLY RECOMMENDS

1. that frequencies for deep-space manned and unmanned telecommunication links be located in the frequency band between 100 MHz and 30 GHz, with additional links for use during near-Earth and recovery phases of manned space-flights in the frequency bands below 25 MHz, in accordance with the following guidelines:

1.1 frequencies in the HF range below 25 MHz are technically suitable for two-way voice and other communications during manned mission near-Earth and recovery phases;

1.2 the band between 100 MHz and 1 GHz is generally more suitable for narrow-band telemetering, tracking, telecommand and voice from launch to intermediate distances;

1.3 the band between 1 GHz and 6 GHz is generally more suitable for wideband telemetering, precision tracking, telecommand, voice and television from launch to extreme distances;

1.4 the band above 6 GHz is generally more suitable for very wideband telemetering, very precise tracking and television at various distances;

1.5 that special consideration should be given to the availability of coherently related frequencies, spaced at 7% or more of the higher frequency in the bands above 1 GHz, and to the availability of frequencies in three bands, widely separated in frequency, such as the 2 GHz, 8 GHz and 15 GHz regions for precision tracking systems;

2. that spectrum space of the order of 2 to 4 MHz per link (due account being taken of the dependency of the radio-frequency bandwidth on the type of modulation used) is technically suitable for the transmission of wideband information for lunar flights.

3. that spectrum space of the order of 2 to 6 MHz per link is technically suitable for the transmission of wideband signals for precision two-way ranging;

4. that bandwidths of the order of 40 to 400 MHz per link are technically suitable for the transmission of very wideband signals for very precise two-way tracking;

5. that tracking be time-multiplexed with lunar television or planetary facsimile where practicable;

6. that where practicable, frequencies be shared among deep-space probes with different launch periods and different celestial coordinates, but not generally with spacecraft with the same celestial coordinates;

7. that the protection criteria for earth stations be established as follows: the total time during which the power spectral density of noise-like interference, or the total power of CW-type interference in any single band and all sets of bands 1 Hz wide, is greater than -222 dB(W/Hz) in the 2 GHz region, -220 dB(W/Hz) in the 8 GHz region, and -218 dB(W/Hz) in the 15 GHz region, at the input terminals of the receiver, shall not exceed an aggregate of five minutes on any one day without prior planning; for frequencies below 1 GHz, the permissible interference power level may be increased at the rate of 20 dB per decreasing frequency decade;

8. that the protection criteria for space stations be established as follows: the total time during which the power spectral density of noise-like interference or the total power of CW-type interference in any single band and all sets of bands 1 kHz wide, is greater than -171 dB(W/kHz) in the 2 GHz region, -170 dB(W/kHz) in the 7 GHz region and -168 dB(W/kHz) in the 15 GHz region, at the input terminals of the receiver, shall not exceed an aggregate of five minutes of any one day; for frequencies less than 300 MHz, the permissible interference may be increased at the rate of 20 dB per decreasing frequency decade;

9. that, when necessary for emergency purposes, manned deep-space flights use the recognized distress frequencies in accordance with the Radio Regulations;

10. that a deep-space research service cannot share Earth-to-space bands with:

10.1 receiving aeronautical mobile stations,

10.2 receiving satellite stations, and

10.3 transmitting terrestrial stations and earth stations utilizing high average e.i.r.p.; for example, transmitting trans-horizon stations, and transmitting fixed satellite earth stations.

When coordination is practicable, sharing is feasible with other stations of all services. In some cases, coordination distances may be unacceptably great;

11. that a deep-space research service cannot share space-to-Earth bands with:

11.1 transmitting aeronautical mobile stations, and

11.2 transmitting satellite stations.

When coordination is practicable, sharing is feasible with other stations of all services. In some cases, coordination distances may be unacceptably great.

RECOMMENDATION 364-3 *

TELECOMMUNICATION LINKS FOR MANNED AND UNMANNED NEAR-EARTH RESEARCH SATELLITES

Frequencies, bandwidths and criteria for protection from interference

(Questions 18/2 and 22/2)

(1963 - 1966 - 1970 - 1978)

The CCIR,

CONSIDERING

(a) that suitable operating frequencies, required radio-frequency bandwidths, and limiting interference criteria for near-Earth satellite telecommunication links are determined by the technical considerations set forth in the appropriate Reports;

(b) that, based on past experience, it is expected that of the order of 100 active research near-Earth satellites may be in orbit simultaneously;

(c) that two-way communication is required for many near-Earth missions, and is vital for manned missions;

(d) that various radio-frequency bands are suitable for near-Earth satellite telecommunication links, and that the variety of functions and the conditions under which they must be performed divide this region into the following suitable regions: below 1 GHz, 1 to 6 GHz, 6 to 10 GHz, and 10 to 30 GHz;

(e) that telemetering data links typically require radio-frequency bandwidths ranging from 10 kHz to 20 MHz per link in the frequency range from 100 MHz to 30 GHz, with a bandwidth of 10 kHz in the lower portion, and up to 20 MHz in the upper portion;

(f) that tracking links typically require radio-frequency bandwidths ranging from 10 kHz to 100 MHz per link in the frequency range from 100 MHz to 15 GHz with bandwidths of 10 kHz in the lower portion and up to 100 MHz in the upper portion of this range, the latter being required for high precision two-way, coherent, range and range rate systems;

(g) that voice links typically require radio-frequency bandwidths ranging from 3 kHz to 45 kHz per link;

(h) that wideband data and television links typically require radio-frequency bandwidths within the range 50 kHz to 300 MHz in the frequency range from 100 MHz to 30 GHz, with preference for 50 kHz in the lower portion and 300 MHz in the upper portion of this range;

(j) that the operating noise temperatures of earth-station telemetering and tracking receiving systems usually range from 30 K above 1 GHz to 3000 K at 100 MHz (equivalent to -214 dB(W/Hz) and -194 dB(W/Hz));

(k) that earth-station antennae for satellite communication do not operate at elevation angles less than 5°, except for initial acquisition;

(l) that typical operating noise temperatures for receivers in near-Earth research 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;

(m) that telecommand requirements can normally be satisfied by one data link channel per craft with radio-frequency bandwidths ranging from 10 kHz at 100 MHz to 500 kHz at 15 GHz, largely determined by the Doppler shift which may be of the order of 1×10^{-4} of the carrier frequency;

(n) that coding techniques and the future use of narrow-beam antennae may make possible the control of several crafts using the same radio-frequency telecommand channel;

(o) that circuit design in spacecraft for high precision coherent tracking systems dictate that two frequencies be used, spaced by at least 6% of the higher one;

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* This Recommendation is brought to the attention of Study Groups 1, 4, 7, 8, 9, 10 and 11.

(p) that, for some frequency sharing situations between near-Earth research satellites and certain representative terrestrial services, separations of several hundreds of kilometres between the earth terminals may be required and that, in many parts of the world, separations of this magnitude are not readily attainable;

(q) that frequency sharing among near-Earth research satellites is desirable and feasible;

(r) that difficulties can be expected when frequencies are shared between near-Earth research satellites and stations in other Services, due to the technical problems of furnishing the required protection against terrestrial Services,

UNANIMOUSLY RECOMMENDS

1. that the range below 1 GHz is technically suitable for near-Earth research satellites, with each satellite using radio-frequency bandwidths varying from 10 to 500 kHz per link, for accomplishing telemetering, wideband data transmission, tracking, telecommand and voice functions;

2. that the range between 1 GHz and 6 GHz is technically suitable for near-Earth research satellites, with each satellite using radio-frequency bandwidths varying from 500 kHz to 4 MHz per link, for accomplishing telemetering, wideband data transmission, tracking, telecommand, voice and television functions;

3. that the range between 6 and 10 GHz is technically suitable for near-Earth research satellites, with each satellite using radio frequency bandwidths varying from 500 kHz to 20 MHz per link, for accomplishing telemetering, wideband data transmission, tracking, telecommand, voice and television functions;

4. that the range between 10 GHz and 30 GHz is technically suitable for near-Earth research satellites, with each satellite using radio frequency bandwidths ranging from 1 MHz to 300 MHz per link, for accomplishing telemetering, wideband data transmission and television functions;

5. that high frequencies below about 25 MHz are technically suitable for two-way voice communication during manned-mission near-Earth and recovery phases;

6. that, when necessary, for emergency purposes in manned near-Earth missions, the recognized distress frequencies be used in accordance with the Radio Regulations;

7. that consideration be given to the availability of coherently related frequencies spaced by more than 6% of the higher frequency for precision tracking systems;

8. that frequency sharing be accomplished to the maximum extent feasible among near-Earth research satellites;

9. that the protection criterion for earth receiving stations be established as follows: for frequencies greater than 1 GHz and up to at least 10 GHz, the total time for which the power spectral density of noise-like interference or the total power of CW-type interference in any single band and all sets of bands 1 Hz wide is greater than -220 dB(W/Hz) at the input terminals of the receiver, shall not exceed 5 minutes per day, for manned research missions (0.1% of the time being permissible for other near-Earth research missions); for frequencies less than 1 GHz, the permissible interference may be increased at the rate of 20 dB per decreasing frequency decade;

10. that the protection criterion for receivers in spacecraft be established as follows: for frequencies greater than 300 MHz and up to at least 10 GHz, the total time during which the power spectral-density of noise-like interference or the total power of CW-type interference in any single band or all sets of bands 1 kHz wide is greater than -171 dB(W/kHz) at the input terminals of the receiver, shall not exceed 5 minutes per day for manned research missions (-161 dB(W/kHz) during a maximum of 0.1% of the time being permissible for other near-Earth research missions); for frequencies less than 300 MHz, the permissible interference may be increased at the rate of 20 dB per decreasing frequency decade;

11. that note be taken of the difficulties to be expected in frequency sharing between near-Earth research satellites and stations in other services.

REPORT 684 *

PRELIMINARY ANALYSIS OF LOW-ORBIT SATELLITE VISIBILITY STATISTICS

(Question 1-1/2)

(1978)

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 low-inclined orbit space research spacecraft to terrestrial services and to the terrestrial segments of space services.

* This Report is brought to the attention of Study Groups 1, 8 and 9.

1.2 *Background*

The present ITU power flux-density constraints (e.g. Article 7, Section VIII 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). The increasing use of circular low-inclined orbit space stations 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 Annex III);
- 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 ** 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.

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.

1.3 *Purpose of Report*

The principal purpose of this Report is to demonstrate some of the relations between the various low-orbit/ground station parameters developed via computer simulation, and to describe the results of a simplified approach to bounding the percentage of time that a ground station may "see" a space station which is in a low-altitude inclined orbit. A brief description of the computer simulation utilised is included in Annex I and the derivation of the bounding equation is included in Annex II.

1.4 *Subsequent Reports*

Subsequent Reports should deal with at least these additional topics which contribute to practical sharing analyses:

- bounding model for long-term low-orbit visibility statistics;
- dynamic I/N models for low-orbit space/ground systems.

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* For the sake of generality the expressions "ground communication system", "ground antenna", "ground station" and so on, refer to systems, antennae, and stations located on the surface of the Earth, regardless of whether they are functioning in a terrestrial or a space service.

** This Report only deals with satellite orbits in which the orbital period is not an even multiple of the Earth's rotational period.

2. Computer modelling

2.1 *Models for maximum satellite visibility*

A space station circling the Earth will, during each orbit, cross every latitude line on the Earth's surface up to a maximum latitude determined by its inclination. This implies that a space station in a true polar (90° inclined) orbit will cross both the north and south pole during each orbit. A ground antenna pointed at the north or south pole of the space station's orbital sphere will therefore see the spacecraft once each orbit. There is no other orientation of the ground antenna for which this situation will occur.

2.2 *Computer simulation*

The computer simulation detailed in Annex I was carried out for various orbital altitudes while maintaining the latitude of the ground station so that the north polar point of the orbital sphere appeared at an elevation angle of 5° from the ground station. Fig. 1 shows the normalised variation of the percentage of time that the spacecraft appeared as a function of azimuth around the ground station for altitudes ranging from 500 to 5000 km. Fig. 2 indicates the normalised percentage of time that the space station appears around the ground station as a function of the latitude of the station, for a space station in a 1000 km, 90° inclined orbit. It should be noted that both of these figures are normalised to the percentage of time that a space station is visible in a 10° azimuth by a 10° elevation region centered about an azimuth of 0° and elevation of 5° for a ground station located at 64.4° N latitude and a spacecraft in a 1000 km, 90° inclined orbit.

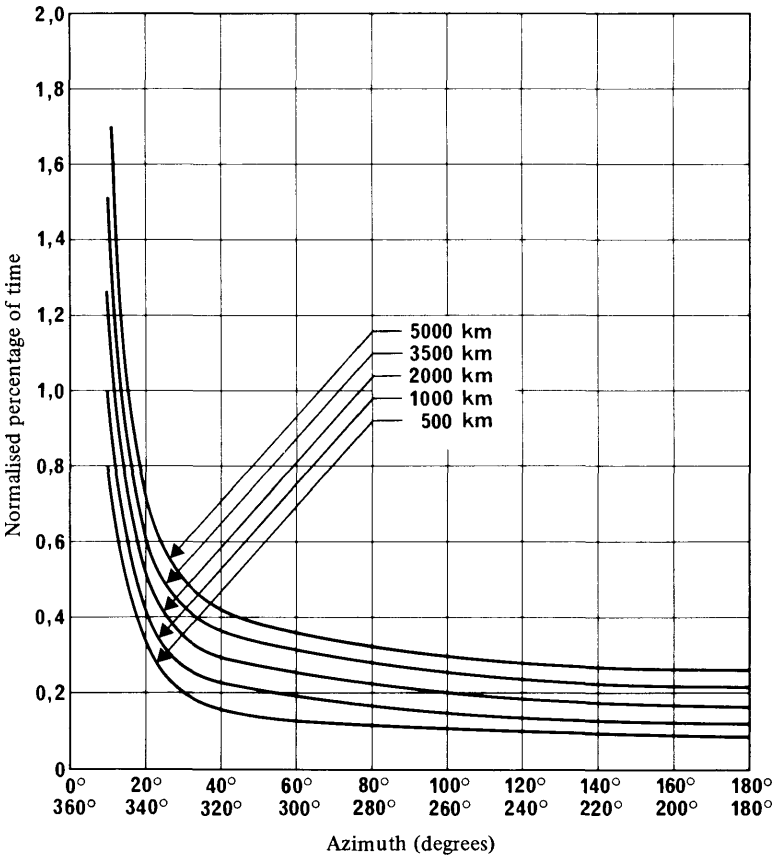


FIGURE 1 – *Comparison of altitude dependence of spacecraft visibility statistics*

(parameter: spacecraft altitude)

In general, the computer simulation used to obtain these results required the simulated flight of a space station in a specific orbit over a specific ground point for several hundred orbits, or at least long enough so that the proportion of time that the space station appeared in a given region of space as seen from the ground station, did not vary appreciably with the addition of several more simulated orbits. This method of attempting to solve the multidimensional dynamic problem is both complex, time-consuming and expensive. It is, however, possible to develop a simplified approach to bounding the proportion of time that a space station will appear in, say, the main beam region of a ground station.

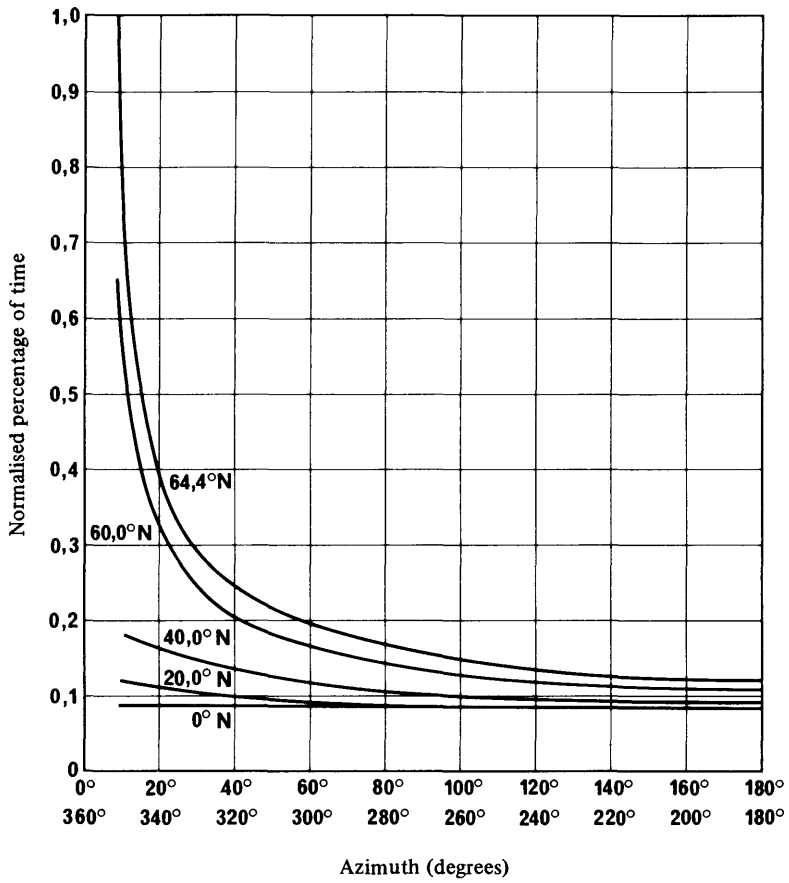


FIGURE 2 – *Comparison of latitude dependence of satellite visibility statistics (orbit: altitude 1000 km, inclination 90°)*

(parameter: latitude)

3. Bounding equation

The bounding equation, derived in Annex II, 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 $L + \Delta L$, and

i is the inclination of the satellite orbit.

(all angles in radians).

The example model outlined in Annex II describes the calculation of the maximum and minimum percentages of time that a spacecraft will appear as a function of:

- inclination;
- altitude;
- ground station latitude angle;
- ground station elevation;
- ground station viewing regions as a function of azimuth and elevation.

Fig. 3 shows these results for one particular spacecraft orbit and compares numerical results obtained from both the computer simulations and the simplified bounding equation for the identical model.

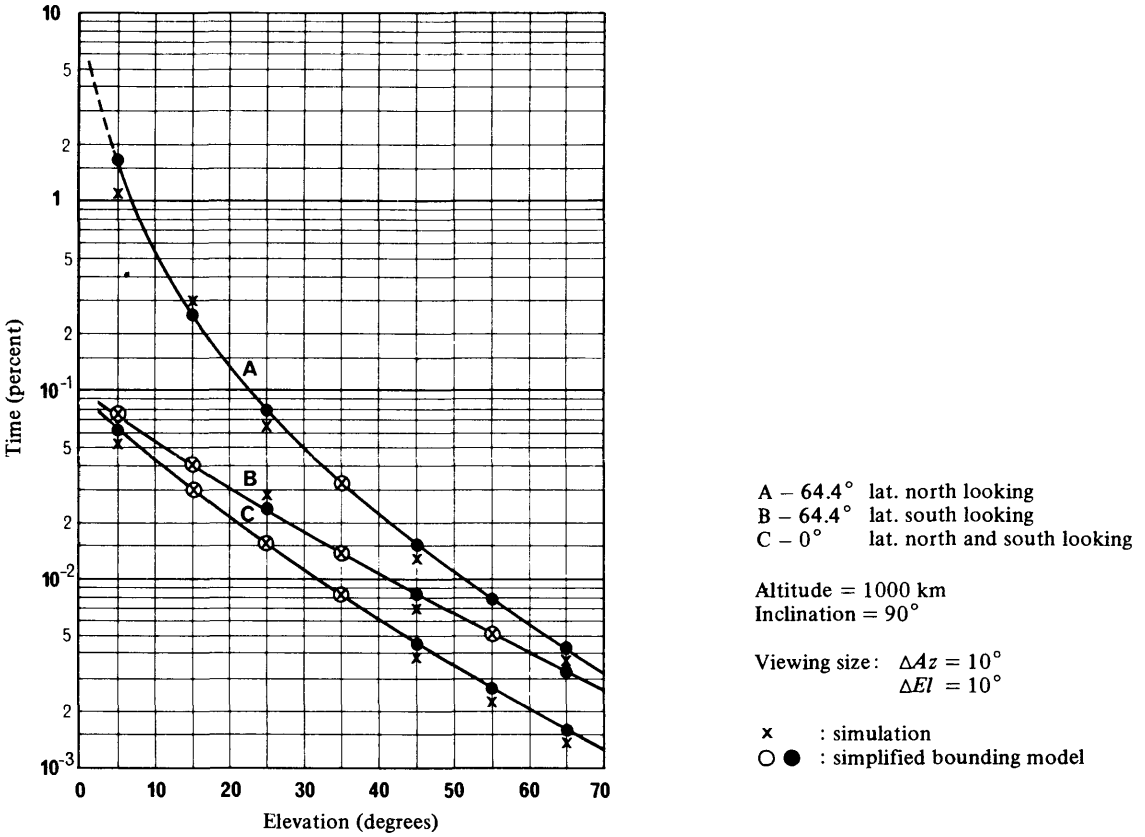


FIGURE 3 – *Comparison of the results of the computer simulation and the simplified model for one specific spacecraft orbit*

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, Annex III presents information on the maximum time that a low-orbit spacecraft can spend in the mainbeam 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.

ANNEX I

COMPUTER SIMULATION OF LONG-TERM SATELLITE VISIBILITY STATISTICS

1. Simulation model

Basically the computer simulation requires the simulated flight of a space station in a circular orbit, and accumulates the number of seconds spent by the space station within an azimuth-elevation grid system surrounding a location on the Earth's surface. Once sufficient orbits have been simulated the cumulative time in each of the 10° × 10° azimuth-elevation regions, is divided by the total time of flight of the spacecraft and converted into a percentage. The result for a space station in a 1000 km, 90° inclined orbit over a ground location of 64.4° N latitude is shown in Table I. Approximately 550 orbits were required to stabilise the statistics represented in Table I, and it is still evident that in order to refine these statistics to several more decimal places many more orbits would be required. (For example, the visibility statistics of the spacecraft should show east/west symmetry. However, they do not do so beyond the second significant place.)

The rows and columns of Table I represent 10° × 10° angular areas. For example the Table entry in row 13, column 4 represents the long-term percentage of time (i.e. 0.01765) that the spacecraft would be visible to the ground station in the angular area defined by 120° to 130° azimuth and 30° to 40° elevation.

TABLE I – *Typical computer simulation output for a spacecraft in a 1000 km, 90° inclined orbit and a ground station located at 64.4° N latitude*

Percentage of time in 10° X 10° angular areas										
		Elevation steps								
		1	2	3	4	5	6	7	8	9
Azimuth steps	1	1.07124	0.27395	0.07434	0.03069	0.01223	0.00364	0.00081	0.00000	0.00000
	2	0.25541	0.20424	0.07570	0.02419	0.01754	0.01077	0.00487	0.00072	0.00000
	3	0.10202	0.14888	0.06177	0.03138	0.00883	0.00938	0.00579	0.00225	0.00001
	4	0.09002	0.12390	0.05356	0.02598	0.01640	0.00399	0.00559	0.00271	0.00018
	5	0.10552	0.10571	0.04246	0.02517	0.01587	0.00445	0.00465	0.00280	0.00034
	6	0.13052	0.07496	0.03481	0.02679	0.00948	0.00517	0.00310	0.00283	0.00046
	7	0.12369	0.08454	0.04280	0.01775	0.00621	0.00630	0.00213	0.00278	0.00053
	8	0.10862	0.07253	0.03204	0.01829	0.00347	0.00727	0.00160	0.00279	0.00057
	9	0.09831	0.05698	0.03353	0.02647	0.01458	0.01458	0.00141	0.00282	0.00057
	10	0.09375	0.05745	0.02945	0.02157	0.00842	0.00772	0.00163	0.00276	0.00057
	11	0.08960	0.05429	0.02376	0.01554	0.01174	0.00607	0.00221	0.00273	0.00049
	12	0.07657	0.04928	0.03604	0.00988	0.01375	0.00367	0.00325	0.00253	0.00056
	13	0.08068	0.04702	0.02461	0.01765	0.01228	0.00105	0.00452	0.00260	0.00038
	14	0.07313	0.05064	0.02337	0.02152	0.00460	0.00424	0.00451	0.00253	0.00026
	15	0.06961	0.04740	0.03441	0.00356	0.00442	0.00779	0.00455	0.00238	0.00007
	16	0.08493	0.04282	0.01315	0.01235	0.01209	0.00754	0.00463	0.00163	0.00000
	17	0.05905	0.04424	0.03385	0.01995	0.01232	0.00712	0.00288	0.00009	0.00000
	18	0.07246	0.04166	0.01889	0.00815	0.00312	0.00032	0.00000	0.00000	0.00000
	19	0.07392	0.05081	0.02706	0.01388	0.00747	0.00362	0.00126	0.00000	0.00000
	20	0.05461	0.03738	0.03169	0.01989	0.01240	0.00732	0.00422	0.00145	0.00005
	21	0.08438	0.04943	0.01416	0.00805	0.01138	0.00751	0.00464	0.00206	0.00033
	22	0.06990	0.03971	0.03515	0.01292	0.00192	0.00706	0.00455	0.00239	0.00044
	23	0.06747	0.05428	0.01806	0.02162	0.00745	0.00210	0.00453	0.00253	0.00049
	24	0.03455	0.04243	0.02836	0.01333	0.01301	0.00205	0.00358	0.00257	0.00060
	25	0.07538	0.05430	0.03242	0.00915	0.01348	0.00514	0.00220	0.00256	0.00067
	26	0.08737	0.05268	0.02347	0.01811	0.00890	0.00731	0.00136	0.00270	0.00065
	27	0.08846	0.05787	0.03074	0.02286	0.00621	0.00829	0.00141	0.00272	0.00171
	28	0.10053	0.05452	0.03486	0.02281	0.01391	0.01422	0.00131	0.00285	0.00197
	29	0.10617	0.07322	0.03428	0.01508	0.00336	0.00743	0.00159	0.00281	0.00073
	30	0.12627	0.07783	0.04635	0.01663	0.00635	0.00689	0.00184	0.00275	0.00078
	31	0.13113	0.07318	0.03724	0.02464	0.00802	0.00634	0.00220	0.00284	0.00075
	32	0.10693	0.10681	0.04577	0.02442	0.01337	0.00586	0.00370	0.00280	0.00072
	33	0.09232	0.12258	0.05180	0.02554	0.01686	0.00391	0.00515	0.00284	0.00063
	34	0.10371	0.14837	0.06234	0.02873	0.01069	0.00764	0.00583	0.00285	0.00041
	35	0.25310	0.20131	0.07202	0.02550	0.01522	0.01088	0.00599	0.00214	0.00021
	36	1.07124	0.26905	0.07724	0.03477	0.01673	0.00701	0.00276	0.00064	0.00000

ANNEX II

SIMPLIFIED MODEL OF LONG-TERM SATELLITE VISIBILITY STATISTICS

1. General relationships

This model is based upon a single assumption that at any given latitude over a long length of time, a random * low-orbit spacecraft has equal probability of appearing at any longitude. This assumption implies that over a specific latitude region, say from L_1 to L_2, (see Fig. 4), the proportion of time spent by the satellite between two longitude bounds (λ_1 and λ_2) will be equal to the ratio of the angular area (A) bounded by L_1 L_2, λ_1 and λ_2 and the total angular area (A_T) of the latitude band between L_1 and L_2.

* This does not apply to orbits that are synchronous or subsynchronous with the Earth's rotation.

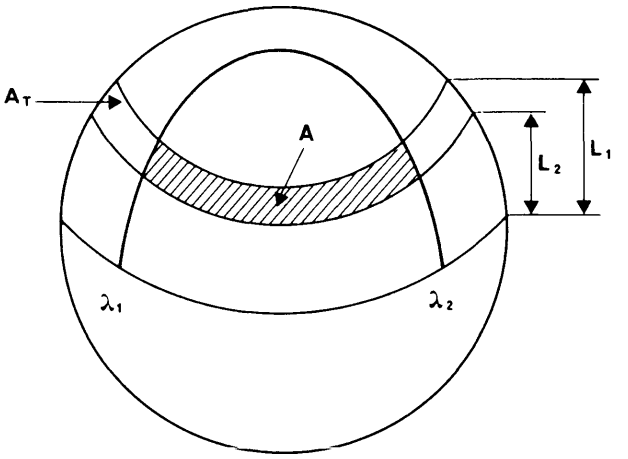


FIGURE 4

In terms of equations:

$$A = (\lambda_1 - \lambda_2)(\sin L_1 - \sin L_2) \tag{2}$$

$$A_T = 2\pi (\sin L_1 - \sin L_2) \tag{3}$$

and the portion of time the satellite spends within the latitude band that it also spends within A, is:

$$A_\lambda = \frac{A}{A_T} = \frac{\lambda_1 - \lambda_2}{2\pi} = \frac{\delta\lambda}{2\pi} \tag{4}$$

where, $\delta\lambda = \lambda_1 - \lambda_2$

Any model which attempts to deal with visibility statistics of low-orbit spacecraft must take into account the fact that the length of time an inclined spacecraft spends within a latitude band is a function of the specific latitudes chosen. For example, a spacecraft in a 60° inclined orbit will transverse the one degree latitude band from 0° to 1° latitude more rapidly than the one degree wide latitude band from 59° to 60°. From elementary orbital mechanics the function that relates the time it takes a satellite to transverse the latitude band delimited by L_1 and L_2 is:

$$\delta t = \frac{\tau}{2\pi} \left\{ \sin^{-1}\left(\frac{\sin L_1}{\sin i}\right) - \sin^{-1}\left(\frac{\sin L_2}{\sin i}\right) \right\} \tag{5}$$

where,

i is the satellite inclination, and

τ is its period.

2. Visibility model

Using the method described above it is possible to construct a general model for the long-term visibility statistics of low-orbit inclined spacecraft and with the addition of some geometrical relations to develop calculations which may be used to check the validity of the computer simulations discussed elsewhere.

The general simplified model involves determining the approximate latitude and longitude bounds of the region of the orbital sphere visible to the ground station. The portion of the latitude ring contained within the longitude is then determined and multiplied by a weighting function dependent upon the relative time the satellite spends within the latitude bounds.

2.1 *Weighting function*

The weighting function mentioned above is based upon equation (5) and can be determined by noting that the sum of all of the latitude dependent weighting functions (W_n) over all possible latitude increments must be set equal to 1, or by using equation (5).

$$\sum_{L=-i}^{i-\Delta L} W_n = \sum \frac{K\tau}{2\pi} \left\{ \sin^{-1}\left(\frac{\sin (L + \Delta L)}{\sin i}\right) - \sin^{-1}\left(\frac{\sin L}{\sin i}\right) \right\} = 1 \tag{6}$$

where, $\Delta L = L_2 - L_1$,

and K = constant of proportionality.

For this particular function the sum of the incremental values (i.e., $L + \Delta L$ as L takes on values from $-i$ to $i - \Delta L$) is equal to:

$$\frac{K\tau}{2\pi}\left\{\sin^{-1}\left(\frac{\sin\ i}{\sin\ i}\right) - \sin^{-1}\left(\frac{\sin\ -i}{\sin\ i}\right)\right\} \tag{7}$$

$$= \frac{K\tau}{2\pi}\left\{\frac{\pi}{2} - \left(-\frac{\pi}{2}\right)\right\}$$

$$= \frac{K\tau}{2}$$

and from equation (6),

$$K = \frac{2}{\tau}$$

or the individual weighting functions can be expressed as:

$$W(L) = \frac{1}{\pi}\left\{\sin^{-1}\left(\frac{\sin\ (L + \Delta L)}{\sin\ i}\right) - \sin^{-1}\left(\frac{\sin\ L}{\sin\ i}\right)\right\} \tag{8}$$

2.2 *Generalised visibility expression*

The generalised expression which may be used to evaluate the percentage of time that a low-orbit inclined satellite will be visible to a ground station is obtained from the product of equations (4) and (8).

$$T = \frac{\delta\lambda}{2\pi^2}\left\{\sin^{-1}\left(\frac{\sin\ (L + \Delta L)}{\sin\ i}\right) - \sin^{-1}\left(\frac{\sin\ L}{\sin\ i}\right)\right\} \tag{9}$$

This equation represents the proportion of a latitude ring visible to the ground station weighted by the relative proportion of time that the satellite had spent within the latitude ring.

3. Example

The following numerical example demonstrates both the validity of the foregoing simplified model of long-term satellite visibility statistics, and in addition, is useful in describing the variations in the expected potential interference signal from low-orbit spacecraft as functions of spacecraft altitude, ground station latitude and ground station antenna pointing azimuth and elevation.

3.1 *Physical model*

The physical model in this example is that of a ground station located at latitude L_A, used in obtaining the approximate long-term visibility statistics of a satellite, from elevations E_{min} to an elevation of E_{max} over an azimuth range of δAz, centred about an azimuth of 0° or 180° from North. The satellite orbital parameters are given by an altitude of H(km) and an inclination of i (degrees).

The only mathematical problem (a minor one), is in obtaining the latitude and longitude bounds on the orbital sphere as a function of ground station latitude, and elevation and δAz (about an azimuth of 0 or 180°) in the ground station co-ordinate system. Referring to Fig. 5, the latitude of the intersection of a vector from the ground station at an elevation angle of El and an orbital sphere of altitude H above the Earth's surface is given by:

$$L = L_A + \gamma \tag{10}$$

where:

$$\gamma = \frac{\pi}{2} - El - \sin^{-1}\left\{\frac{R_e}{R_e + H}\ \cos\ El\right\}$$

(all in radians).

For a region of interest oriented at an azimuth of 180°:

$$L = L_A - \gamma$$

Since the region of interest is assumed to lie along a meridian the orbital sphere longitude range ($\delta\lambda$) represented by an azimuth range δAz can be approximated as follows:

- since azimuth is actually measured in the horizontal plane at the ground station location, the angle between the vectors whose intersection with the orbital sphere represents $\delta\lambda$ is $\delta Az \cdot \cos(El)$;
- the distance S (km) between the longitudinal intersection points of the vectors on the orbital sphere, is a function of the range R between the ground station and the elevation of the vectors, or:

$$S = R\,(\delta Az \cos El) \tag{11}$$

where,

$$R \approx \frac{R_e + H}{\cos El} \sin \gamma$$

or,

$$S \approx (R_e + H)\,\delta Az \sin \gamma$$

- the angle φ at the centre of the Earth corresponding to a distance on the orbital sphere of S (km) is:

$$\varphi = \frac{S}{R_e + H} \approx \delta Az \sin \gamma \tag{12}$$

- the longitude spread ($\delta\lambda$) corresponding to a central angle φ at a latitude of L is given by:

$$\delta\lambda = \varphi \cos L \approx \frac{\delta Az \sin \gamma}{\cos L} \tag{13}$$

Substituting equation (13) into (9), yields the proportion of all time spent by a satellite (altitude H, inclination i) in a region δEl, δAz about an elevation angle of (El) and looking along a meridian; as seen by a ground station located at latitude L_A, or:

$$T \approx \frac{\delta Az \sin \bar{\gamma}}{2\pi^2 \cos \bar{L}} \left\{ \sin^{-1}\left(\frac{\sin (L + \Delta L)}{\sin i}\right) - \sin^{-1}\left(\frac{\sin L}{\sin i}\right) \right\} \tag{14}$$

$$\gamma = 90° - El - \sin^{-1}\left(\frac{R_e}{R_e + H} \cos El\right)$$

$$\gamma' = 90° - (El + \delta El) - \sin^{-1}\left(\frac{R_e}{R_e + H} \cos (El + \delta El)\right)$$

$$\bar{\gamma} = (\gamma + \gamma')/2$$

$$\bar{L} = (2L + \Delta L)/2$$

North pointing:

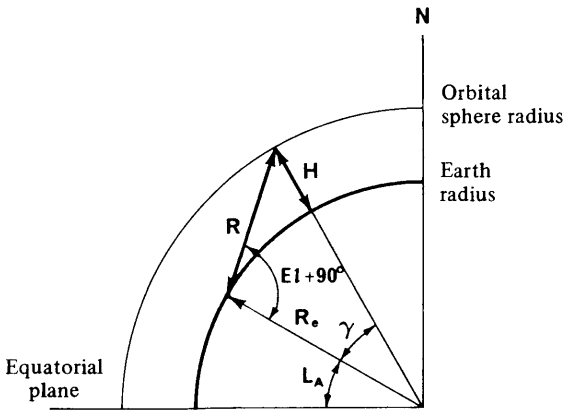
$$L + \Delta L = L_A + \gamma$$

$$L = L_A + \gamma'$$

South pointing:

$$L + \Delta L = L_A - \gamma'$$

$$L = L_A - \gamma$$



El : elevation in ground station coordinate system

R : range from ground station to orbital sphere at elevation *El*

H : orbital altitude

R_e : Earth radius ≈ 6371.217 km

L_A : ground station latitude

γ : central angle between ground station and intersection of vector at elevation *El* and orbital sphere

FIGURE 5

ANNEX III

THE MAXIMUM TIME A SATELLITE SPENDS IN THE BEAM OF A GROUND STATION

1. Introduction

The purpose of this Report is to provide 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 (α), the elevation of the beam (β) and the altitude of the satellite *(H)*. The worst case, i.e. when the satellite spends 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 *(T)* the satellite spends in the beam depends upon the satellite's velocity (V_{sat}) relative to the velocity of the beam (V_{beam}) as it rotates with the Earth, and upon the length of the intersection of the orbit with the beam *(X)*, and may be derived from the simple relation:

$$T = \frac{X}{V} \qquad \begin{cases} X \text{ in km} \\ V \text{ in km/s} \end{cases} \tag{15}$$

where:

$$X = (R_e + H)\left\{\alpha - \sin^{-1}\left[\frac{R_e \cos\left(\beta - \frac{\alpha}{2}\right)}{R_e + H}\right] + \sin^{-1}\left[\frac{R_e \cos\left(\beta + \frac{\alpha}{2}\right)}{R_e + H}\right]\right\} \tag{16}$$

$$V = V_{sat} - V_{beam} = \sqrt{\mu/a} - \frac{2\pi (R_e + H)}{24\ h} \tag{17}$$

(all angles in radians)

and,

$\mu = 390\,000\ \text{km}^3/\text{s}^2$

$a = R_e + H$

α = beamwidth (in radians)

β = elevation of the beam (radians)

R_e = Earth radius 6371.217 km

H = orbital altitude (km)

The maximum time that a spacecraft can spend in the main beam of an antenna is shown in Figs. 6 and 7 for antenna elevations of 0° and 90° respectively, and refers to a variety of orbital altitude and beamwidths.

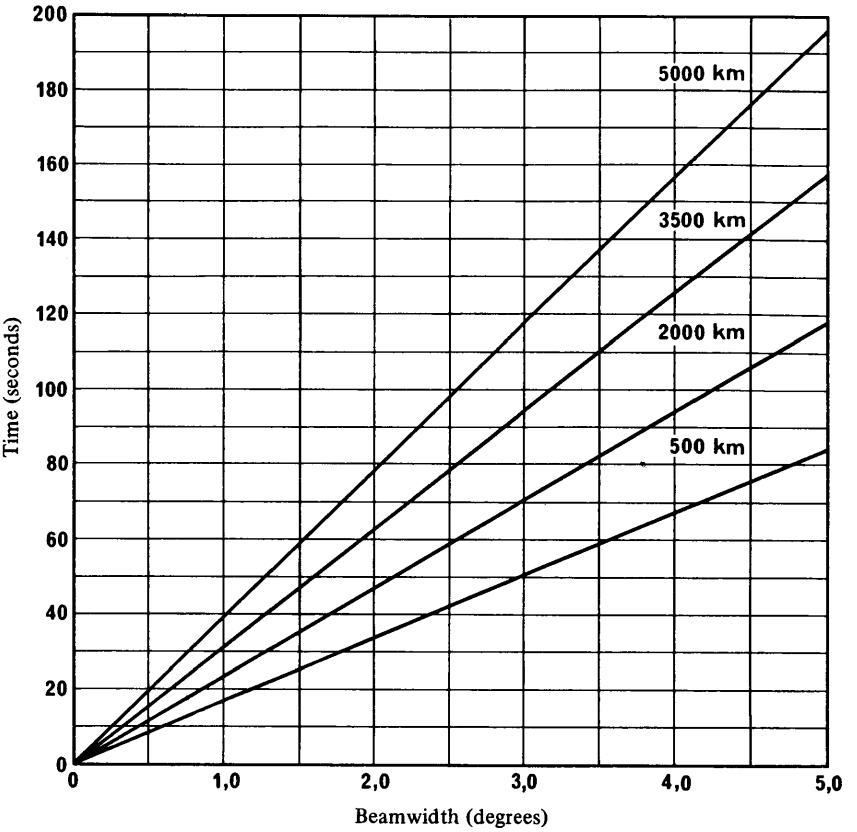


FIGURE 6 – *Maximum time in beam plotted against beamwidth at elevation of 0°*

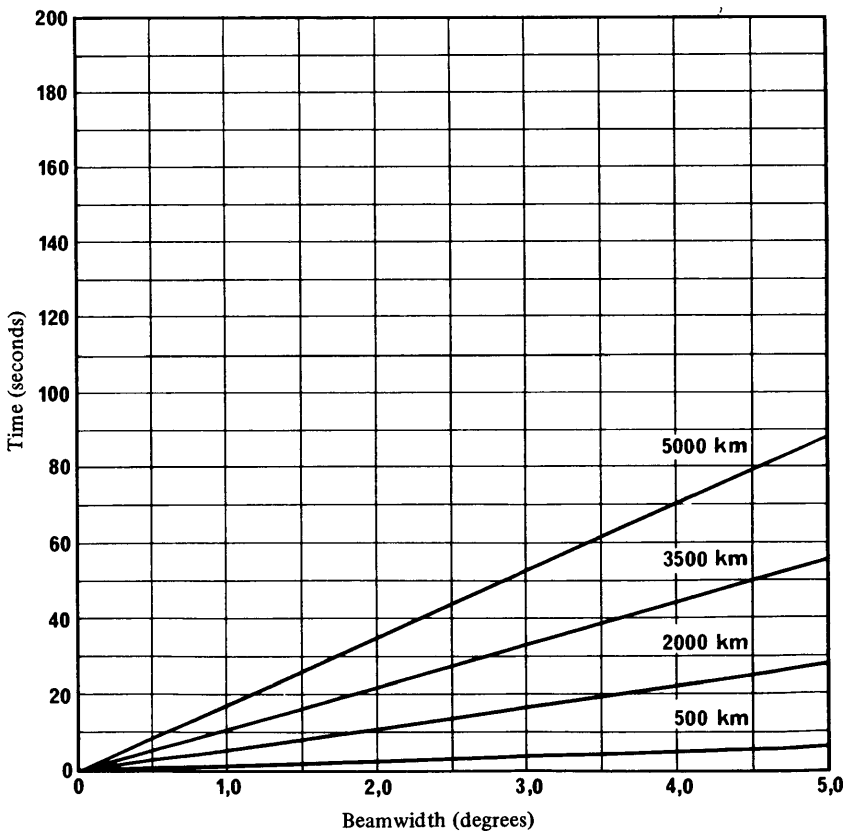


FIGURE 7 – *Maximum time in beam plotted against beamwidth at elevation of 90°*

REPORT 685

PROTECTION CRITERIA AND SHARING CONSIDERATIONS RELATING TO DEEP-SPACE RESEARCH

(Question 1-1/2)

(1978)

1. Introduction

This Report discusses the sharing of frequencies in the range 1 to 20 GHz between deep-space research stations and stations of other services. Deep-space earth and space station protection criteria are discussed. Potential interference is considered, and conclusions are drawn about the feasibility of sharing.

The 1 to 20 GHz range includes current allocations applicable to deep-space research and some of the frequencies desired for future operational use. Preferred frequencies are given in [CCIR 1974-78a]. United States earth and space station characteristics for deep-space research are given in [CCIR 1974-78b].

2. Deep-space earth station factors pertinent to sharing

The principal deep-space earth station parameters which pertain to interference and sharing are transmitter power, antenna gain and pointing, receiver sensitivity (including noise temperature) and bandwidth. Typical values of these parameters are given in [CCIR 1974-78b]. This section of the Report considers some aspects of antenna pointing, and develops protection criteria for receivers at deep-space earth stations. The section finishes with remarks about co-ordination. Considerations of transmitter power are given in a later section.

2.1 *Intersections of satellite orbits and antenna beams from deep-space earth stations*

The locations of the US deep-space earth stations are given in [CCIR 1974-78b]. The stations are spaced approximately equally in longitude (120° apart) with two stations in the northern hemisphere, and the third in the southern hemisphere. Spacecraft in deep space currently remain in or near the plane of the ecliptic, which is tilted at 23.5° from the Earth's equatorial plane. The daily rotation of the Earth causes the antenna beam of at least one earth station to intersect the equatorial plane and hence the geostationary satellite orbit when tracking a given spacecraft. The earth station may be subjected to interference from satellites within the antenna beam, and may cause interference to those satellites.

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 altitude orbits are contained in Report 684.

In the future the United States plans to deliver deep-space probes into orbits out of the plane of the ecliptic. These missions will also result in some earth station tracking beams passing through the orbits of both geostationary and non-geostationary satellites.

2.2 *Susceptibility of deep-space earth station receivers to interference*

A deep-space telecommunication system is typically a phase-sensitive system. The earth station receiver utilizes phase-locked loops for carrier tracking and data recovery. CW or noiselike interference in these loops can result either in degradation or loss of tracking and data. Report 544 contains information on the effects of interference in phase-locked loops. Report 545 presents information on the degradation of telemetering performance due to interference.

2.2.1 *CW signal interference*

2.2.1.1 *Receiver capture*

The changing Doppler shift of a received desired signal can cause the receiver pass band to move past a fixed frequency unwanted CW signal. Depending upon rate of motion and the amplitude of the unwanted signal, the receiver may lock to the interfering signal if R, the ratio of the CW signal power to the desired signal power, satisfies the relation:

$$R > \frac{\mathrm{d}f}{\pi f_n^2} \qquad (1)$$

where $\mathrm{d}f$ is the rate of frequency change in Hz/s and f_n is the loop natural frequency in Hz.

An interfering CW signal that is 10 dB above a strong desired signal and is moving through the receiver passband at 100 Hz/s would cause the receiver to lock to the interfering signal. At a lower rate of movement, the required interfering signal level is proportionately lower until at a signal-to-interference ratio greater than one, the interfering signal will no longer capture the receiver, even if the movement rate is zero. Undesired CW signals not strong enough to cause receiver capture may cause interference to carrier tracking.

2.2.1.2 *Carrier tracking degradation*

An interfering CW signal can induce a phase modulation on the desired carrier signal when the frequency separation between the two signals is comparable to, or less than, the phase locked loop bandwidth. A maximum acceptable phase modulation of 10° amplitude results from an interference-to-carrier power ratio of −15 dB. The design margin for carrier tracking is typically 10 dB with reference to the noise power in the carrier tracking loop bandwidth. For maximum acceptable carrier tracking degradation, the power in a CW interfering signal that may be within the phase locked loop bandwidth must not be greater than the amount shown in Table I.

TABLE I – *CW interference with carrier tracking*

Frequency (GHz)	Noise in 1 Hz loop (dBW)	Minimum carrier power (dBW)	Maximum CW interference (dBW)
2.3	−216.6	−206.6	−221.6
8.5	−215.0	−205.0	−220.0
15.0	−213.4	−203.4	−218.4

2.2.1.3 *Telemetering degradation*

Telemetering degradation is defined as the amount by which the signal-to-noise ratio must be increased to make the bit error rate, when an interfering signal is present, equal to that which it would be if the interfering signal were absent. The maximum allowable degradation for deep-space telemetering is 1 dB. For coded telemetering with a threshold signal-to-noise ratio of 2.3 dB, CW interference 6.8 dB below the noise power will result in 1 dB degradation. For uncoded telemetering with a threshold signal-to-noise ratio of 9.8 dB, CW interference 5 dB below the noise will result in 1 dB degradation. The noise power is proportional to the data bandwidth and the receiver noise spectral density. Examples of allowable level of CW interference are shown in Table II.

TABLE II – *CW interference with telemetering*

Frequency (GHz)	Data rate (bit/s)	Noise power in data bandwidth (dBW)	Interference-to-noise ratio for 1 dB degradation (dB)	Maximum CW interference (dBW)
2.3	40, uncoded	−200.6	−5.0	−205.6
8.4	40, coded	−200.0	−6.8	−206.8
	115 k, coded	−164.4	−6.8	−171.2
15.0	40, coded	−197.4	−6.8	−204.2
	115 k, coded	−162.8	−6.8	−169.6

2.2.2 *Wideband interference*

Wideband signals or noise which reduces the signal-to-noise ratio, affects both the carrier tracking and the data channels. In the case of the telemetering channel, the spectral density of the interfering signal must be at least 5.9 dB below the spectral density of the receiver noise, in order not to degrade the threshold performance by more than 1 dB. Maximum levels of wideband interference are shown in Table III.

TABLE III – *Wideband interference with telemetering*

Frequency (GHz)	Noise spectral density (dB(W/Hz))	Interference-to-noise ratio (dB)	Maximum wideband interference (dB(W/Hz))
2.3	–216.6	–5.9	–222.5
8.4	–215.0	–5.9	–220.9
15.0	–213.4	–5.9	–219.3

2.2.3 *Interference to maser operation*

Mixing of signals with the idler frequency of the maser pump can cause interference and saturation in the receiver passband. There are many frequencies at which such mixing can occur, all of which are far removed from the normal frequency of reception. Table IV gives possible interference frequencies for the two frequency bands currently used for reception at deep-space research earth stations.

Interfering signals must be above –120 dBW in the idler bandwidth (which is very broad) at the maser input, to be significant.

TABLE IV – *Frequencies at which interference may be caused by mixing in the maser*

Receiver frequency band	2290 to 2300 MHz	8400 to 8500 MHz
Maser pump frequency	12.7 GHz	19.3 and 24.0 GHz
Interference frequencies	15.0 GHz 10.4 7.5 5.2	32.4 GHz 27.8 15.6 10.9

2.2.4 *Adjacent channel receiver saturation*

The cryogenically cooled maser of the deep-space receiver has a bandpass of approximately 50 MHz. Adjacent channel signals, if received at total power levels greater than –120 dBW, can generate intermodulation products in the mixer and other receiver elements, causing saturation of the receiver.

2.2.5 *Interference protection for deep-space earth station receivers*

Interruption of telecommunications can result from interference that is strong enough to cause receiver capture or saturation. Weaker interference may result in degraded carrier tracking and telemetering performance. The level of interference that can be tolerated is determined by acceptable performance degradation. To protect deep-space earth station receivers, 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, should not be greater than the values shown in Table V, for an aggregate of five minutes in any one day *. Table V also shows the maximum power flux-density of interference, considering the effective area of a 70 m earth station antenna.

TABLE V – *Interference protection for earth station receivers*

Band (GHz)	Maximum power spectral density (dB(W/Hz))	Maximum spectral power flux-density (dB(W/(m^2.Hz)))
2.3	–222.5	–256.2
8.4	–220.9	–253.8
15.0	–219.3	–250.2

2.3 *Co-ordination considerations*

The practicability of co-ordination is determined partially by the number of stations with which co-ordination must be effected. This is in turn controlled by the co-ordination distance. For deep-space research, the practicable co-ordination distance is currently considered to be 1500 km.

Co-ordination distance may be calculated by the method of Appendix 28 of the Radio Regulations. An alternative method of evaluating propagation factors is given in Report 724. The two ways of determining distance give different results. For example, assuming a transhorizon station (i.e., 93 dB(W/10 kHz), in the 2.3 GHz band), the distances are 2100 and 800 km, respectively.

A decision on the practicability of sharing with transhorizon stations is thus not possible, and further study is necessary.

3. Deep-space station parameters and protection pertinent to sharing

The principal deep-space station parameters which pertain to interference and sharing are antenna gain and pointing, transmitter power and receiver sensitivity. Details of these parameters are given in [CCIR 1974-78b].

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 as susceptible to interference as 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 1 kHz band should be no larger than the amount shown in Table VI, for an aggregate of 5 minutes per day.

Deep-space station e.i.r.p. is normally reduced while near the Earth, thus minimizing the potential for interference to other stations.

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.

* Five minutes per day is generally taken as 0.001% of the time, as discussed in Report 536-1.

TABLE VI – *Interference protection for deep-space station receivers*

Frequency (GHz)	Maximum interference level (dB(W/kHz))
2.1	−170.8
7.2	−169.6
15.0	−168.1

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. 470F of the Radio Regulations.

Aircraft stations within line-of-sight of a deep-space earth station will 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. Co-ordination 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, co-ordination should provide sufficient protection for terrestrial receivers and earth station receivers. See § 2.3 for co-ordination 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 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 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.

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. Fig. 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 antennae pointing away from the ecliptic plane, have less potential for interference.

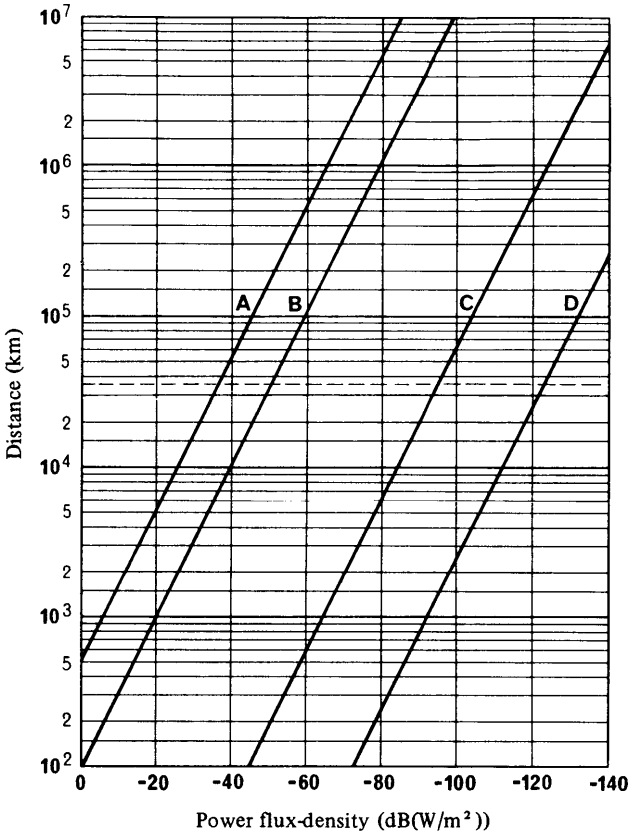


FIGURE 1 – *Power flux-density from earth station transmitter 100 kW, 64 m antenna*

A: Main beam, 15 GHz

B: Main beam, 2.1 GHz

C: 5° off axis
(14.5 dB gain, Recommendation 509)

D: ⩾48° off axis (–10 dB gain, Rec. 509)

– – –: Altitude of geostationary satellite orbit, 3.56 × 10^4 km

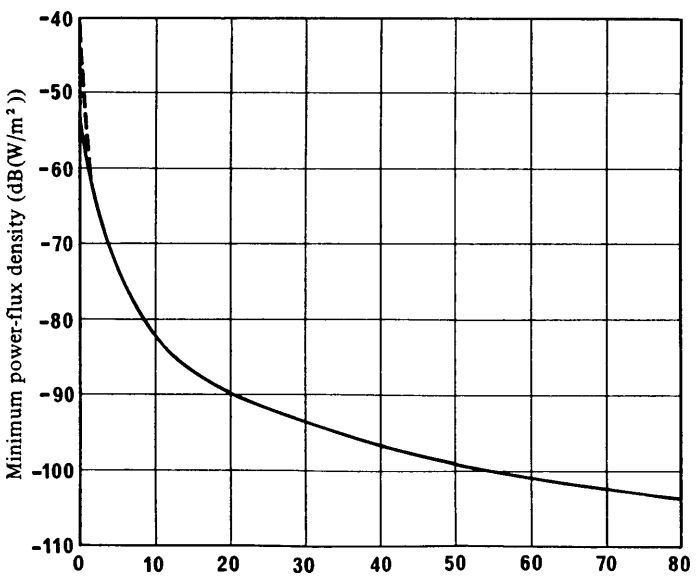


FIGURE 2 – *Duration of potential interference to geostationary satellite intersecting beam axis from earth station with 100 kW transmitter and 64 m antenna*

———: 2.1 GHz

– – – –: 15 GHz

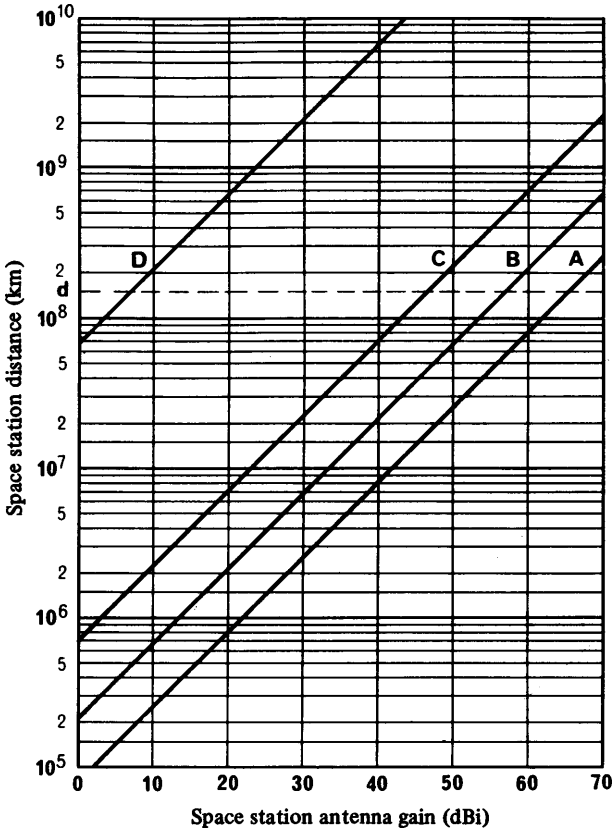


FIGURE 3 – *Space station distance from terrestrial transmitter for interference power equal to receiver noise power*

A: 15 GHz relay transmitter, 55 dB(W/10 kHz); –168 dB(W/kHz) receiver noise power

B: 7.2 GHz relay transmitter, 55 dB(W/10 kHz); –170 dB(W/kHz) receiver noise power

C: 2.1 GHz relay transmitter, 55 dB(W/10 kHz); –171 dB(W/kHz) receiver noise power

D: 2.1 GHz transhorizon transmitter, 93 dB(W/10 kHz); –171 dB(W/kHz) receiver noise power

d: Space station range of 1 astronomical unit, 1.5×10^8 km

4.4 *Potential interference to deep-space station receivers from near-Earth satellite transmitters*

Near-Earth satellites typically have antennae 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 near the ecliptic plane. 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.

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*

Fig. 4 shows power flux-density at the surface of the Earth caused by deep-space stations with characteristics as shown in [CCIR 1974-78b]. These stations typically use low gain, wide beam antennae 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 Radio Regulations for protection of line-of-sight radio-relay systems. For example, the MARINER Jupiter Saturn spacecraft is expected to use 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.

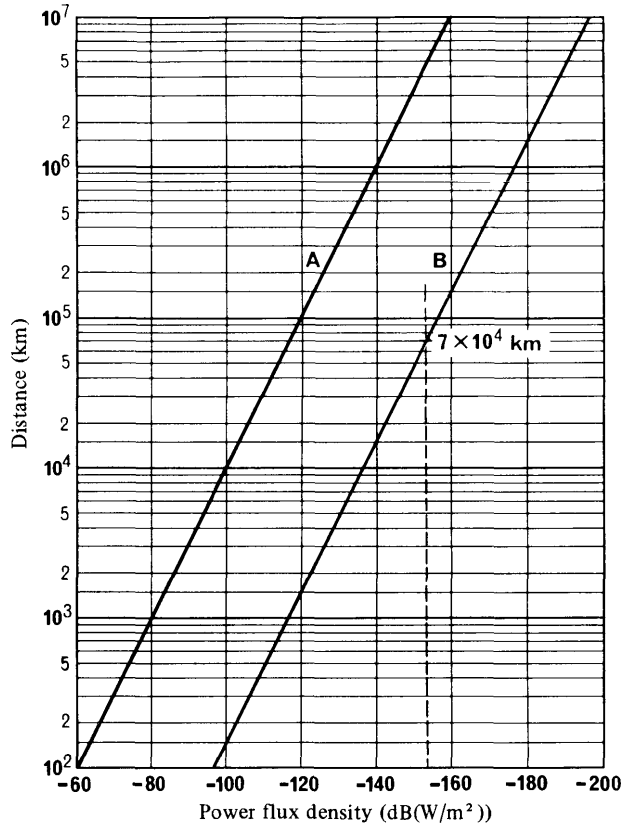


FIGURE 4 – *Power flux density at surface of Earth from space station transmitter*

A: 14 dBW transmitter, 37 dBi antenna

B: 14 dBW transmitter, 0 dBi antenna

– – –: –154 dB(W/m^2) (Number 470 NE 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 antennae are directed in the ecliptic plane. 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 transhorizon 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 transhorizon phenomena, or by rain scatter. For co-ordination considerations see § 2.3.

Other services with high power transmitters and high gain antennae are potential interference sources. Radiolocation stations are an example. Earth station transmitters are less likely sources of interference, depending on e.i.r.p. in the direction of the deep-space earth station. Co-ordination 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.

Co-ordination 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. It is concluded that sharing is not feasible. This conclusion is also valid for satellites in circular and moderately eccentric orbits.

6. Discussion

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 [CCIR 1974-78b], this means an average e.i.r.p. no greater than 82 dBW at 2 GHz, and 92 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*

Deep-space research cannot share Earth-to-space bands with:

- receiving aeronautical mobile stations,
- receiving satellite stations, and
- transmitting terrestrial stations and earth stations utilizing high average e.i.r.p., for example, transmitting transhorizon stations, and transmitting fixed-satellite earth stations.

When co-ordination is practicable, sharing is feasible with other stations of all services. In some cases, co-ordination distances may be unacceptably great.

7.2 *Sharing of space-to-Earth bands*

Deep-space research cannot share space-to-Earth bands with:

- transmitting aeronautical mobile stations, and
- transmitting satellite stations.

When co-ordination is practicable, sharing is feasible with other stations of all services. In some cases, co-ordination distances may be unacceptably great.

The matter of unacceptably long co-ordination distance requires further study.

REFERENCES

CCIR Documents

[1974-78]: **a.** 2/168 (USA); **b.** 2/167 (USA).

REPORT 688

FEASIBILITY OF SHARING BETWEEN SPACE RESEARCH SATELLITES IN ECCENTRIC ORBITS AND DEEP-SPACE RESEARCH EARTH STATIONS

(Question 14-2/2)

(1978)

1. Introduction

The purpose of this Report is to describe potential interference situations between spacecraft operating in highly elliptic orbits, and deep-space network earth stations sharing the band 2290 to 2300 MHz.

The Deep-Space Network (DSN), established by the US National Aeronautics and Space Administration, provides two-way communication between the Earth and spacecraft travelling at lunar to planetary distances. This communication requirement includes tracking, telemetering, command, monitoring, and operations control.

To achieve continuous radio contact with the spacecraft, three deep-space ground stations have been located approximately 120° longitude apart, thus ensuring that at least one station is within the field of view of the spacecraft at all times. Furthermore, since most spacecraft on deep-space missions follow orbits within 30° of the equatorial plane, these three major DSN stations are located within 45° north or south of the equator. They are listed in Table I.

TABLE I – *Major deep-space network sites*

Location	Antenna reflector diameter (m)	Geocentric radius (km)	Geocentric latitude (degrees)	Geocentric longitude (degrees)
USA (Goldstone)	64	6371.993	35.24435	243.11408
Australia (Canberra)	64	6371.709	–35.22123	148.98128
Spain (Madrid)	64	6370.019	40.24099	355.75119

Since the great distances involved in deep-space communications result in signal attenuations of 200 to 300 dB, the successful operation of the DSN requires the ability to receive and amplify very low field strength signals. This is accomplished by the use of high-sensitivity receivers characterized by low noise temperatures, high stability, and both narrow and wideband reception.

The DSN operational requirements render it more susceptible to interference than most other communications systems. The possibilities of interference to the DSN discussed in this Report are confined to a band-sharing situation between the DSN and space research spacecraft that operate in highly elliptic orbits in the space research band 2290 to 2300 MHz.

2. Interference criterion

The DSN sites used in the interference model are the three 64 metre parabolic reflectors located at Goldstone, Madrid, and Canberra.

Concerning noise interference into these sites, any wideband signal or noise spectrum that would, in effect, degrade the signal-to-noise ratio of the receiver would affect both the phase servo loop and the data channels. In this case the spectral density of the interfering signal must be at least 5 dB below the spectral density of the receiver noise in order not to degrade the receiver more than 1 dB *. With a system noise temperature at 2 GHz of 15 K, the corresponding receiver noise spectral density is given by kT or:

$$10 \log k + 10 \log T = -217 \text{ dB(W/Hz)} \qquad \text{at 2 GHz}$$

Using the 5 dB interference signal criterion, the maximum allowable interference spectral density must be not greater than –222 dB(W/Hz) at 2 GHz at the receiver front end.

* See Report 536-1.

Due to the nature of operation of the DSN antennae (i.e., normally tracking from horizon to horizon in the ecliptic plane), and the non-linear function of the spacecraft relative velocity with respect to time, any statistical/probability model attempting to describe the off-axis coupling between the spacecraft and DSN antennae is overwhelmed by the number of parametric variations. It is for this reason that the DSN antenna gain has been assumed in this analysis to be represented by an isotropic response. *

Using this assumption, the effective area of the DSN antenna is given by:

$$A_r = \lambda^2/4\pi \text{ or } A_r = 0.08\ \lambda^2 \quad (1)$$

where λ is the wavelength of interest.

For the 2.3 GHz (15 cm) region, this corresponds to an effective normalized antenna pattern gain of +28.6 dB referred to an antenna of 1 square metre; or, when used in conjunction with the front end interference spectral density criterion of −222 dB(W/Hz), yields a power flux-density maximum toleration of ~ −193.4 dB(W/(m^2·Hz)).

3. Spacecraft orbital and electrical assumptions

For the purpose of this study, it was assumed that the highly elliptical spacecraft orbit is 4-day earth synchronous (i.e., the spacecraft passes over the same point every four sidereal days). To accomplish this, the model assumed an apogee of 199 455 km and a perigee of 300 km. Additionally, an inclination of 40° was used. In order to visualize the orbit in relation to the Earth, Fig. 1 shows the position of the spacecraft projected on to the Earth for one particular ascending node, and argument of perigee, of 90°. As an example, Goldstone was chosen as the ground station of interest (shown with an *). Fig. 1 indicates spacecraft positions at which there is a direct line-of-sight visibility from the spacecraft to the station. In order to show the relative velocities involved in this highly elliptic orbit, Fig. 1 shows two points on either side of perigee P. The time required to traverse from point 1 to 2 is approximately 54 min. The time required to complete the rest of the orbit is ~5690 min, resulting in a ratio of time spent above the equator of less than 1%.

The spacecraft emission characteristics were assumed to be 6 W transmitter power, −2 dB antenna gain, 100 kHz emission spectrum, and 10 dB spectral peaking factor. Additionally, the spacecraft was assumed to be continuously transmitting (i.e., the programme calculated only those times at which, if the spacecraft were to transmit with a gain of −2 dB in all directions, the power flux-density at the surface of the Earth would be above the DSN threshold interference levels).

The characteristics of the model as stated above are summarized in Table II.

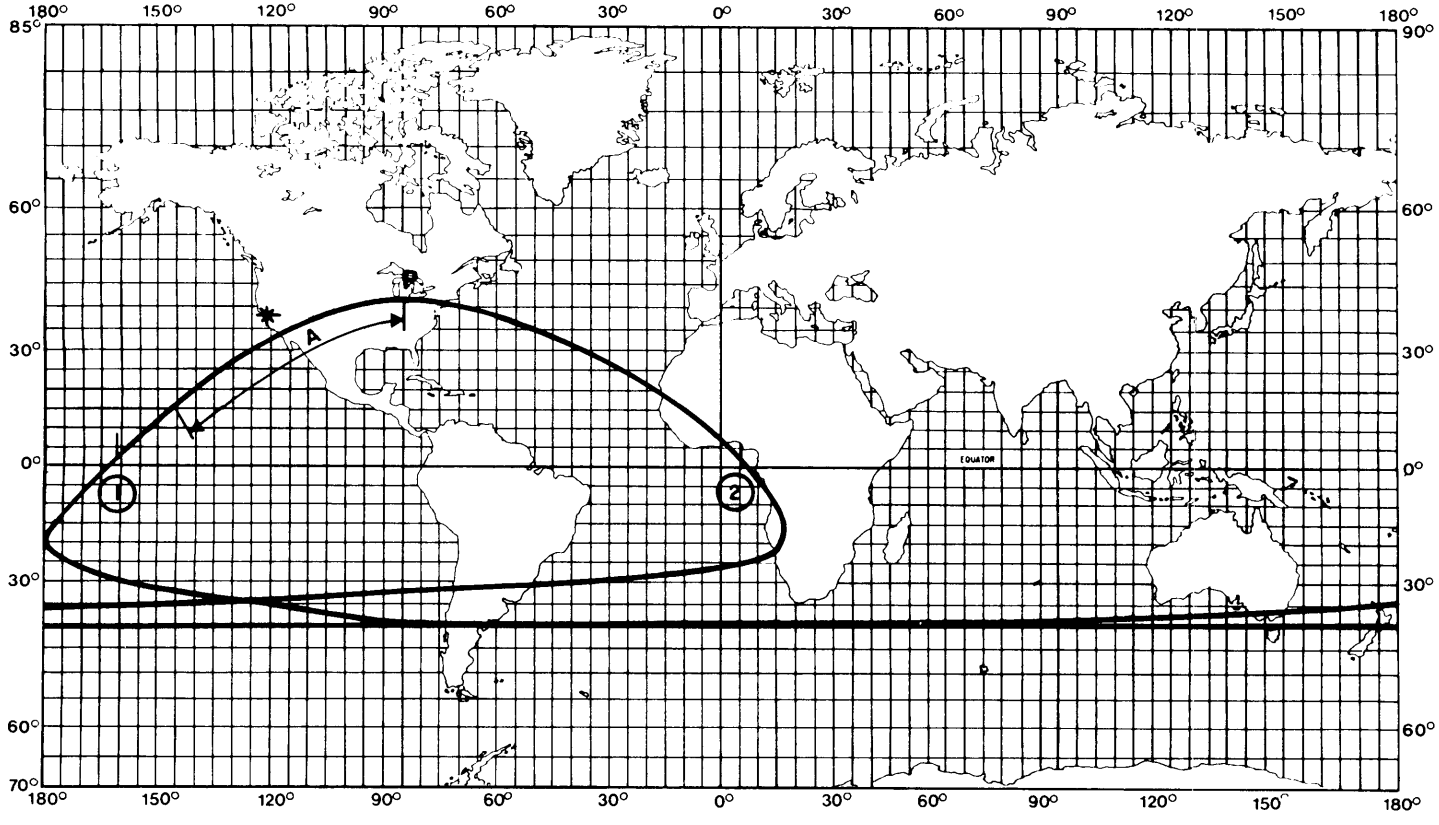
4. Results and conclusions

Fig. 2 presents the results for an argument of perigee of 90° (northern perigee); and Fig. 3 shows the results for an argument of perigee of 270° (or southern perigee). Both figures give the percentage of time that the interference criterion of −222 dB(W/Hz) at the DSN receive front end is exceeded, as a function of the orbital longitude of the ascending node. These values range from no interference to some stations at particular ascending nodes, to orbital values of ~1.4%.

TABLE II – *Model parameters*

Orbit	
Apogee	199 455 km
Perigee	300 km
Inclination	40°
Argument of perigee	90° and 270° (nothern and southern perigee)
Longitude of the ascending node	−180° to 180°
Spacecraft	
Power	6 W
Gain	−2 dB omnidirectional
Bandwidth	100 kHz
Spectral peaking factor	10 dB

* This assumption represents a compromise between a gain of greater than 0 dBi for off-axis angles of 0 to 20° and a gain of less than 0 dBi for off-axis angles of greater than 20° (see Recommendation 509).



*GOLDSTONE

FIGURE 1 – *Orbital ground track and visibility to Goldstone*

A: Visibility

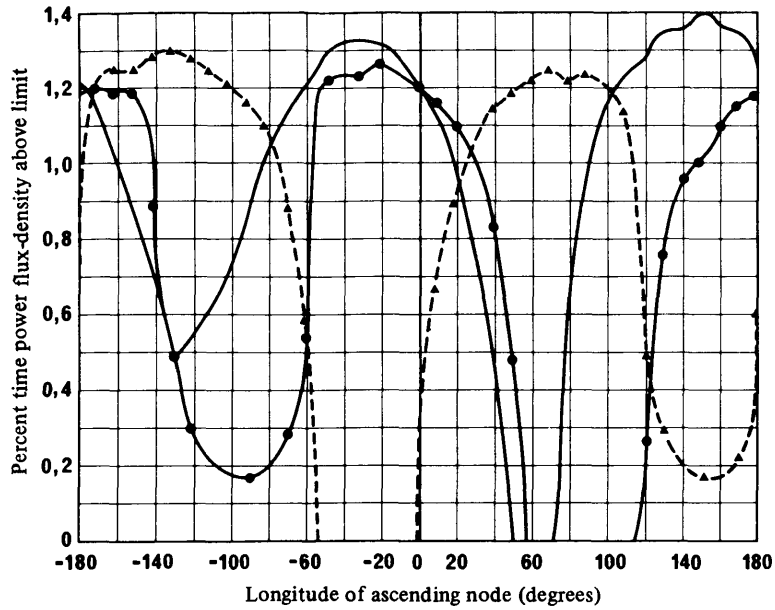


FIGURE 2 – *Interference levels for argument of perigee of 90°*
CANBERRA
MADRID
GOLDSTONE

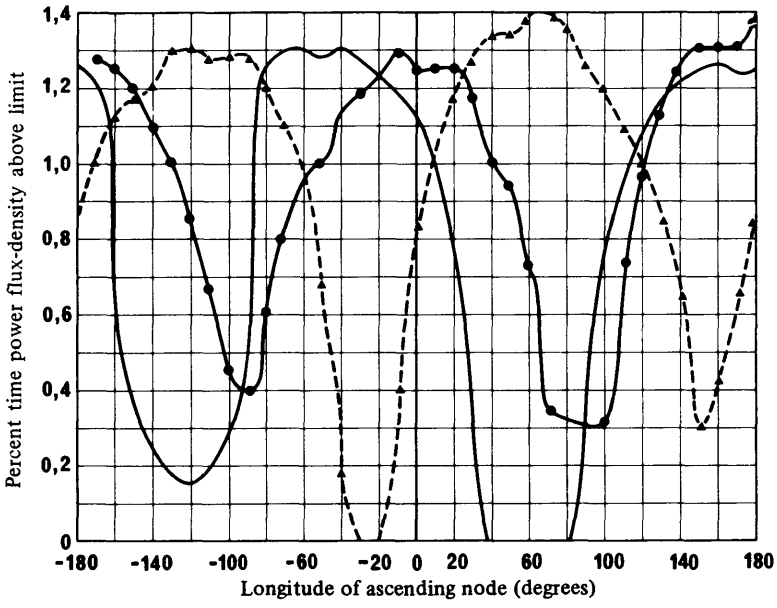


FIGURE 3 – *Interference levels for argument of perigee of 270°*
CANBERRA
MADRID
GOLDSTONE

The particular conclusion to be drawn from these data is that for 40° inclination no ascending nodes exist at which the spacecraft could be injected into orbit, and which would not cause interference to at least one of the DSN sites. In fact, a majority of the ascending nodes would cause excess interference levels to all three DSN ground stations. It is based up on this observation, with the orbit and spacecraft parameters assumed in this analysis, that sharing between the DSN and spacecraft operating in the space research band 2290 to 2300 MHz in highly elliptic orbits is seen to be not feasible.

REPORT 544

THE EFFECTS OF INTERFERENCE ON NARROW-BAND PHASE-LOCKED LOOPS AS USED IN SPACE RESEARCH

(1974)

1. Introduction

An experimental investigation of the effects of interference on narrow-band phase-locked loops has been conducted to determine the degree of performance degradation caused by interfering signals on the ground-station receivers of space-research communication systems [Britt *et al.*, 1965]. A summary of the results of this investigation is presented below.

2. Summary of results

Experimental data were taken with narrow-band (1, 12, 48 and 152 Hz, effective noise bandwidths) phase-locked circuits which had the same transfer characteristics as those currently used in space-research receivers. These circuits were subjected to two types of interfering signal:

- varying levels of CW interfering signals which were swept through the loop passband at varying rates;
- varying levels of a noise-modulated frequency-modulation interfering signal of low modulation index which simulated the power spectral density of a frequency-modulation radio-relay system with 1800 loaded voice channels.

The degradation of loop performance due to interference under those conditions, that did not cause cycle skipping or loss of lock, was measured by defining an "equivalent signal-to-noise ratio" (R_0) for the loop signal-to-noise ratio, as the inverse of the loop mean-square phase error:

$$R_0 = 1/\sigma_\varepsilon^2 \tag{1}$$

where σ_ε^2 is the mean-square phase error. This definition is a natural one, since an analysis of a linearized phase-locked loop yields a value for loop mean-square error due to random receiver noise of:

$$\sigma_\varepsilon^2 = B_L \varphi_n / S \tag{2}$$

where S is the wanted signal power, B_L is the equivalent noise bandwidth of the phase-locked loop and φ_n is the power spectral density of the noise at the input of the loop. The term $\varphi_n B_L$is thus the noise power referred to the loop bandwidth.

Use of the mean-square phase error as a measure of system performance led to a difficulty when dealing with slowly-sweeping interfering signals because of the transient nature of the interference. This difficulty was overcome by averaging squared error only over the period of time during which the interference was within the passband of the loop. In the experiments, the squared values of phase error were averaged over a time period corresponding to the time the sweeping interfering signal was within -6 dB points of the loop amplitude-frequency response curves. Repeated trials were used to obtain sufficient data for fast-sweep cases.

During periods when a phase-locked loop is out of lock, its usefulness is lost. Therefore certain noise-interference environments can be designated as definitely placing the loop beyond its limit of operation. However, because a loop can often be caused to "skip cycles" without losing lock for extended periods, it is difficult to define the boundary of this destructive environment from phase-error records alone. In particular, it is usually impossible to determine whether the phase error has simply dwelt near 90°, or whether the loop has skipped one or more cycles before the phase detector responds; simple phase detectors do not give unambiguous outputs except over a range of ± 90°.

To define the threshold of useful loop operation, the average cycles skipped were counted for various interference-to-signal ratios. A good indication of cycle skipping activity was obtained by totalling net cycles skipped over many counting periods. The usual signals were recorded during the skipped cycle counts, so that counts could be correlated with phase-error measurements.

For CW interference sweeping across the input signal, a rather simple programme was set up for treating the different possibilities. The ranges of experimental parameters were primarily determined by the fact that lock was nearly always lost in the following cases:

- with no interference present and a loop signal-to-noise ratio (R) below 6 dB;
- with no additive noise present and a loop input signal-to-interference ratio (R_i) of about -3 dB.

The experiments were conducted with values of R of 3, 6, 9, 12 and ∞ dB and R_i of -3, 0, 3, 6, 9 and ∞ dB. A complete test sequence was used for the 12 Hz bandwidth loop and interference signal sweep rates of 1, 10, 100, 500 and 1000 Hz/s. Sample data were taken at the other loop bandwidths to determine that the data at 12 Hz were typical. The raw data was interpolated and smoothed to obtain the best fitting curves by subjecting the data to a step-wise multiple regression procedure.

A summary of the experimental data taken with interfering CW signals, having a sweep rate of 1 Hz/s and with a loop bandwidth of 12 Hz, is presented in Figs. 1 and 2. Fig. 1 shows the variation in loop threshold as a function of interfering CW signal-to-noise power ratio, where loop threshold is defined as the point where the numbers of cycles skipped per second by the loop equals 0.025 B_L (loop bandwidth). Fig 2 shows the decrease of equivalent loop signal-to-noise ratio as a function of the interference-to-noise ratio. This increase in mean-square error due to the interference signal may be considered a measure of the degradation of the loop. Experimental data indicates that these figures may be scaled to other loop bandwidths.

Tests with slowly-swept simulated frequency-modulation radio-relay signals indicated that the effect on the loop of signals of this type is essentially the same as a CW signal. For cases where frequency separation places the carrier well outside the intermediate-frequency passband, the frequency-modulation sidebands falling within the loop bandwidth have an effect on the loop that is similar to additive noise of the same power level.

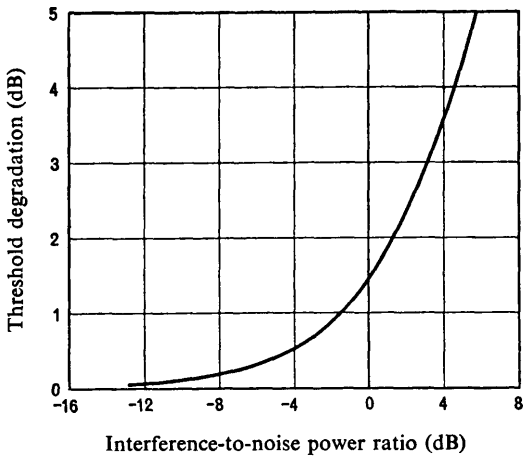


FIGURE 1 – *Variation in loop threshold as a function of interfering CW signal-to-noise power ratio*

Loop threshold is defined as the point where the number of cycles skipped per second by the loop equals 0·025 B_L (loop bandwidth)
(From data taken $B_L \approx 12$ Hz and interfering sweep rate ≈ 1 Hz/s)

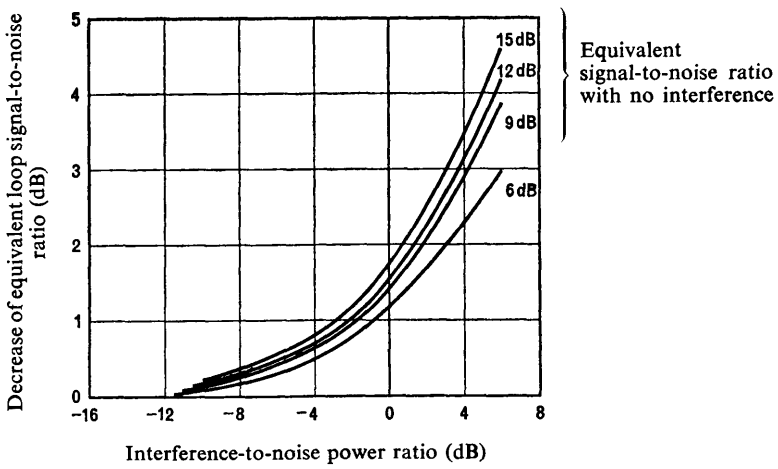


FIGURE 2 – *Degradation of equivalent loop signal-to-noise ratio as a function of CW interference-to-noise power ratio*

(From data taken with $B_L \approx 12$ Hz and interfering sweep rate ≈ 1 Hz/s)

3. Conclusions

For CW interfering signals at levels within several decibels of the level of the receiver thermal noise power in the loop noise bandwidth, interference effects are negligible if the frequency of the interfering signal is separated from that of the desired signal by several multiples of the loop noise bandwidth of the phase-locked receiver, or if the interfering signal sweeps through this bandwidth at a sweep rate of the rate of ten times the square of the loop bandwidth. However, when the interfering signal sweeps slowly through, or remains within the bandwidth of the loop, it can cause large phase errors, cycle skipping, or cause the receiver to break lock, in which case it will often transfer lock to the interfering signal. This latter effect can occur if the interference level exceeds the signal level.

Slowly-sweeping CW interference will cause a decrease in effective signal-to-noise ratio in the loop of as much as 1 dB for interference to noise levels of −3 dB and as much as 0.5 dB for interference to noise levels of −6 dB. These levels of interference can cause cycle skipping or loss of lock to occur if the R in the absence of interference is of the order of 6 dB.

Frequency-modulation signals with low modulation index have essentially the same effect as CW signals when the carrier component sweeps through the loop passband. The sidebands of a noise modulated frequency-modulation signal have an effect similar to white additive noise at the same power level.

REFERENCE

BRITT, C. L., PALMER, D. F. and SMITH, P. G. [1965] A study of the effects of interference on narrow-band phase-lock loops. NASA Contractor Report CR-66036. National Aeronautics and Space Administration, Washington, DC.

REPORT 545

THE EFFECTS OF INTERFERENCE ON RESEARCH SPACECRAFT TELEMETERING

(Questions 1-1/2 and 2-1/2)

(1974)

1. Introduction

This Report presents a discussion of the effect of interfering signals in the passband of a telemetering or telecommand link between earth stations and a space research spacecraft. The purpose of the Report is to provide information on the effect of interference on the pulse-code modulation bit detection process, as well as information on the various classes of research spacecraft data. The Report also considers the calculation of an acceptable interference power level, and uses the results to compute an interference criterion in agreement with the presently defined value of −220 dB(W/Hz) for maximum spectral density of noiselike interference.

2. General considerations

Consideration is to be given to the effect of interference on the different portions of a communication system; interference affects the carrier demodulator, the sub-carrier demodulators, and the symbol (bit) demodulators in different ways. The contributing effects combine to produce an overall degradation which may be made the subject of a calculation based on an understanding of the constituent effects. Carrier and sub-carrier demodulators are usually phase-locked loops for research spacecraft links; the effect of interfering signals on phase-locked loops is discussed in Report 544 and will not be dealt with here. This Report will present some material [Koerner, 1968] on the effect of interfering signals on the performance of bit demodulators (§ 3.1 below).

Consideration must also be given to the effect of interference on different types of data, e.g. telecommand, maintenance telemetering, stored scientific data, and real-time unstored scientific data. These effects will be discussed in § 3.2 of this Report.

From the results of § 3.1, specific calculations may be made. This is done in § 3.3, in which an allowable interference level is computed for an assumed set of link parameters.

3. Effects of interference

3.1 *Effects on different parts of a channel*

Phase-locked loops have been used extensively in space research communication systems. In PCM/sub-carrier PSK-carrier phase modulation systems, the carrier and sub-carriers are generally demodulated with phase-locked loops. Typical bandwidths for carrier loops are 3 to 300 Hz (closed loop effective noise bandwidth), and for sub-carrier loops, 0.01 to 10 Hz. The experimental investigation of interference effects in phase-locked loops (see Report 544) is applicable to the former and may be applicable to the latter systems, although caution should be used in extrapolating data to the data-suppressed sub-carrier narrow-band loop case.

Theoretical work [Koerner, 1968] on the effect of interference on a maximum-likelihood binary receiver using known signals in the presence of white Gaussian noise is pertinent to the problem of interference with bit detection. Useful results are shown in Figs. 1 to 7; the parameters are defined in Table I. Figs. 1 and 2 consider the degradation δ as a function of the interference-to-signal ratio η and the signal-to-noise * ratio λ, with sinusoidal interference. Figs. 3 and 4 are corresponding curves for Gaussian interference. The precise definitions of δ, η and λ are given in Table I.

---

* Internal system thermal noise.

Figs. 5 and 6 are plots of δ as a function of the interference-to-noise ratio ξ and the signal-to-noise ratio λ with sinusoidal interference. Fig. 7 is the corresponding curve for Gaussian (noiselike) interference. Precise definitions of the ratios ξ and $\lambda$are given in Table I.

The degradation δ plotted in the figures as a function of the signal-to-noise and interference-to-signal (or interference-to-noise) ratios is the required additional transmitter power needed to make the channel bit error rate equal, in the presence of the interference, to the error rate without interference.

Figs. 8 and 9 compare the effects of sinusoidal and Gaussian interference. It is seen that for small signal-to-noise ratios the effects are almost the same, but that they diverge at largest signal-to-noise ratios: for fixed values of total interference power, sinusoidal interference causes a lesser degradation than Gaussian (noiselike) interference at higher signal-to-noise ratios.

3.2 *Effects on different classes of channels*

Four types of space research channels are telecommand, maintenance telemetering, stored scientific data and real-time non-stored scientific data. The effect of blockage or error introduction in each of these is somewhat different, as follows:

In telecommand, a fundamental principle of design of most research spacecraft is that no false command can result in a completely aborted mission. Sequencing and timing machinery is provided on spacecraft for eventual recovery from falsely commanded modes, and great pains are taken to insure that no unalterable state may be reached via any command. However, there is usually an unavoidable severe dependence on the spacecraft telecommand system during critical mission phaşes such as a trajectory correction manoeuvre. Interference during this critical periods, which are sometimes of several hours duration, could severely compromise the mission. For example, if it were necessary to postpone a trajectory correction manoeuvre because of interference the correction capability of the spacecraft trajectory correction propulsion system would be lower for orbital mechanical reasons. This situation could result, for instance, in a less accurate fly-by of a planet.

Maintenance telemetering is not usually stored but is sampled and transmitted in real-time. Except during critical periods, such as a trajectory correction manoeuvre, a maintenance telemetry system is fairly tolerant of interruptions and interference. Such critical periods of read-out 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 tens of hours) in which the maintenance telemetry must be protected from harmful interference. For other periods of a mission, however, this class of channel 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 most tolerant of interference of limited duration.

Real-time non-stored data are the most easily susceptible to interference. This data may be the real-time output of a spacecraft sensor such as a vidicon, or a measure of audio-frequency signal strength during occulation (passage of the signal from a spacecraft through the atmosphere of the Earth or of another planet). Because it occurs only once and is unrepeatable this type of data is most sensitive to interference. 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 occurrence of interesting non-stored data is known in advance to within several hours.

3.3 *Interference level calculation*

The preceding two sections allow an interference criterion to be set up for a particular link at a particular time. A most pessimistic or conservative criterion will consider the most sensitive link at the most critical time. Reasonable typical parameters for a link from a spacecraft-to-Earth during an important part of its mission (e.g. at a planetary encounter) are:

- signal-to-noise ratio: $\lambda = +5.0$ dB,
- acceptable degradation: $\delta \leqslant 1.0$ dB.

Using Fig. 7 we find that the Gaussian interference-to-noise ratio, ξ, must be less than -6.0 dB. Consequently the interference-to-signal ratio $\eta = \xi/2\lambda$ must be less than -14 dB. A reasonable figure for received signal level is -196 dBW (10 baud channel, 50 K effective ground system temperature). Thus, the received interference power must be less than -210 dBW and consequently, since the noise bandwidth of the 10 baud bit detector is 10 Hz, the spectral density of interference, the spectrum of which is flat, must be less than -220 dB(W/Hz).

4. Conclusions

From the discussions and results given above, it may be concluded that:

- the degradation in a modulation system due to interference includes effects on the carrier demodulator, the sub-carrier demodulator and the bit detector, all of which must be taken into account;
- the effect of interference, both CW and noiselike, on pulse-code modulation bit detectors, can be quite severe;
- research spacecraft involve different classes of data to be communicated, of which the sensitivities to interference range from "relatively insensitive" to "extremely sensitive";
- a reasonable criterion for interference level is that the spectral density of interference must be less than -190 dB(mW/Hz) during critical phases of a mission.

REFERENCE

KOERNER, M. A. [1968] Effect of interference on a binary communication channel using known signals. JPL Technical Report 32-1281.

TABLE I – *Definition of interference parameters*

Name	Symbol on Figures	Definition
Signal-to-noise ratio	λ	$\lambda = \dfrac{E_0 + E_1 - 2\rho (E_0 E_1)^{1/2}}{4\Phi}$
Energy in "zero" signal		$E_0 = \int_0^T s^2(0:t)\,dt$
Energy in "one" signal		$E_1 = \int_0^T s^2(1:t)\,dt$
"One" and "zero" signal		$s(1:t)$ and $s(0:t)$, $0 \leqslant t \leqslant T$
Cross-correlation between the signals		$\rho = \int_0^T \dfrac{s(0:t)\,s(1:t)\,dt}{(E_0 E_1)^{1/2}}$
Noise spectral density (one-sided)		Φ
Interference-to-signal ratio	η	$\eta = \begin{cases} \dfrac{P_i A_F^2(\omega_i)}{(4\lambda)^2} & \text{for sinusoidal interference} \\ (4\lambda)^{-2} \int_{-\infty}^{\infty} G_i(f) A_F^2(\omega)\,df & \text{for Gaussian interference} \end{cases}$
Power of the interfering sine wave		P_i
Frequency of the interfering sine wave		ω_i
Amplitude response of the bit detector		$A_F(\omega)$
Power spectral density of the Gaussian interference (two-sided)		$G_i(f)$
Interference-to-noise ratio	ξ	$\xi = \begin{cases} \dfrac{P_i A_F^2(\omega_i)}{8\lambda} & \text{for sinusoidal interference} \\ \dfrac{1}{8\lambda} \int_{-\infty}^{\infty} G_i(f) A_F^2(\omega)\,df & \text{for Gaussian interference} \end{cases}$ $= 2\lambda\eta$
Degradation factor	δ	The factor by which λ must be increased to make the receiver bit error probability, when an interfering signal is present, equal to what it would be were the interfering signal absent.

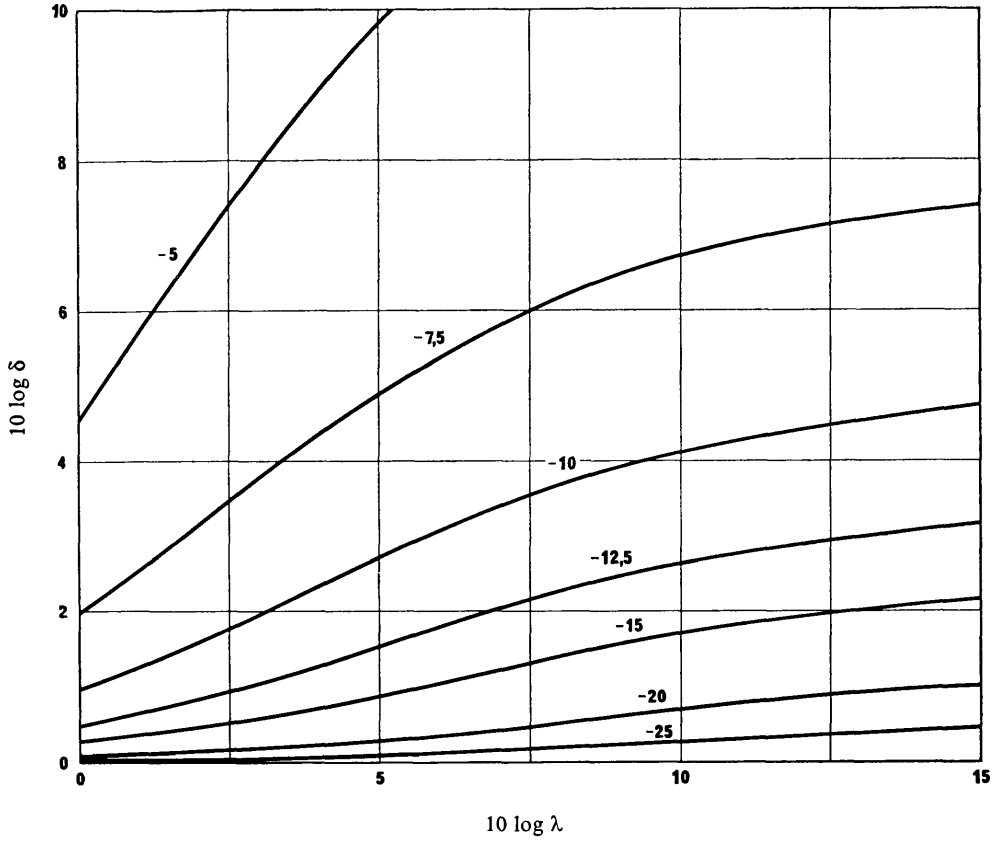


FIGURE 1 – *10 log δ for sinusoidal interference and constant η as a function of 10 log λ for selected values of 10 log η*

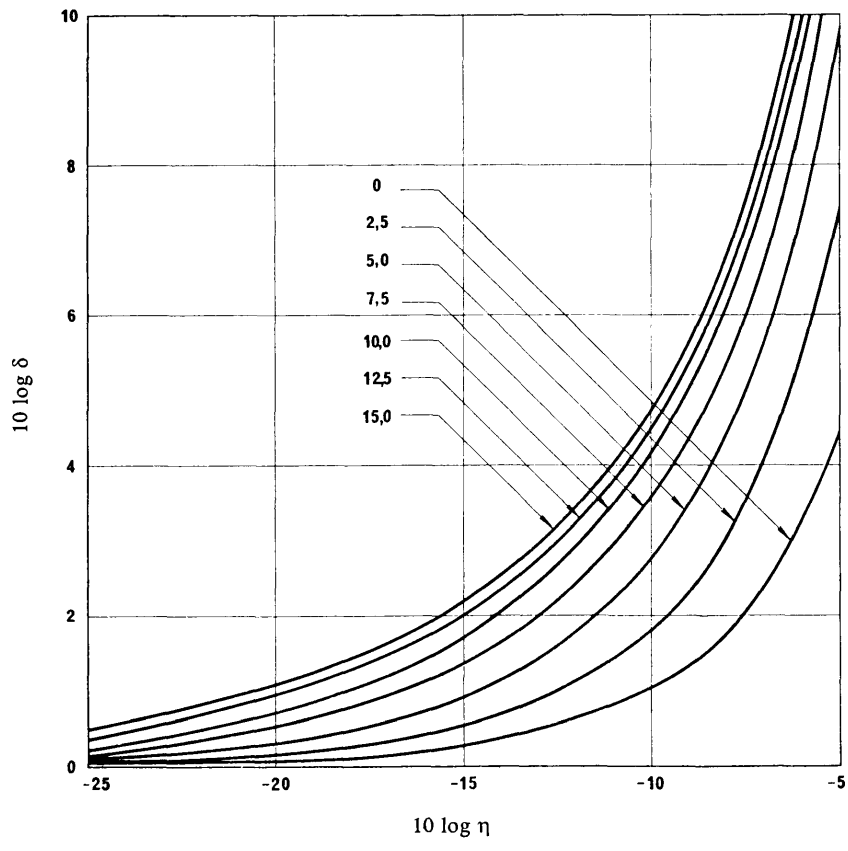


FIGURE 2 – *10 log δ for sinusoidal interference and constant λ as a function of 10 log η for selected values of 10 log λ*

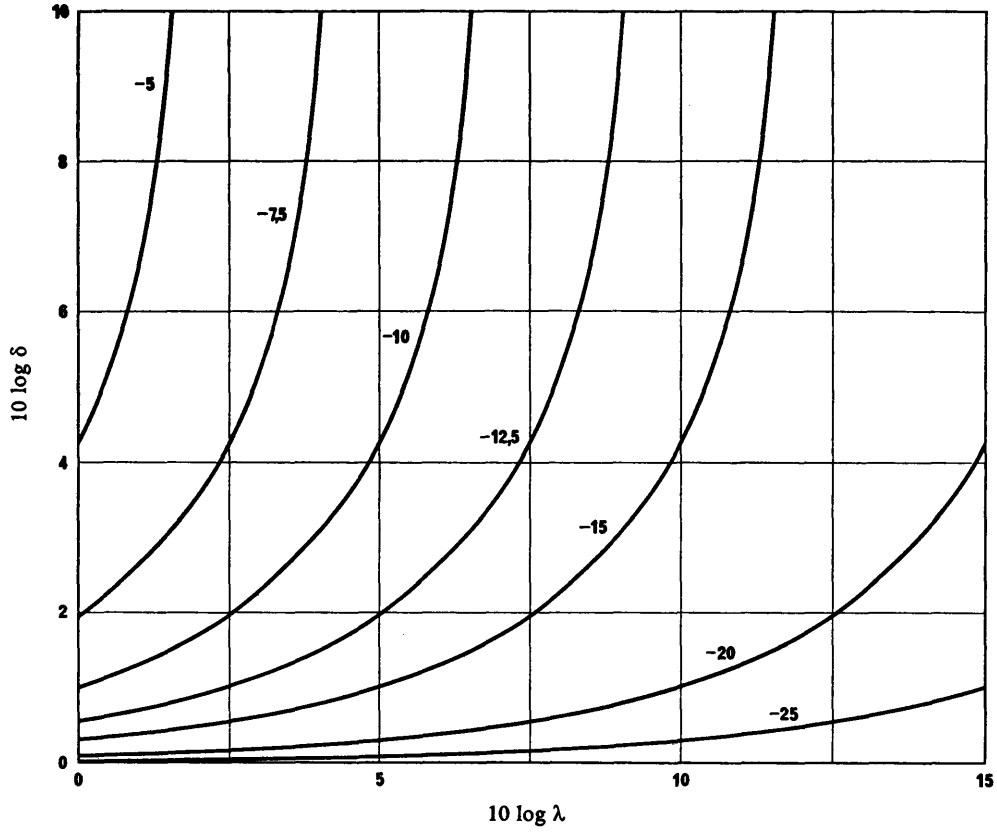


FIGURE 3 – *10 log δ for Gaussian interference and constant η as a function of 10 log λ for selected values of 10 log η*

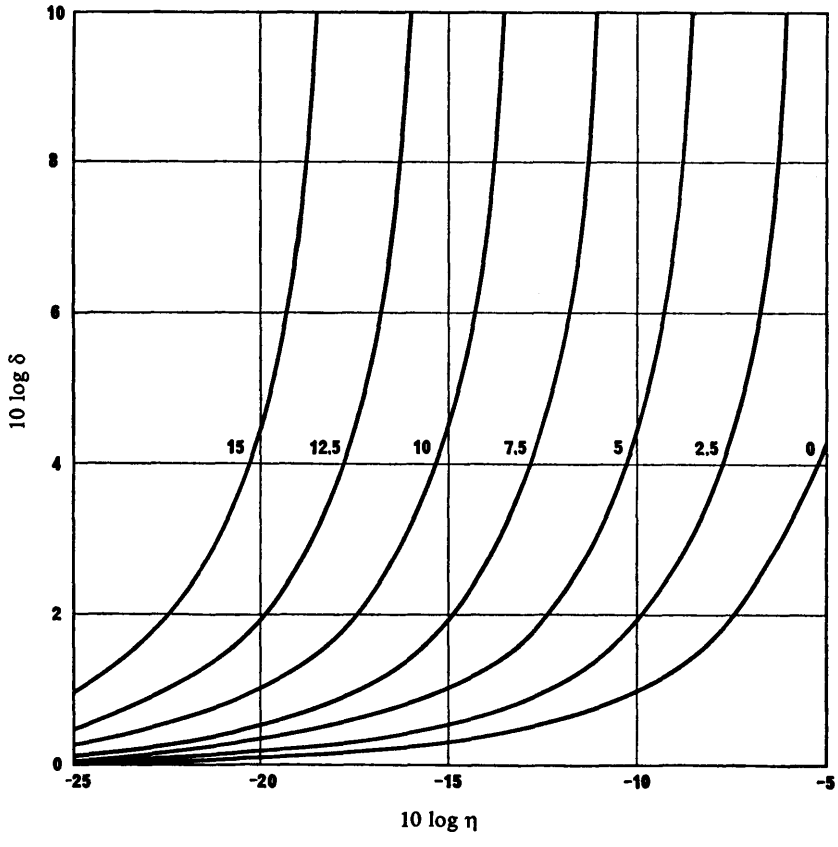


FIGURE 4 – *10 log δ for Gaussian interference and constant λ as a function of 10 log η for selected values of 10 log λ*

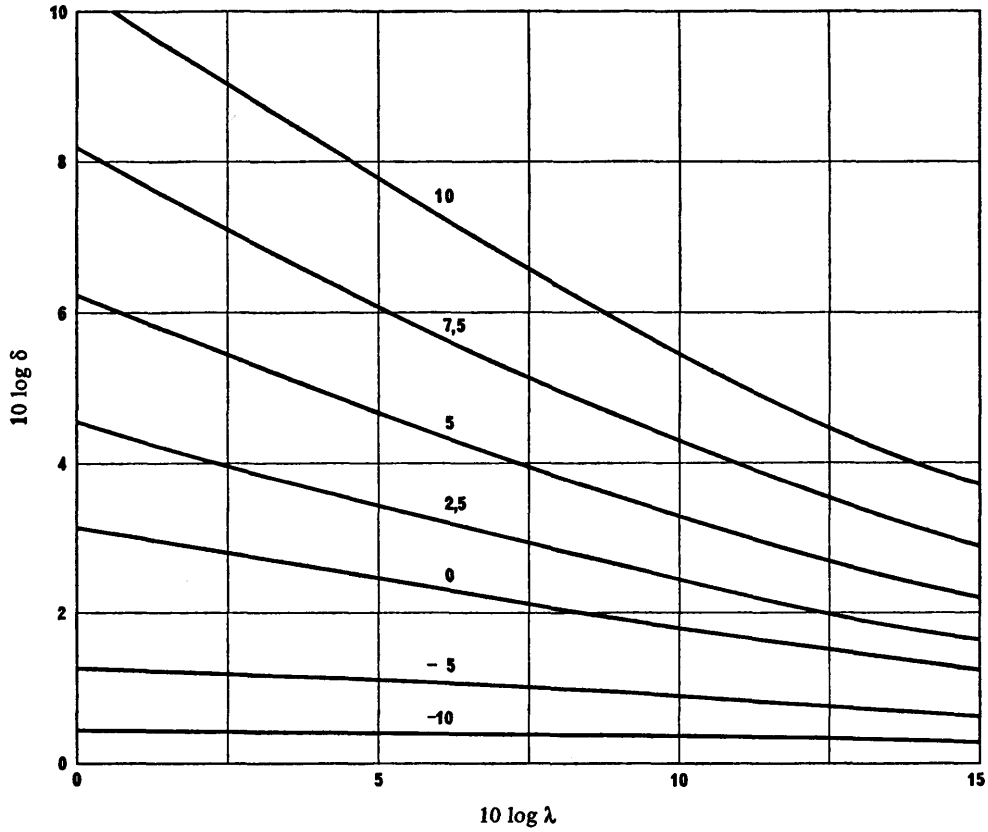


FIGURE 5 – *10 log δ for sinusoidal interference and constant ξ as a function of 10 log λ for selected values of 10 log ξ*

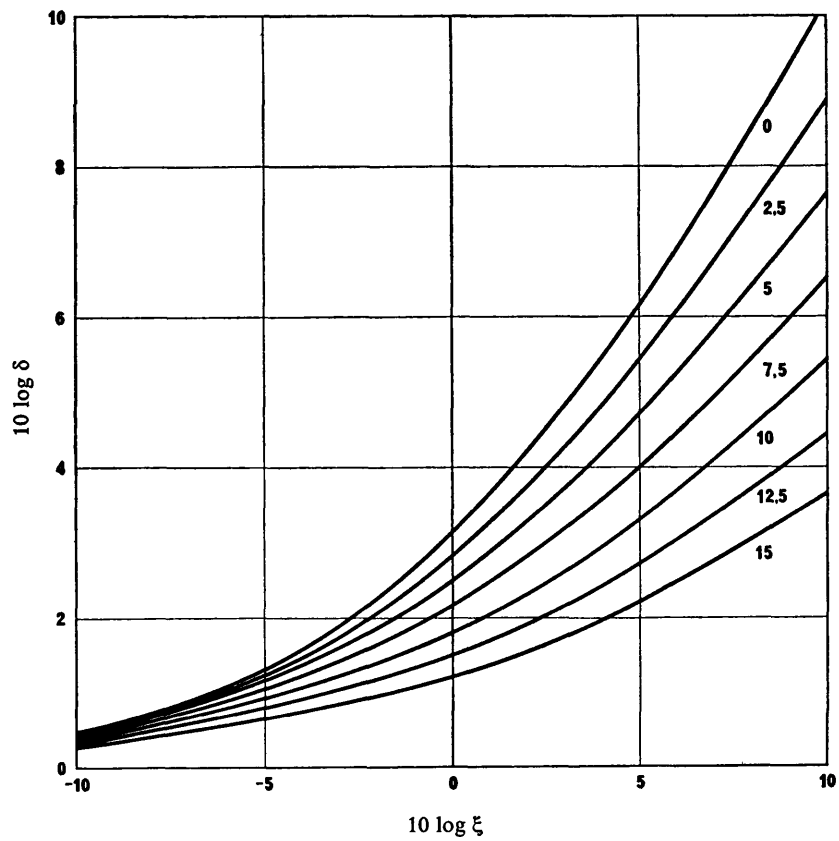


FIGURE 6 – *10 log δ for sinusoidal interference and constant λ as a function of 10 log ξ for selected values of 10 log λ*

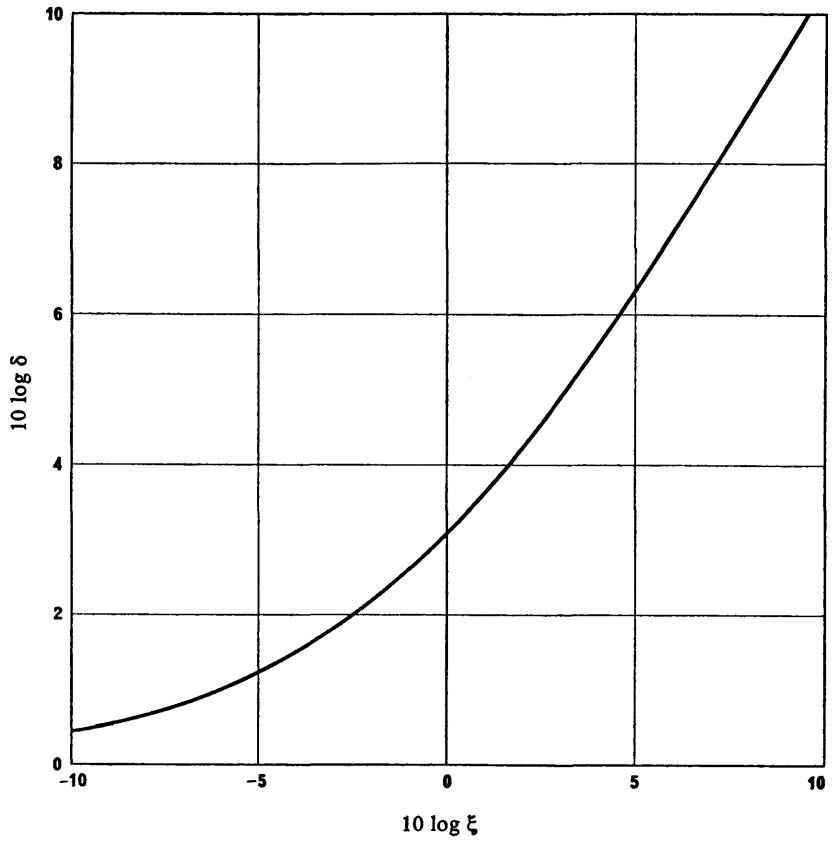


FIGURE 7 – *10 log δ for Gaussian interference as a function of 10 log ξ for all values of λ*

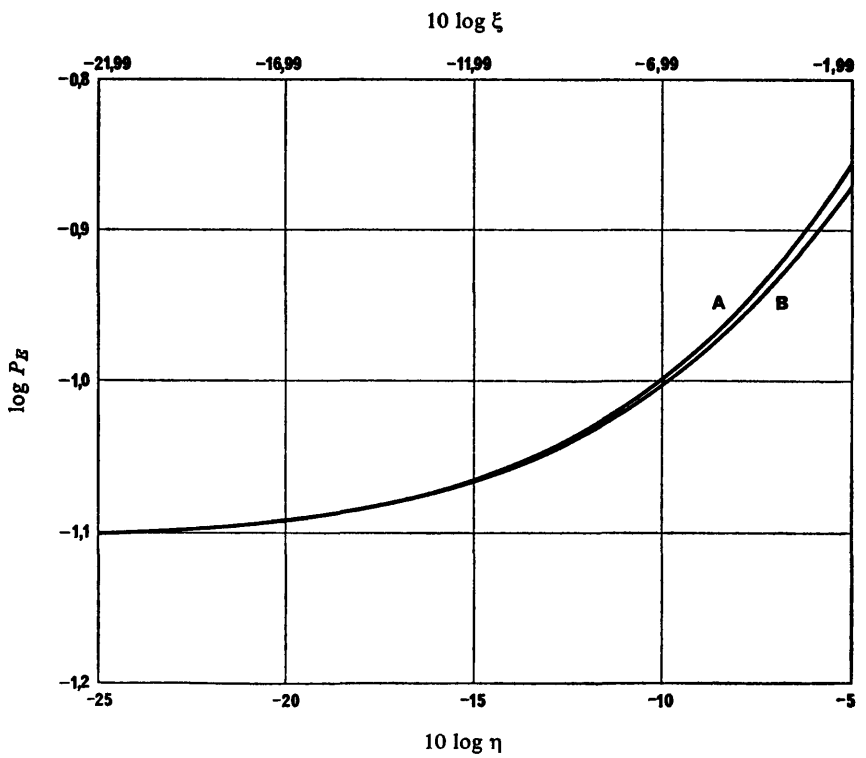


FIGURE 8 – *Comparison of receiver error probability for sinusoidal and Gaussian interference as a function of 10 log η and 10 log ξ for 10 log λ = 0.0*

A: sinusoidal B: Gaussian

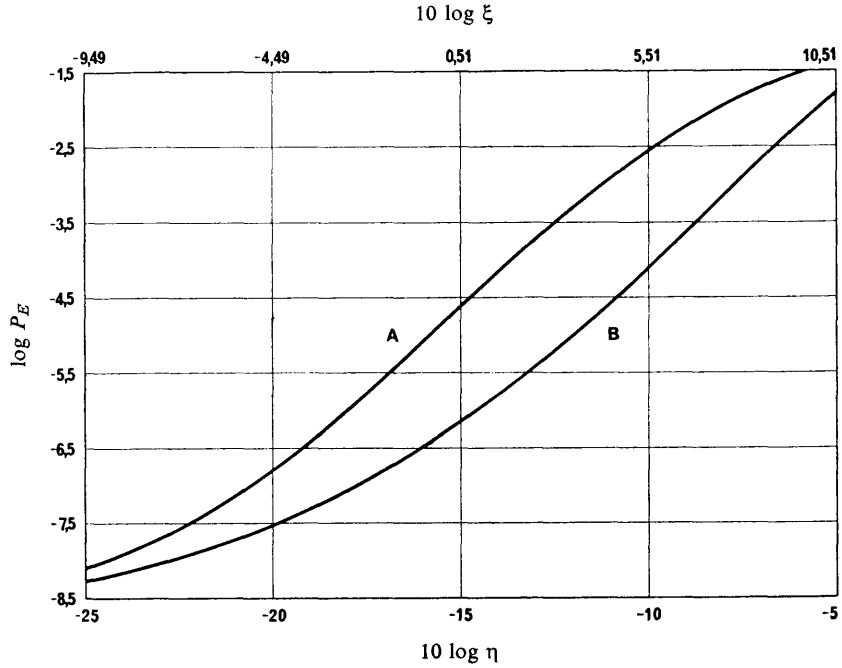


FIGURE 9 – *Comparison of receiver error probability for sinusoidal and Gaussian interference as a function of 10 log η and 10 log ξ for 10 log λ = 12.5*

A: Gaussian B: sinusoidal

REPORT 537-1

TECHNICAL CHARACTERISTICS AND SHARING CONSIDERATIONS FOR RADIO LINKS BETWEEN EARTH STATIONS AND RESEARCH SPACECRAFT BY MEANS OF SPACE STATIONS, IN BANDS 8, 9, 10 AND 11

(Question 11-1/2)

(1974 - 1978)

1. Introduction

This Report presents a summary of technical characteristics and system parameters of telecommunications links in bands 8, 9, 10 and 11, between earth stations and near-Earth orbiting space stations, which use one or more geostationary satellites as intermediate relays.

The possibility of using data relay space stations is mentioned in Report 548-1. The present Report will indicate the extent to which the conclusions of Report 548-1 are affected by arrangements which use intermediate satellites, as compared with direct communication between earth stations and earth-orbiting mission spacecraft.

Annex I of this Report provides a general analysis of sharing considerations for radio links between earth stations and space research by means of space stations. Annex II presents the results of experiments performed to test the concept of a geostationary relay satellite system, using the NASA experimental satellite ATS-6 as the relay satellite.

2. General system considerations

There are four classes of telecommunication systems which are required by nearly all spacecraft. These are:

- a telemetering maintenance system for transmitting to the earth station data obtained from the sensor systems in the spacecraft, or from its human occupants;
- a mission telemetry system capable of transmitting mission-gathered data, including sensor data in unmanned missions and sensor, television and voice communications in manned missions;

– a tracking system to provide information regarding the position and velocity of the spacecraft, which is necessary for computing its orbit;

– a telecommand system to effect guidance and control of the spacecraft from the ground.

Ideally, it should be possible to communicate with the spacecraft at all times. With available land based tracking stations, various factors combine to limit coverage to only a fraction of a given orbit. Frequently, critical decision points in a space mission occur when the research spacecraft is beyond the line-of-sight of these stations.

There are two alternative approaches to improving the degree of coverage of the terrestrial network. One approach is by expanding the network, a procedure which is restricted by geographical and economic considerations. The other approach is to use communications repeaters contained in earth-satellites preferably in geostationary orbit, to relay data between research spacecraft and a few strategically located earth stations.

A system of tracking and data relay satellites (TDRS) can provide continuous or nearly continuous communication between research spacecraft and the Earth. The basic geometry of the coverage obtainable from the geostationary satellite orbit is illustrated in Fig. 1. This figure shows the angles subtended at the geostationary orbit satellite by the Earth (α), by a 645 km orbit (β), by a 6450 km orbit (Ψ), and the figure also gives the percentages of these two orbits that are visible to a single data relay spacecraft (AA, BB respectively).

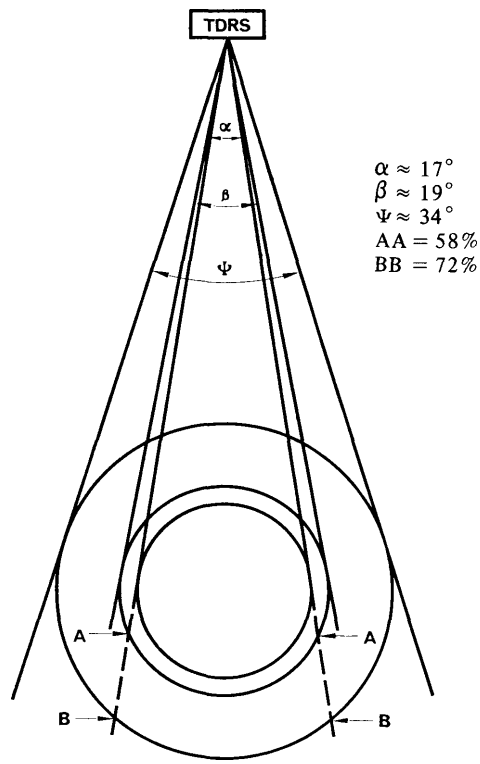


FIGURE 1 – *Geometric relations in a tracking and data relay satellite system (TDRS)*

The introduction of a system of data relay satellites will, as a broad generalization, introduce the need for new frequency bands for communication between an earth station and a data relay spacecraft (it being assumed that the frequencies which would normally be used for direct communication between the mission spacecraft and the earth stations will, instead, be used between the mission spacecraft and the data relay satellite). In this Report, the links between a data relay spacecraft and a mission spacecraft are assumed to operate in bands 8, 9, 10 or 11, and the links between a data relay spacecraft and an earth station are assumed to operate in band 10. It is also assumed that low-data-rate maintenance telemetry can be multiplexed with high-rate data.

An analysis using frequency independent techniques for relay space link sharing considerations is given in Annex I of this Report. Under system configurations which are not easily represented by the approach taken in the body of this Report, the more general approach used in Annex I may prove to be more useful.

3. Detailed considerations of the systems and of the interference

3.1 *Communication between earth stations and tracking and data relay satellites (TDRS)*

3.1.1 *Transmissions from earth station to intermediate relay satellite*

The primary functions served in this link are telecommand and tracking to the data relay satellite, and telecommand, voice and tracking through the data relay satellite to the mission spacecraft. The bandwidths usually required for telecommand and voice links are of the order of tens of kilohertz, but the need might arise for video or high-speed data transmission.

The bandwidth requirements for spacecraft tracking vary, but using side-tone ranging as a typical example, an 800 kHz sub-carrier, together with a phase measurement accuracy approaching 1°, yields a range accuracy approaching 1 m. Hence, 2 MHz is a typical bandwidth requirement for tracking functions.

The minimum required e.i.r.p. from the earth station, shown in Table I for two typical values of system noise temperature, T, and emission bandwidth, B, has been derived from the following relationship:

$$(P_T + G_T) = 10 \log k + 10 \log T + 10 \log B + C/N - G_R + L_s + L_P \quad (1)$$

where,

P_T: earth station transmitter power (dBW),

G_T: earth station antenna gain (dB),

k: Boltzmann's constant = 1.38×10^{-23} J/K,

T: noise temperature of the tracking and data relay satellite receiving system (K),

B: bandwidth required by the receiver (Hz),

C/N: carrier-to-noise ratio of the receiving system at threshold (dB),

G_R: TDRS receiver antenna gain (dB),

L_P: Basic transmission loss = $32.44 + 20 \log f + 20 \log d$ dB
(see Fig. 2),
with f in MHz and d in km

L_s: system losses (dB).

The actual value of $P_T + G_T$, and the corresponding G/T of the space station receiver, will be influenced by whether the frequency band is shared or not, and if it is shared, it will be influenced by the aggregate power from terrestrial transmitters expected at the input of the data relay satellite receiver. By using attainable values of $(P_T + G_T)$ considerably greater than those indicated in Table I to achieve minimum carrier-to-noise ratio C/N, it is anticipated that the values of unwanted interference power, P_i, can be allowed to be equal to the value of the product kTB, for the space station receiver of the tracking and data relay satellite.

3.1.2 *Transmission from TDRS spacecraft to earth stations*

Six functions can be identified with this link, viz.:

- data relay satellite telemetry;
- data relay satellite tracking;
- mission spacecraft telemetry;
- mission spacecraft voice channel;
- mission spacecraft video channel;
- mission spacecraft tracking.

Assuming earth stations with antennae of about 2.5 to 10 m in diameter and with system noise temperatures ranging from 100 to 300 K, and then, on this basis, using the formula in § 3.1.1, the required e.i.r.p. from data relay satellites is found to range from 39 to 56 dBW (see Table II). The corresponding *minimum* values of emission bandwidth (flat), B, to comply with the limitations of No. 470 NM Spa2, of the Radio Regulations (-152 dB(W/m^2) in any 4 kHz), are 3.16 and 158 MHz. Since the latter bandwidth exceeds the assumed bandwidth of 100 MHz, the G_T of the earth station must be increased by 2 dB.

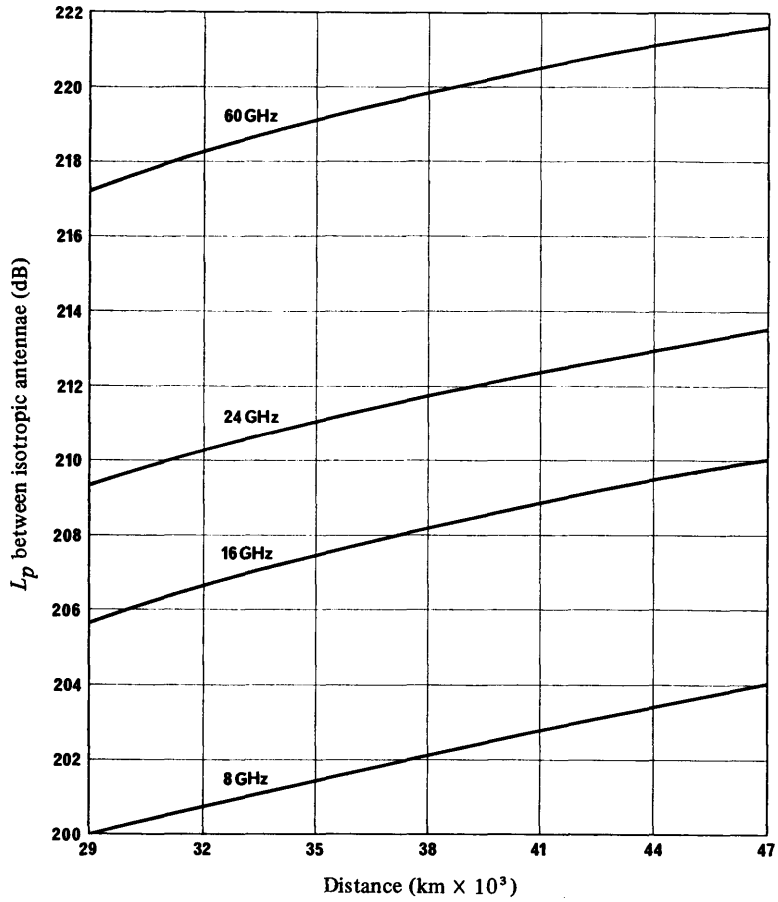


FIGURE 2 – *Basic transmission loss as a function of distance and frequency*

$L_P = 32.44 + 20 \log D + 20 \log f$
with D in km and f in MHz

TABLE I – *Example of the calculation of the link: tracking and data relay earth station to the satellite, for the frequency of 15 GHz*

Data relay satellite receiver parameters:		
T (K)	600	300
B (MHz)	3	20
kTB (dBW)	−136·0	−130·8
C/N (dB)	16	16
P_R (dBW)	−120·0	−114·8
G_R (D = 1·5 m) (dB)	42·3	42·3
Losses:		
L_P (42 000 km) (dB)	208·5	208·5
L_S (dB)	2	2
Minimum required earth station e.i.r.p.:		
($P_T + G_T$) (dBW)	+48·2	+53·4

These values of e.i.r.p. are not frequency dependent if the area of the data relay satellite receiving antenna is maintained constant. This assumption is valid up to about 20 GHz if minimum beamwidth of the satellite antenna is limited to 1°. If the data relay spacecraft antenna gain is maintained constant, the required e.i.r.p. will increase 20 dB per frequency decade. Margins for rain attenuation are not considered.

Table II – *Example of the required e.i.r.p. of TDRS satellite in relation to the earth station sensitivity, 15 GHz*

TABLE II – A

Earth station receiving system characteristics:	
T_S (K)	100
B (MHz)	100
kTB (dBW)	−128·6
C/N min. (dB)	16·0
P_R (dBW)	−112·6
G_R (D_R = 2·5 m) (dB)	48·5
Losses:	
L_P (42 000 km) (dB)	208·5
L_S (dB)	4
Minimum required satellite e.i.r.p.:	
($P_T + G_T$) (dBW)	+51·4

TABLE II – B *Values of ($P_T + G_T$) for other combinations of D_R and T_S (These values of ($P_T + G_T$) are frequency-independent if D_R is fixed)*

D_R (m)	T_S (K)	10 log G/T	$P_T + G_T$ (dBW)
5	100	34·5	45·4
10	100	40·5	39·4
2·5	300	23·7	56·2
5	300	29·7	50·2
10	300	35·7	44·2

3.2 *Communication between tracking and data relay satellites and mission spacecraft*

3.2.1 *Transmission from mission spacecraft to tracking and data relay space stations*

These links are required principally for telemetering, voice, video and tracking purposes. The baseband requirements for telemetering purposes will vary over a wide range, from a small fraction of a MHz for systems having voice or equivalent low data rate outputs, to a maximum of the order of 100 MHz for systems with multiple imaging sensors.

The ranges of those technical characteristics of spacecraft which, during the next decade, will influence the choice of frequency, and which affect sharing feasibility, are expected to be as shown in Table III.

TABLE III – *Technical characteristics of spacecraft*

	1970	1980
Attitude stabilization (degrees)	0·1	0·01
Antenna diameter (m)	3·0	10·0
Receiving system noise temperature, (K)	600	290
Prime power capability, (W)	300	20 000
Transmitter power output, (W)	100	5 000
Antenna gain, (dB)		
3 GHz	36·5	47·0
30 GHz	56·5	67·0
300 GHz	76·5	87·0

Using the characteristics of the spacecraft receiver of the tracking and data relay satellite as given in Table I, and assuming a maximum bandwidth, B, of 100 MHz, the minimum usable values of desired signal, and the corresponding values of e.i.r.p. from the mission spacecraft, have been derived from the values in Table IV, using relation (1), viz.:

$$(P_T + G_T)\ \text{(mission spacecraft)} = 10 \log k + 10 \log T + 10 \log B + C/N - G_R + L_s + L_P$$

Typical minimum values for the desired signal, from Table IV, are -104.8 and -107.8 dBW (these values are also power flux-densities in decibels relative to 1 W/m^2, since a 1.5 m antenna has an effective area of 1 m^2).

3.2.1.1 *Interference from terrestrial transmitter to data relay satellite*

The tolerable value of e.i.r.p. from transmitters in shared services toward the tracking and data relay satellite, will depend upon the station separation plus the atmospheric attenuation in the direction of the tracking and data relay satellite; and the discrimination of the satellite receiving antenna in the direction of the interference. As indicated in Fig. 1, the maximum angle between the limb of the Earth and the space research spacecraft is of the order of 7° to 8°, at which point the isotropic gain of a 1.5 m satellite antenna would be about +10 dB. At all other points towards the Earth, the gain in the direction of the interference sources would be higher.

In general, values of terrestrial e.i.r.p. in the direction of a geostationary tracking and data relay satellite are limited by the relationship:

$$P_U = P_W + \Delta G_U - C/N - N/I - \Delta L_P \qquad (2)$$

where,

P_U: e.i.r.p. of the undesired signal (dBW),

P_W: e.i.r.p. of the mission spacecraft (dBW),

ΔG_U: TDRS antenna discrimination, in the direction of P_U (dB),

C/N: minimum usable carrier-to-noise ratio of the tracking and data relay satellite (dB),

N/I: allowable ratio between the satellite thermal noise and terrestrial interference (dB),

$\Delta L_P = L_{P_W} - L_{P_U}$: differential path loss of desired and undesired signal.

3.2.1.2 *Interference from the mission spacecraft transmitter to terrestrial receivers*

Interference effects of the transmissions from the mission spacecraft to the data relay spacecraft (see Table IV) will depend on a number of factors, such as, the emission bandwidth, the effective antenna gain in the direction of the Earth, the atmospheric attenuation, and the maximum permissible power flux-density which will not cause harmful interference to the terrestrial system. When the path between the data relay satellite and the mission spacecraft is nearly tangential to the surface of the Earth, the spacecraft antenna gain in the direction of the Earth is greatest, but the satellite range and the atmospheric attenuation are also at their maxima. For a space research satellite in a 6450 km circular orbit, the horizon range is approximately 11 000 km, the free space spreading loss is 151.7 dB, and the power flux-densities are -88.3 and -91.3 dB(W/m^2) for the values of e.i.r.p. as given in Table IV.

TABLE IV – *Example of the calculation of required values of e.i.r.p. from a mission spacecraft to a TDRS space station*

TDRS receiving system parameters:		
T (K)	600	300
B (MHz)	100	100
kTB (dBW)	−120·8	−123·8
C/N (min.) (dB)	16	16
P_R (dBW)	−104·8	−107·8
G_R (D = 1·5 m, 15 GHz) (dB)	42·3	42·3
System losses:		
L_P (42 000 km) (dB)	208·5	208·5
L_S (dB)	2	2
Mission spacecraft e.i.r.p.:		
$(P_T + G_T)$ (dBW)	+63·4	+60·4

These values of e.i.r.p. are not frequency dependent if the area of the data relay satellite receiving antenna is maintained constant. This assumption is valid up to about 20 GHz if minimum beamwidth of the satellite antenna is limited to 1°. If the data relay spacecraft antenna gain is maintained constant, the required e.i.r.p. will increase 20 dB per frequency decade.

3.2.2 *Transmissions from data relay spacecraft to mission spacecraft*

The link from the data relay satellite to the mission spacecraft is essentially a telecommand and tracking channel having a possible bandwidth of from 3 to 20 MHz (see Table I).

The required e.i.r.p. from the data relay satellite is essentially the same as that given in Table I, assuming similar parameters for the relay satellite and the mission spacecraft receiving systems.

3.2.3 *Antennae and frequencies used for future links between TDRS and mission spacecraft*

The number of satellites will increase because of the progress of satellite launch vehicles. Near-Moon spacecraft will appear in addition to numerous near-Earth orbiting satellites. A related tracking and data relay satellite (TDRS) could then have the following capabilities:

- transmission of several video channels and high-accuracy ranging signals;
- transmission of data from both near-Earth and near-Moon spacecraft;
- simultaneous service for several mission spacecraft.

The necessary diameter of a TDRS antenna oriented towards a mission spacecraft is determined by distance, link performance, frequency, transmitter power, receiver characteristics, spacecraft structure, etc. The major parameters concerning electrical performance anticipated in about 10 years time for such a system are as shown in Table V. The difference compared with the case in § 3.2.1 is that the receiving system noise temperature is a function of frequency. Fig. 3 shows the relationship between the TDRS antenna diameter and frequency which is derived from Table V and formulae in § 3.1.1. This figure indicates that the antenna diameter becomes large at low frequencies. A TDRS which has the three capabilities mentioned above needs to be equipped with a number of tracking antennae with wide steerability. The diameters are determined by this condition and the size of the TDRS. The maximum size of a TDRS with the characteristics and capabilities as stated, will not exceed 4 m because large space stations at synchronous altitude are not likely to appear within 10 years. Therefore the diameters of the antennae will be probably less than 0.5 m. According to Fig. 3, a TDRS with 0.5 m diameter antennae is capable of relaying video signals or voice signals from near-Earth orbiting spacecraft using frequencies higher than 170 GHz or 1 GHz, respectively, and voice signals from near-Moon spacecraft using frequencies higher than 40 GHz.

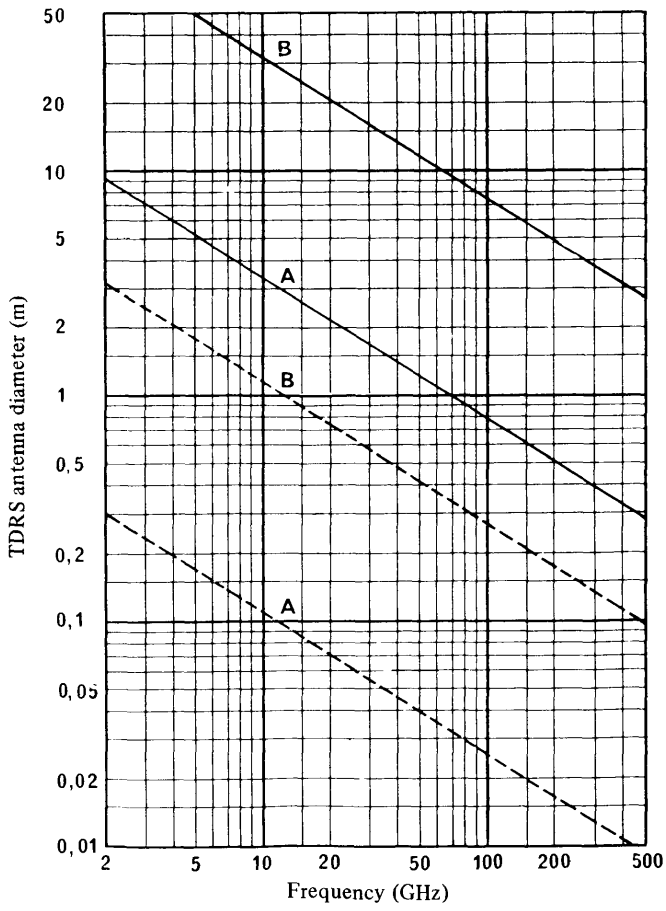


FIGURE 3 – *Relationship between TDRS antenna diameter and frequency*

d : distance between TDRS and mission spacecraft

A: $d = 4.2 \times 10^4$ km (for low altitude mission spacecraft)

B: $d = 4 \times 10^5$ km (for mission spacecraft near the Moon)

——— video
– – – – voice

TABLE V – *Example of TDRS system characteristics*

Mission spacecraft characteristics:	
Transmitter power output (W)	0.5
Antenna diameter (m)	1.5
Aperture efficiency (%)	50
TDRS system parameters:	
Aperture efficiency (%)	50
Feeder loss (dB)	2
Receiving system noise temperature (K)	
3 GHz	500
20 GHz	1300
200 GHz	4000
Performance of transmission channel:	
Bandwidth (MHz)	
video	5
voice	0.01
C/N (dB)	10
Margia (dB)	3

Table VI shows an example of calculations of the link at 185 GHz between a TDRS and a mission spacecraft. A TDRS operating at 185 GHz and using a number of 0.5 m diameter antennae can relay video signals from near-Earth orbiting spacecraft and voice signals from near-Moon spacecraft simply by changing the bandwidth of TDRS receiver filters. Consequently, the low-data-rate link between near-Moon spacecraft and a TDRS can be provided on an economical basis by common use of the link with near-Earth orbiting spacecraft. Thus studies of devices and equipment using the 185 GHz band help to make possible the above-mentioned tracking and data relay satellites in the future.

TABLE VI – *Example of the calculation of the link: mission spacecraft to tracking and data relay satellite at 185 GHz*

	Spacecraft near the moon	Low altitude mission spacecraft
Mission spacecraft:		
P_T (0.5 W) (dBW)	−3	
G_T (D = 1.5 m) (dB)	66	
e.i.r.p. (dBW)	63	
Free space transmission loss:		
L_P (dB)		
(4.2×10^4 km)		230
(4×10^5 km)	250	
Data relay satellite receiver parameters:		
G_R (D = 0.5 m) (dB)	57	
Feeder loss (dB)	2	
kT (dBW/Hz)	−192	
P_R (dBW)	−132	−112
B (MHz)	0.05	5
kTB (dBW)	−145	−125
Margin (dB)	3	3
C/N (dB)	10	10

ANNEX I

SHARING CONSIDERATIONS FOR RADIO LINKS BETWEEN EARTH STATIONS AND RESEARCH SPACECRAFT BY MEANS OF SPACE STATIONS

1. Introduction

In Report 548-1 it is noted that some, or all, of the functions of telemetry, tracking and telecommand, may be accomplished either by means of radio links directly between the spacecraft and earth station, or by means of space stations contained in earth satellites for the purpose of relaying data.

The main part of this Report presents a summary of typical technical characteristics and system parameters of telecommunication links between earth stations and near-Earth orbiting space stations, using one or more geostationary satellites as intermediate relays.

The purpose of this Annex is to examine the technical feasibility of frequency sharing between space research systems using intermediate satellite relays, and other terrestrial systems. Sharing with other space systems is not considered.

2. Approach

In the analysis which follows, for purposes of illustration, frequencies in bands 9 or 10 are assumed so that both the near-Earth satellite and the intermediate relay satellite can use antennae with substantial gain and directivity.

Fig. 4 illustrates a hypothetical system involving an intermediate geostationary satellite to relay data from the near-Earth satellite to an earth station. The two paths from earth station to relay spacecraft and from relay spacecraft to mission spacecraft are combined in tandem for analysis to form a forward link which is considered in the context of this Annex to be an Earth-to-space link. The two return paths are combined to form a return link which is considered in this context to be a space-to-Earth link. The potential interference paths to and from terrestrial systems, together with inherent noise sources, are shown in Fig. 4.

The forward link is used primarily for telecommand purposes to guide and control the mission spacecraft and on-board experiments, or to communicate with astronauts aboard manned spacecraft. The return link is used primarily for transmission of telemetered data from sensor systems aboard the mission spacecraft, or for communications from astronauts. Both forward and return links are also normally used for tracking data for spacecraft guidance and control. Data rate requirements on both the forward and return links could range from 100 bit/s to 50 Mbit/s.

3. Interference analysis

The objective of this interference analysis is to determine the limitations or constraints on space research system designs necessary to ensure that no harmful interference is suffered by either terrestrial systems or the space research system. The analysis is based on the detailed interference model as shown in Fig. 4 which assumes a linear relay satellite transponder, a separate receiver and transmitter aboard the user spacecraft, interference sources from terrestrial system transmitters at each of the frequencies used in the system, and system noise contributions at each of the transponder or receiver inputs.

3.1 *Definition of terms and nomenclature*

The following terms are used in the interference analysis based on the model shown in Fig. 4. Numbered subscripts are used to designate the basic path with which the elements are associated.

R_B: desired signal data rate (bit/s)

B_I: radio-frequency bandwidth of the interference signal (Hz)

B_{RF}: transmitted bandwidth of the desired signal (Hz) (after spread-spectrum techniques are applied)

D: spreading factor due to spread-spectrum techniques (dimensionless)

E: signal (or interference) e.i.r.p. of transmitter system (W/Hz)

E^*: composite signal, interference, and noise e.i.r.p. of space research transmitter system (W/Hz)

f: operating frequency (MHz)

G_R: main beam receiver antenna gain relative to isotropic (dimensionless)

G_T: main beam transmitter antenna gain relative to isotropic (dimensionless)

ΔG: off-axis antenna gain discrimination relative to main beam (dimensionless)

h: altitude of spacecraft (km)

I: interference power density at input to relay spacecraft receiver (W/Hz)

k: Boltzmann's constant (1.38×10^{-23} J/K)

L_p: free space path loss as a function of frequency and distance (dimensionless)

N: noise power density in receiver system (W/Hz)

PFD: power flux-density at the surface of the Earth ($W/m^2 \cdot 4$ kHz)

R: distance from relay satellite or from the user spacecraft to the terrestrial receiver (km)

S: desired signal power density at input to relay satellite receiver (W/Hz)

S^*: composite power spectral density of desired signal, interference, and noise at input to a given receiver (W/Hz)

T: receiver system noise temperature (K)

η: post-detection signal to interference-plus-noise energy ratio (dimensionless)

ω: transmission gain from relay satellite transponder input to user spacecraft (or earth station) receiver input (dimensionless)

$\alpha = ED/L_p$
$\beta = E'/(Lp'D')$
$r = kT$
} parameters used to simplify expression.

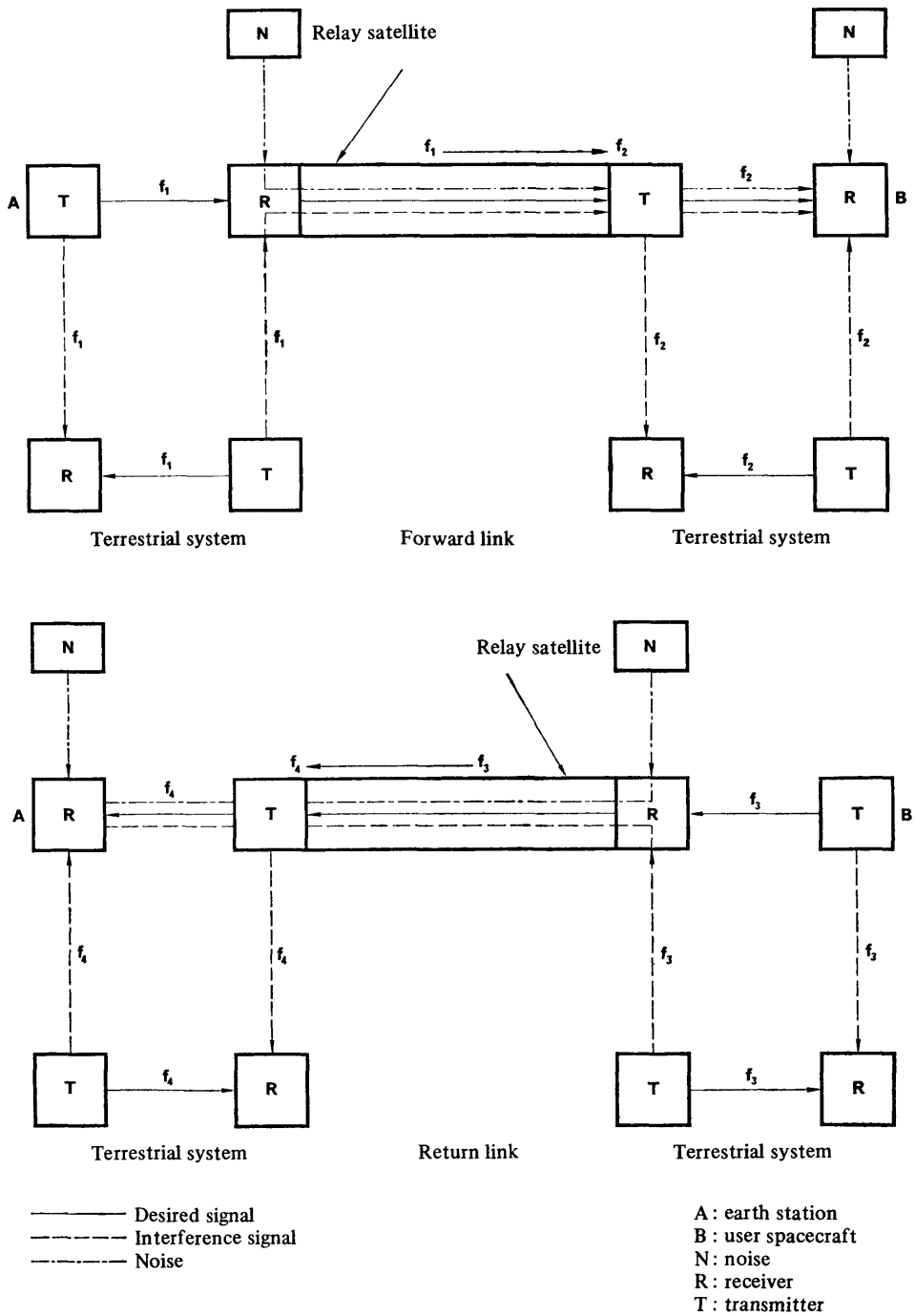


FIGURE 4 – *Satellite relay system*
Desired signal and potential interference paths

3.2 *Standard expressions*

Certain standard expressions used in the analysis are concerned with determining the spreading factor, the e.i.r.p. at a spacecraft that yields a specific power flux-density at the surface of the Earth, and the free-space path loss. In these equations, the subscript "i" represents the basic path with which the term is associated. Single primes designate interference from terrestrial transmitters to the space research system and double primes designate interference to terrestrial receivers from the space research system.

The spreading factor due to pseudo random coding of the desired signal is given by:

$$D_i = B_{RFi}/R_B \tag{3}$$

and for the interfering signal by:

$$D'_i = B_{RFi}/B_{Ii} \tag{4}$$

The spacecraft e.i.r.p. required for a specific power flux-density at the surface of the Earth is given by:

$$E''_i = \pi\,(10^3\,R_i)^2\,B_{RFi}\,PFD_i \qquad \text{W/Hz} \tag{5}$$

This equation assumes a uniform distribution of e.i.r.p. over the radio-frequency bandwidth and that the radio-frequency bandwidth is equal to or greater than 4 kHz.

The free-space path loss as a function of frequency and distance is given by:

$$L_{pi} = (1.754 \times 10^3) f_i^2\,R_i^2 \tag{6}$$

3.3 *Constraints and procedures used in the analysis*

3.3.1 *Assumptions and constraints*

The following assumptions and constraints were used in this analysis:

- a linear transponder is assumed for the relay satellite;
- the space research relay system capacity requirements are defined in Table VII;
- the space research and terrestrial system characteristics used are shown in Table VIII;
- a signal to interference-plus-noise energy ratio of 10 dB is assumed to provide a sufficiently low bit error rate for the space research system;
- digital modulation and the use of spread-spectrum techniques (pseudo-random coding) are considered essential to protect the space research system receivers from terrestrial interference. In addition, this type of modulation will limit power flux-density at the surface of the Earth, to values specified in the Radio Regulations;
- the mission satellite has a directional antenna to track the relay satellite.

TABLE VII – *Space research capacity requirements*

Forward link

Path	Data rate
Earth station to relay satellite	Composite of all signals sent to user satellite (50 Mbit/s)
Relay satellite to user satellite	100 bit/s to 100 kbit/s and/or data up to video bandwidths (50 Mbit/s)

Return link

User satellite relay satellite	100 bit/s to 1 Mbit/s and/or data up to video (50 Mbit/s)
Relay satellite to earth station	Composite of all signals received from user satellites

TABLE VIII – *Space research and terrestrial system parameters*

A – Space research

	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)	
Earth station receive system noise temperature (K)						420

B – Terrestrial system (fixed and mobile) parameters

Terrestrial station e.i.r.p. (dB(W/Hz))	−30	−22	−30	−36	−30	−30
Radio-frequency bandwidth (MHz)	26	18	26	18	26	26

(1) Composite of all signals sent to user spacecraft.

(2) Composite of all signals received from user spacecraft.

(3) Based upon slant range to the horizon.

3.3.2 *Procedures*

Based on the analysis constraints listed above, the procedure used in the analysis is essentially as follows:

- forward and return path transmission equations were developed which included interference and noise sources (see § 3.3.3);
- inequalities were developed to define the limitation on the design variables subject to terrestrial system interference constraints (power flux-density limitations) and performance requirements (signal to noise-plus-interference energy ratio equal to or greater than 10 dB).
- the inequalities were reduced to numerical form by the use of:
  - nominal space research system parameters (noise temperatures, path losses, antenna gains, etc.);
  - expected values of interference derived from the terrestrial service characteristics listed in Table VI-B; and
  - the highest *allowable* values of space station and earth station e.i.r.p.'s;
- the inequalities were evaluated to yield bounds on the mission satellite main-beam gain and off-beam discrimination, for the forward link, and on earth station main-beam gain and mission off-beam discrimination for the return link, so as to ensure negligible interference to both the space and terrestrial systems;

– the antenna gain and off-beam discrimination constraints were used to define minimum antenna sizes for the space system. Using these values and a known off-main-beam discrimination pattern, such as the CCIR antenna pattern, the allowable angle between the mission satellite main beam and terrestrial systems can be computed. This angle can then be used to compute the percentage of a visible mission orbit within which space system operation will not cause or receive harmful interference.

3.3.3 *Mathematical analysis of the interference model*

3.3.3.1 *Forward link*

For the forward link (Fig. 4), the post-detection signal to interference-plus-noise ratio (η_{12}) at the mission spacecraft must be equal to or greater than 10 dB. This ratio is given by:

$$\eta_{12} = \frac{S_{12}}{I_{12} + N_{12}} \geqslant 10 \tag{7}$$

The desired signal (S_{12}), interference (I_{12}) and noise (N_{12}) depend in part upon the forward link transmission gain since the signal, interference, and noise components at the input of the relay spacecraft are amplified by the relay satellite transponder and transmitted to the mission spacecraft. This transmission gain is defined as:

$$\omega_{12} = \frac{S_2^*}{(S_1/D_1) + I_1 + N_1} \tag{8}$$

and the mission spacecraft post detection ratio becomes:

$$\eta_{12} = \frac{\omega_{12}\, S_1}{\omega_{12}\,(I_1 + N_1) + (I_2 + N_2)} \geqslant 10 \tag{9}$$

Assuming free space propagation, all of the terms in equation (9) can be defined as follows:

$$S_1 = \alpha_1\, G_{R1} \qquad \alpha_1 = E_1\, D_1/L_{p1}$$

$$S_2^* = \alpha_2\, G_{R2} \qquad \alpha_2 = E_2^*/L_{p2}$$

$$I_1 = \beta_1\, G_{R1} \qquad \beta_1 = E_1'/(L_{p1}'\, D_1')$$

$$I_2 = (\beta_2/\Delta G_{R2})\, G_{R2} \qquad \beta_2 = E_2'/(L_{p2}'\, D_2')$$

$$N_1 = r_1 \qquad r_1 = kT_1$$

$$N_2 = r_2 \qquad r_2 = kT_2$$

The term E_2 * is the output e.i.r.p. of the relay spacecraft at f_2 and is constrained by the power flux-density limitations set out in the Radio Regulations.

The design parameters of interest are the mission spacecraft antenna gain (G_{R2}) towards the relay spacecraft, the mission spacecraft antenna gain discrimination (ΔG_{R2}) towards the terrestrial receivers, and the relay satellite antenna gain (G_{R1}). Inequalities for these parameters can be derived from the expression for η_{12}, under the conditions that the signal at the mission spacecraft (α_1) is at least 10 times greater than the interference (β_1) or:

$$\alpha_1 > 10\,\beta_1 \tag{10}$$

Under this condition:

$$G_{R1} > \frac{10\, r_1}{\alpha_1 - 10\,\beta_1} \tag{11}$$

$$\Delta G_{R2} > \frac{\beta_2\{[(\alpha_1/D_1) + \beta_1]\; G_{R1} + r_1\}}{\alpha_3\{[(\alpha_1/10) - \beta_1]G_{R1} - r_1\}} \tag{12}$$

$$G_{R2} > \frac{r_2\{[(\alpha_1/D_1) + \beta_1]\; G_{R1} + r_1\}}{\alpha_2\{[(\alpha_1/10) - \beta_1]\; G_{R1} - N\} - (\beta_2/\Delta G_{R2})\{[(\alpha_1/D_1) + \beta_1]\; G_{R1} + r_1\}} \tag{13}$$

where each of these inequalities is based upon the condition that the denominator of the following inequality be greater than zero.

These inequalities show the trade-offs between mission spacecraft and the relay satellite receive antenna characteristics the necessary to ensure that the forward communication link does not cause or receive harmful interference.

3.3.3.2 *Return link*

The return link analysis is similar, but not identical, to that for the forward link (see Fig. 4). The basic difference is that the propagation path from an interfering terrestrial transmitter to the space research earth station is not free space. Therefore, this interference term must be considered separately. In the return link, the post detection signal to interference-plus-noise ratio (η_{34}) at the earth station receiver determines the feasibility of sharing with terrestrial systems. The equations derived from this ratio are similar to those used in the forward link, and also require the inclusion of the transmission gain (ω_{34}) from the input to relay satellite to the input of the earth station.

$$\eta_{34} = \frac{S_{34}}{I_{34} + N_{34}} \geqslant 10 \tag{14}$$

$$\omega_{34} = \frac{S_4^*}{(S_3/D_3) + I_3 + N_3} \tag{15}$$

$$\eta_{34} = \frac{\omega_{34}\, S_3}{\omega_{34}\,(I_3 + N_3) + (I_4 + N_4)} \geqslant 10 \tag{16}$$

Except for the interference term, I_4, all the terms in the last equation can be defined as follows, using free space propagation:

$$S_3 = (\alpha_3\, \Delta G_{T3})\, G_{R3} \qquad \alpha_3 = E_3''\, D_3/L_{p3}$$

$$S_4^* = \alpha_4\, G_{R4} \qquad \alpha_4 = E_4^*/L_{p4}$$

$$I_3 = \beta_3\, G_{R3} \qquad \beta_3 = E_3'/(L_{p3}'\, D_3')$$

$$N_3 = r_3 \qquad r_3 = kT_3$$

$$N_4 = r_4 \qquad r_4 = kT_4$$

The terms E_3'', and E_4^* are determined as the values required to ensure that the power flux-density at the surface of the Earth is less than the limitations at f_3 and f_4 respectively, and can be obtained from previous equations using the required parameters. The term ΔG_{T3} is the off-axis gain *discrimination* of the user spacecraft transmit antenna.

The design parameters of interest are the levels of interference (I_4) at the earth station from terrestrial transmitters, the earth station antenna gain (G_{R4}), the off-axis gain discrimination of the user spacecraft transmit antenna (G_{T3}). The inequalities required to establish these parameters are:

$$\Delta G_{T3} > \frac{10\,(\beta_3\, G_{R3} + r_3)}{\alpha_3\, G_{R3}} \tag{17}$$

$$G_{R4} > \frac{r_4\,\{[(\alpha_3\, \Delta G_{T3}/D_3) + \beta_3]\, G_{R3} + r_3\}}{\alpha_4\,\{[(\alpha_3\, \Delta G_{T3}/10) - \beta_3]\, G_{R3} - r_3\}} \tag{18}$$

$$I_4 < \frac{\alpha_4\, G_{R4}\,\{[(\alpha_3\, \Delta G_{T3}/10) - \beta_3]\, G_{R3} - r_3\}}{\{[(\alpha_3\, \Delta G_{T3}/D_3) + \beta_3]\, G_{R3} + r_3\}} - r_4 \tag{19}$$

where the inequality for G_{R4} is the condition that the right-hand side of the inequality for I_4 be positive (i.e., the interference transmitted from the mission spacecraft towards the terrestrial receivers cannot be a negative number) and the inequality for ΔG_{T3} is the condition that the denomination of the G_{T3} inequality be positive.

These inequalities show the trade-offs between mission spacecraft and relay spacecraft antenna characteristics.

4. Discussion

The two sets of inequalities set forth above, defining allowable values of the parameters G_{R2}, ΔG_{R2}, G_{R1}, α_1 and I_4, G_{R4}, ΔG_T, G_{R3}, α_3 establish the constraints under which sharing is feasible between terrestrial systems and space research systems involving intermediate relay spacecraft.

Figs. 5 and 6 show some sample results of this type of analysis when typical system parameters are used. Fig. 5 shows the inequalities for a relay satellite system which uses band 9 between the mission spacecraft and relay satellite and band 10 between the relay satellite and the earth station. Fig. 6 shows the results when all communications take place in band 10. These figures should be interpreted as explained below. *

A decision as to whether or not frequency sharing is feasible between terrestrial systems and a relay system depends upon the practicality of designing the relay system subject to constraints imposed on the antennae aboard the relay spacecraft, mission spacecraft and receiving earth stations. These constraints arise from the necessity of having sufficient antenna main-beam gain in the desired direction and at the same time, adequate off-axis discrimination toward the terrestrial system. Thus, the feasibility is dependent upon the proper design of the various antenna systems.

Figs. 5*(a)* and 6*(a)* show the minimum relationships between the mission spacecraft (at 500 km altitude) receiver main-beam antenna gain and the off-axis discrimination toward the terrestrial transmitter, required to protect the forward link from interference. Any point that lies above and to the right of the curves (shaded area) represents combinations of main-beam gain and discrimination that will satisfy the sharing criteria.

In a similar manner, the return link constraints are shown in Figs. 5*(b)* and 6*(b)*. In these figures, the minimum relation is between the main beam of the receiving earth-station antenna and the relay satellite transmit antenna off-axis gain discrimination toward the terrestrial receiver. Again, any point that lies above and to the right of the curves represents combinations that will satisfy the sharing criteria.

Based upon the analysis presented in this Annex, it is concluded that a space research system involving a space station relay can be designed to share frequency bands with terrestrial systems. The constraints imposed upon the design of the system will be the need for limiting the e.i.r.p., for adjusting the emission bandwidth of the relay satellite and the mission satellite to values so that power flux-density limitations of the Radio Regulations are not exceeded, and the careful selection of relay satellite and user spacecraft antennae to provide the required off-beam discrimination in the direction of terrestrial systems.

The use of space stations for radio links between earth stations and research spacecraft can provide virtually uninterrupted command, telemetering and tracking capabilities for low and medium altitude research spacecraft (depending upon the number and location of relay space stations); can improve operational efficiency and flexibility; and many improve the efficiency of spectrum utilization, owing to the use of higher frequencies and more directive antennae.

The preliminary analysis presented in this Annex indicates that terrestrial systems might not cause interference to space research systems, and that this approach to frequency sharing is essentially independent of the direction of use (Earth-to-space or space-to-Earth) of frequency bands in the space research service.

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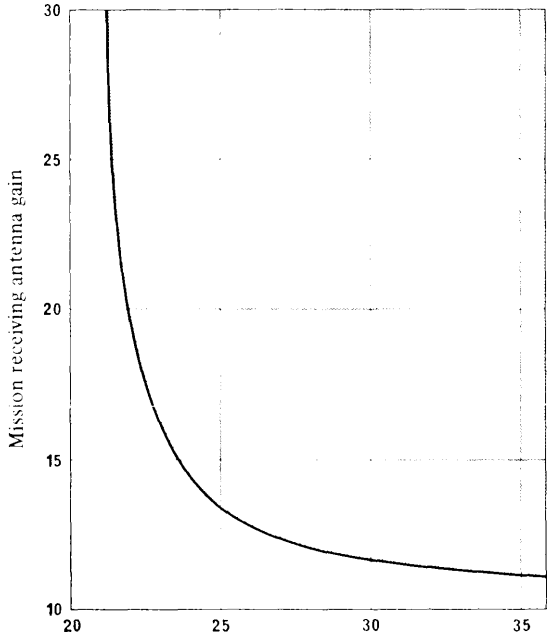
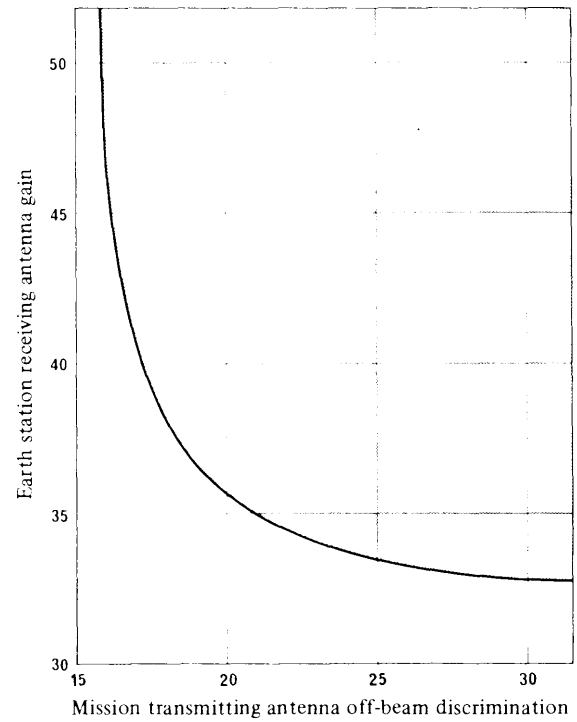
* The typical system parameters used in this analysis are in accordance with those shown in Tables II to V of Report 536-1, except that a wider bandwidth is used to account for pseudo-noise modulation.



Mission receiving antenna off-beam gain discrimination
(dB below main beam gain)

(a) Forward link

Band 10: Earth station to relay satellite
Band 9: Relay satellite to mission spacecraft

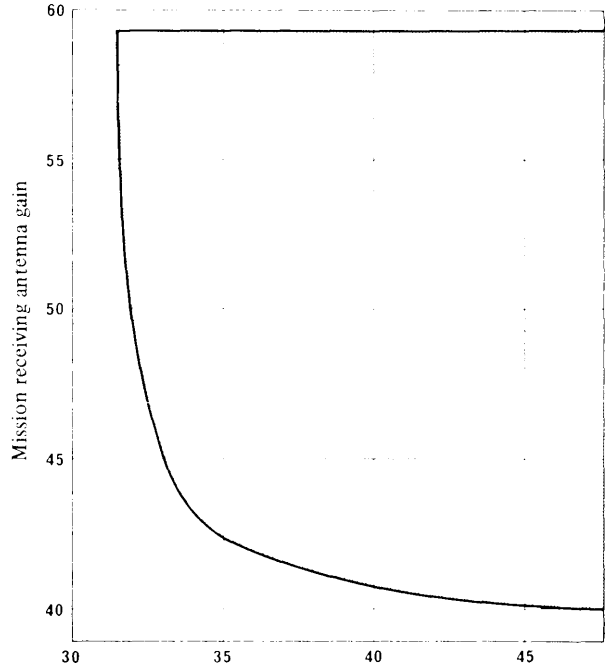


Mission transmitting antenna off-beam discrimination

(b) Return link

Band 9: Mission to relay spacecraft
Band 10: Relay spacecraft to earth station

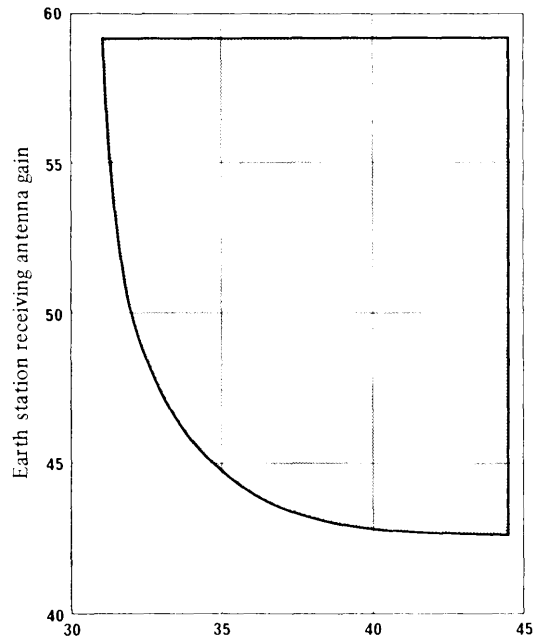
FIGURE 5 – *System constraints for sharing (bands 9 and 10)*



Mission receiving antenna off-beam gain descrimination
(dB below main beam gain)

(a) Forward link

Earth station to relay satellite
Relay satellite to user spacecraft



Mission transmitting antenna off-beam
discrimination

(b) Return link

Mission to relay spacecraft
Relay spacecraft to earth station

FIGURE 6 – *System constraints for sharing (band 10 only)*

ANNEX II

RESULTS OF EXPERIMENTS

1. Introduction

The Report illustrates generally the increased spectrum efficiency which can be provided by an inter-satellite relay system. The purpose of this Annex is to describe an experiment of the feasibility of such a system and to contribute further to the knowledge of the technical characteristics of relayed radio links.

An elevation of relay communication with low orbit satellites resulted from the Tracking and Data Relay Experiment (TDRE) using the NASA experimental satellite ATS-6. Tests were made with low orbit simulators operated at ground test sites, and with two low orbit satellites, GEOS-3 and NIMBUS-6, using ATS-6 as the relay satellite in both cases (see Fig. 7). The tests were designed to demonstrate the effectiveness of relay systems during performance of the normal ground station functions, i.e.,

- command and control;
- acquisition of "housekeeping" and payload telemetry data;
- tracking for orbit determination.

Test results for each of the functions are described in subsequent sections of this Annex. Details of the test data are provided in [CCIR, 1974-78].

2. Frequencies utilized in the experiment

As shown in Fig. 7, links between the ground station and ATS-6 used C-band frequencies. The frequencies for the uplink (ground station to ATS-6) varied between 5900 and 6400 MHz for both the GEOS-3 and NIMBUS-6 tests. Downlink frequencies were between 3700 and 4200 MHz.

Both the GEOS-3 and NIMBUS-6 satellite transponders transmitted and received in S-band. The nominal receive frequency of the GEOS-3 satellite transponder was approximately 2069 MHz and the nominal transmitted frequency was 2247 MHz. The NIMBUS-6 nominal receive frequency was 2062 MHz and the nominal transmit frequency was 2253 MHz.

3. Command and control

Command and control capability were demonstrated by relaying a sequence of mode changing commands and command data for the loading of the memory of the antenna programmer from a ground station at Rosman, N. C. via ATS-6 and NIMBUS-6 simulation equipment in Greenbelt, Maryland. Command bandwidth at the predicted worst case signal level of -135.8 dBW was greater than 30 kHz.

Similarly, in tests involving actual low orbit satellites, command data was reliably relayed, and all systems performed within design specifications. A typical signal level received at GEOS-3 via an ATS-6 retransmission varied less than $\pm$ 3 dBW from the nominal signal level over a 50 minute testing period. Antenna switching, antenna feed switching, and selection of telemetry data format were all successfully achieved by relay of command data within the predicted limits.

4. Acquisition of telemetry and payload data

In the ground simulator tests, telemetry data at 4 kbit/s, from a NIMBUS-6 type transponder, were transmitted virtually error free at all the transmitter levels (2, 4 and 8W). In combination with ranging tones or an experimental data channel on an FM subcarrier, accurate transmission was effected using the 8W power level. Relayed payload data carried on the FM subcarrier were comparable to data directly sent to the ground station from NIMBUS. All GEOS-3 PCM telemetry data transmissions at 1.562 kbit/s, separately or in combination with ranging tones, were within 3 dB of nominal expected performance.

A digital evaluation mode (DEM) was used to determine bit error rate (BER) curves which, when averaged over several test runs, were very close to the predicted BER curve, for various DEM bit rates and transmitter power levels [CCIR, 974-78].

5. Tracking of the low orbit satellites by way of the relay satellite

The purpose of the tracking and orbit determination phase of TDRE was to demonstrate the feasibility of tracking a near-Earth satellite via a geostationary satellite. Orbit computations were successfully performed without the aid of multiple ground station tracking. Range measurement was determined from the delay between transmission and reception of a relayed signal. Range rate data were acquired by Doppler shift measurements. Initial ground tests involved sequentially interrogating widely deployed transponders over a period of time. For several 24-hour tracking tests, results were consistently of high quality, with data noise typically from 0.2 to 0.5 mm/s for range rate, and from 1 to 2.5 m in range.

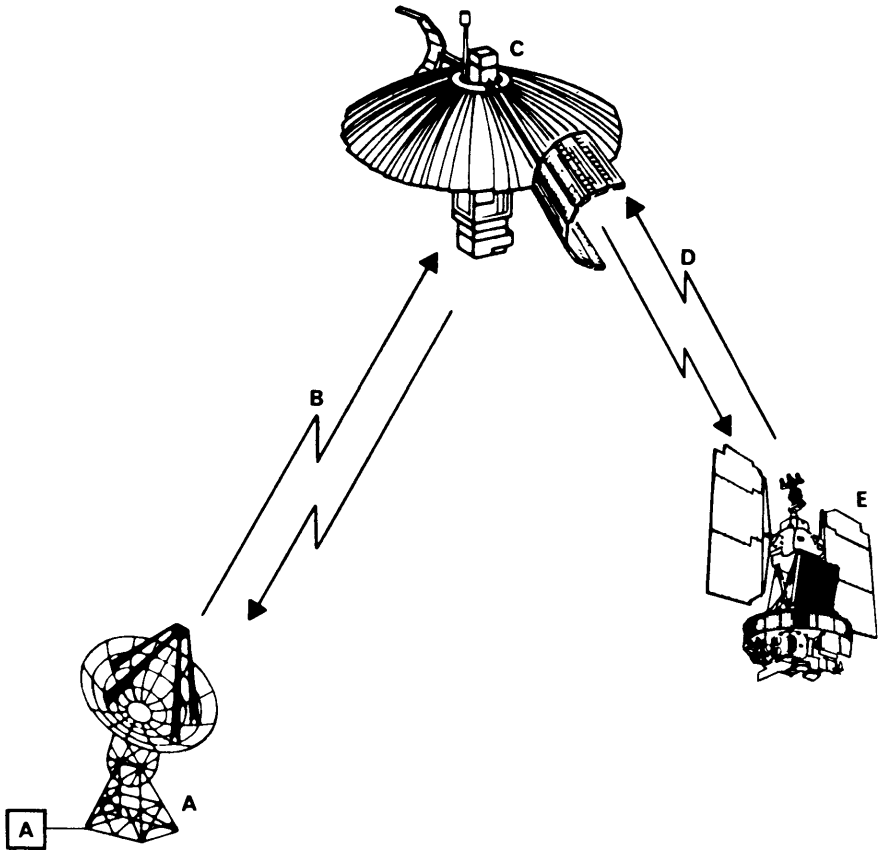


FIGURE 7 – *Experiment configuration*

A : ATS earth station
B : C-band links
C : ATS-6 spacecraft
D : S-band links
E : Low orbit spacecraft

Satisfactory satellite-to-satellite tracking and orbit determination of the GEOS-3 satellite was demonstrated in several 50-hour tracking tests using Doppler data only. In one 34-hour test using both range and range-rate data, the r.m.s. range residual (difference between observed and calculated) was 50 m, and the r.m.s. range rate residual was 0.7 cm/s.

6. Summary and conclusions

The performance of functions normally transmitted in a direct link to an earth station to a low orbit satellite and vice versa have been successfully achieved in an experimental relay system. The experiments were performed using the NASA experimental satellite ATS-6 which provided a convenient method for preliminary testing of the concept of a geosynchronous relay satellite system. The ATS-6 satellite differs from the concept of a geosynchronous data relay satellite, as described in the main body of this Report, in antenna size and in tracking. The tracking of the low-orbit satellites is accomplished by utilizing the physical motion of the ATS-6 spacecraft. Future developments described in the main body of this Report will probably include fully automated electronically scanned and steerable antenna arrays capable of rapidly accessing and interrogating multiple near-Earth satellites. This would permit practical utilization of all the data relay options demonstrated as feasible in the tracking and data relay tests.

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REPORT 687 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH (NEAR-EARTH) AND FIXED AND MOBILE SERVICES IN THE 6 TO 8 GHz SPECTRAL REGION

(Question 1-1/2)

(1978)

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 Earth-to-space transmissions is covered in § 2, sharing with space-to-Earth stransmissions 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 358-2, 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.

TABLE I – *Technical characteristics of space research satellites*

Transmitter power (dBW)	+16
Maximum antenna gain(1) (dBi)	+6
Emission bandwidth (MHz)	100
Spreading loss to satellite horizon (1000 km orbit) (dB/m^2)	−142
Bandwidth conversion (dB(4 kHz/100 MHz))	−44
Spectral distribution factor (dB)(2)	+10
Power flux-density (dB(W/m^2 in 4 kHz))	−154

(1) Pattern shaped to provide constant pfd across satellite field of view.

(2) The spectral distribution factor is the ratio of the maximum spectral power to the mean spectral power averaged over 4 kHz. The value of 10 dB is assumed to be the worst case.

This level of pfd is 2 dB below the limit of -152 dB(W/(m^2 · 4 kHz)) for low angles of arrival.

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.

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 -132.6 dBW.

* This Report is brought to the attention of Study Groups 5, 8 and 9.

TABLE II – *Technical characteristics of space research earth station receivers*

Receiver noise temperature, T_δ(K)	150
Receiver bandwidth, B (MHz)	100
$kT_\delta B$ (100 MHz) (dBW)	−126.8
Average power flux-density(1) (dB(W/m²))	−120
Effective area of receiving antenna, A_R(2) (10 log A_R)	+14.4
Miscellaneous losses (dB)	2.0
P_r (dBW)	−107.6
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 %.

The sharing criterion for this interference path is based upon the application of co-ordination 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:

$$L\,(1\%)^{*} = P_t + G_t - (P_i - G_r) \quad \text{dB} \tag{1}$$

where

P_t: terrestrial transmitter power (dBW)

G_t: terrestrial antenna gain in direction of earth station (dBi)

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

$$L\,(1\%) = P_t + G_t + G_r + 132.6 \quad \text{dB}$$

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 382-3 suggest a value of G_t 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:

$$L\,(1\%) = 8 + 47 + 4.5 + 132.6 \quad \text{dB}$$

or

$$L\,(1\%) = 192.1 \text{ dB}.$$

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 be of the order of 6 dB below the receiver noise power of −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.

* 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. Co-ordination distance data is not yet available for L (1%).

TABLE III – *Technical characteristics of near-Earth space research earth stations and satellites*

Earth station transmitter power (dBW)	8
Earth station antenna gain (dBi)	55
Spreading loss (dB/m²)	−131
Satellite antenna gain (dBi)	+6
Satellite isotropic area	−39.5
Received carrier power (dBW)	−101.5
Satellite receiver noise power (dBW) (2000 K noise temperature, 100 MHz bandwidth)	−115.5
C/N (dB)	14

Transmitter power (dBW)	13
Antenna gain (dBi)	+42
Spreading loss (dB/m²)	−142
Satellite antenna gain (dBi)	+6
Antenna isotropic area	−39.5
Received interference power (dBW)	−120.5

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.

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 co-ordination 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:

$$L\ (0.01\%) = P_t + G_t - (P_i - G_r) + (B_T/B_E) \quad \text{dB} \qquad (2)$$

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.

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:

$$L\ (0.01\%) = 8 + 4.5 + 45 + 136.8 - 7 \quad \text{dB}$$

or

$$L\ (0.01\%) = +187.3 \text{ dB}$$

and the required co-ordination distance is determined to be 250 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 250 km has been determined using Appendix 28 to the Radio Regulations. Report 382-3 from which Appendix 28 was developed, is at present under review in Study Group 4. Consequently, it is expected that a co-ordination distance of the order of 290 km would be reached for the above conditions.

TABLE IV – *Technical characteristics of fixed systems*

Transmitter power (dBW)	10
Antenna gain (dBi)	45
Bandwidth (MHz)	20
Receiver noise temperature (K)	750
Receiver noise power (dBW)	−126.8

4. Conclusions

Although co-ordination 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.

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 689 **

FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE RESEARCH SERVICE AND THE FIXED AND MOBILE SERVICES NEAR 15 GHz

Potential interference from data relay satellite systems

(Question 11-1/2)

(1978)

1. Introduction

This Report examines the problems of frequency sharing between the space reasearch service, the fixed service, and the mobile service in the vicinity of 15 GHz. An evaluation is made of interference from a data relay satellite system in the space research service to fixed and mobile terrestrial systems.

2. The Data Relay Satellite (DRS) system

In the following analysis it is assumed that the DRS system will use two geostationary satellites and one earth station in its operations (see Fig. 1). This system will be capable of relaying data from research spacecraft to an earth station, and of tracking other spacecraft. The two DRS are positioned so that a minimal area of the Earth's surface around the earth station is above the horizon (i.e., in view) of both simultaneously. Each relay satellite will provide a forward link from the earth station to the user spacecraft, and a return link from the user spacecraft to the ground. Characteristics assumed for the DRS system are identical to those given in Report 691.

3. The fixed and mobile radio-relay systems

A fixed terrestrial radio-relay circuit typically consists of a number of fixed relay stations, each of which receives and retransmits a signal to its ultimate destination. All transmitting and receiving antennae within the relay system are assumed to be stationary, directional and precisely pointed for the duration of a transmission or longer. The fixed stations have permanently fixed locations and fixed antenna orientations. Use of mobile stations in the bands concerned will be assumed to be at locations temporarily "fixed" for the duration of a transmission and which do not operate while in motion. Thus the analysis is the same for both.

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* This matter is brought to the attention of Study Group 5, with a view to extending the coverage of Report 724.

** This Report is brought to the attenion of Study Groups 8 and 9.

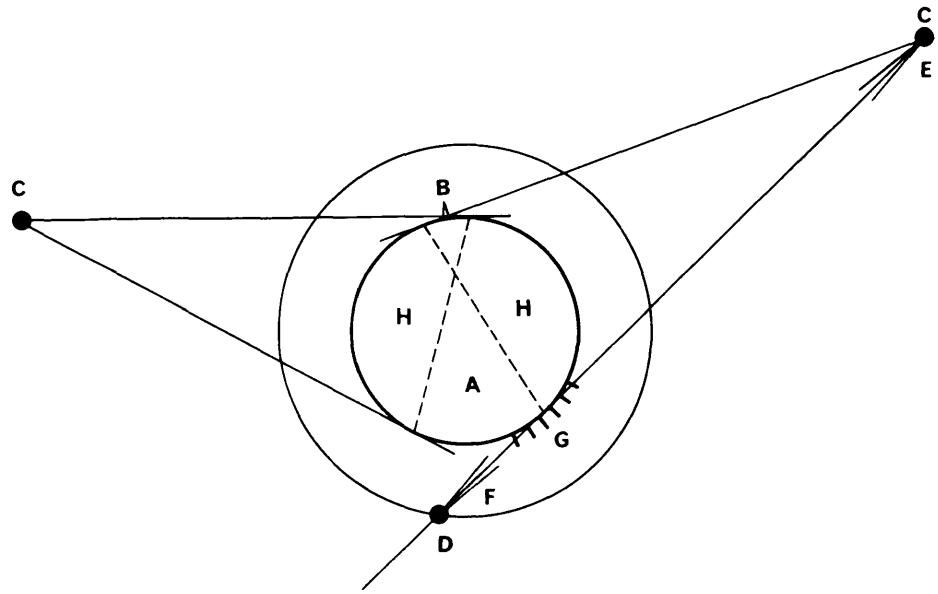

FIGURE 1 – *Data relay satellite system*

A: Earth

B: Earth station

C: Data relay satellite

D: User spacecraft

E: DRS transmitter beam

F: User spacecraft transmitter beam

G: Fixed or mobile terrestrial system

H: Horizon

4. Interference paths

Four possible interference paths exist for the DRS system in bands shared with the fixed and mobile services. Emissions from the DRS transmitters may irradiate the terrestrial services during both forward and return link operations. During return link operations, the DRS-to-Earth transmissions will irradiate fixed and mobile stations in the vicinity of the DRS earth station. During forward link operations, the narrow beam DRS antenna is transmitting towards a low-orbit user satellite. In this case, the DRS emissions will sweep across the terrestrial systems. Transmissions from the DRS earth station to the DRS satellite are the third potential interference path. Finally, transmissions from the low-orbit user satellite, in the direction of the DRS, may also irradiate terrestrial systems.

Potential interference from transmissions of the fixed and mobile services to the receivers of the space research systems is not considered in this Report. However, it is not thought to be a major factor affecting operation of the space research service.

5. Potential interference from DRS transmissions to fixed and mobile systems

Recommendation 358-2 indicates that the following power flux-density (pfd) limits have been developed for frequency bands between 12.5 and 15.4 GHz, where these bands are shared between the fixed and mobile services, and the fixed satellite service:

-148	dB(W/m^2)	for	$\delta \leq 5°$
$-148 + (\delta - 5)/2$	dB(W/m^2)	for	$5° < \delta \leq 25°$
-138	dB(W/m^2)	for	$25° < \delta \leq 90°$

in any 4 kHz band; δ is the angle of arrival of the radio frequency wave, measured in degrees above horizontal.

The DRS e.i.r.p. for both forward and return link operations is -26 dB(W/Hz). The following computation shows that the DRS meets the criteria put forth in Recommendation 358-2.

DRS e.i.r.p.	$-$ 26 dB(W/Hz)
Dispersion loss (36 000 km)	-162 dB
Bandwidth conversion (4 kHz)	+ 36 dB
DRS pfd	-152 dB(W/m^2)in 4 kHz

6. Potential interference from DRS earth station to fixed and mobile systems

The DRS earth station characteristics (i.e., e.i.r.p. of 4 dB(W/Hz) and a 60 dBi antenna) listed in Report 691 are comparable to those expected to be utilized by the fixed-satellite service earth station in the same frequency range. The interference potential and resultant co-ordination contours for the DRS earth station should be comparable to those of the fixed-satellite service.

7. Interference from user satellite to the fixed and mobile services

The user satellite transmits to the DRS satellite with an e.i.r.p. density of -28 dB(W/Hz) and will utilize a 40 dBi antenna. The maximum resultant pfd at the Earth's surface would occur, should the user-to-DRS line-of-sight graze the Earth's limb. The slant range for a 200 km altitude orbit to the Earth's limb is approximately 1600 km, yielding a maximum pfd of -125 dB(W/m^2) in a 4 kHz band. In order to protect the fixed and mobile services, 23 dB of discrimination must be provided by the user satellite. This discrimination is best accomplished by constraining the user satellite from transmitting whenever the user satellite antenna is pointed closer to the Earth's surface than 7° (assuming a 38-35 log φ antenna pattern, for the small antenna involved). For a user satellite in a 12 000 km orbital altitude, this angle is reduced to 0°. This does not impose a severe operational constraint on the DRS system.

8. Conclusions

Sharing between the fixed and mobile services and spaceborne transmitters of the DRS systems is feasible if the maximum pfd produced at the surface of the Earth by emissions from a satellite in the space research service for all conditions and methods of modulation does not exceed, in any 4 kHz band:

-148 dB(W/m^2) for $\delta \leqslant 5°$
$-148 + (\delta - 5)/2$ 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 radiofrequency wave above the horizontal.

The co-ordination between transmitting earth stations of the DRS system and stations of the fixed and mobile service may be accomplished on the basis of Appendix 28 or Report 382-3.

RECOMMENDATION 510 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH SERVICE, THE FIXED AND MOBILE SERVICES NEAR 15 GHz

Potential interference from data relay satellite systems

(Question 11-1/2)

(1978)

The CCIR,

CONSIDERING

(a) that Report 689 indicates the feasibility of frequency sharing between near-Earth space research service (transmitters of the Data Relay Satellite System) and fixed and mobile services near 15 GHz;

(b) that it is desirable to limit the power radiated from space research systems so as not to degrade the functions of fixed and mobile terrestrial communication systems,

UNANIMOUSLY RECOMMENDS

1. that frequency sharing between the Fixed and Mobile services and transmitters in the Space Research Service is feasible near 15 GHz range provided that appropriate power flux-density limits are specified for the Space Research Service;

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* This Recommendation is brought to the attention of Study Groups 8 and 9.

2. that, in frequency bands near 15 GHz shared between systems in the Space Research Service (data relay satellite systems), the Fixed Service and the Mobile 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:

$$\begin{array}{lll} -148 & \text{dB(W/m}^2\text{)} & \text{for} \quad 0° < \delta \leqslant 5° \\ -148 + (\delta - 5)/2 & \text{dB(W/m}^2\text{)} & \text{for} \quad 5° < \delta \leqslant 25° \\ -138 & \text{dB(W/m}^2\text{)} & \text{for} \quad 25° < \delta \leqslant 90° \end{array}$$

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;

3. that, in frequency bands near 15 GHz shared between systems in the Space Research Service (data relay satellite systems) the Fixed and Mobile Services, coordination should be effected between fixed and mobile radio-relay stations and earth stations according to Appendix 28 of the Radio Regulations or Report 382-3, to protect receivers of fixed and mobile services.

REPORT 690 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE RESEARCH SERVICE AND THE AERONAUTICAL RADIONAVIGATION SERVICE NEAR 13 GHz **

Potential interference to airborne helicopter Doppler navigation receivers by transmissions from a data relay satellite system

(Question 11-1/2)

(1978)

1. Introduction

This Report examines the potential for frequency sharing between the space research service and the aeronautical radionavigation service at frequencies near 13 GHz. This Report deals specifically with the question of sharing between a Data Relay Satellite (DRS) system and an airborne Doppler radar navigation equipment. Consideration is given to the case of potential interference from the DRS system transmitters to the Doppler radar navigation receivers when they share frequencies. Conclusions are presented defining the limiting operational criteria which would be acceptable to the DRS system under such sharing situations.

This Report deals with present and proposed near future use of this region of the spectrum by the aeronautical radionavigation service ** and the space research service. Future uses and sharing by systems in these services whose operational characteristics may differ from those presented here would be possible, provided those characteristics permit compliance with the limiting conditions assumed in this Report.

Potential interference from transmissions of the aeronautical radionavigation service to the receivers of the space research service systems is not considered in this Report. However, this aspect is unlikely to be a serious factor affecting operation of the space research service.

2. Data relay satellite system

In analysis it has been assumed that the DRS system will use geostationary satellites for relaying data acquired by research spacecraft to DRS system users and for tracking other spacecraft. Each DRS will provide two links between the DRS system earth station and the user spacecraft. The forward link, from the earth station to the user spacecraft, and the return link from the user spacecraft to the ground, are both illustrated in Fig. 1.

3. The Doppler navigation system

A Doppler navigation system employs a low-power, lightweight Doppler radar to transmit narrow beam signals to the ground. These signals are reflected from the Earth's surface with a Doppler frequency shift proportional to aircraft velocity (generally helicopter aircraft). This velocity is measured through the frequency shift and transmitted to a self-contained navigation computer. In the computer, velocity is combined with heading, integrated and presented to the pilot as an indication of present position. Characteristics of a typical Doppler navigation system are listed in Table I.

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* This Report is brought to the attention of Study Group 8.

** See No. 406 of the Radio Regulations.

4. Interference paths

Possible interference paths between DRS system components and airborne Doppler navigation equipment are illustrated in Fig. 1. The DRS-to-earth station portions of the forward and return links utilize narrow beams which are relatively stationary with respect to the Earth's surface. The region in which potential interference to aircraft may occur would thus be limited to the vicinity of the earth station (up to about 350 km, a function of the size of the antenna pattern footprint).

Interference due to transmissions from a DRS to a user spacecraft could possibly occur at any location on the Earth's surface, provided the power flux-density is high enough at the Doppler navigation system receiver antenna. The angle of arrival of potentially interfering signals will normally be limited to the hemisphere above the aircraft equipped with a Doppler navigator as shown in Figs. 1 and 2.

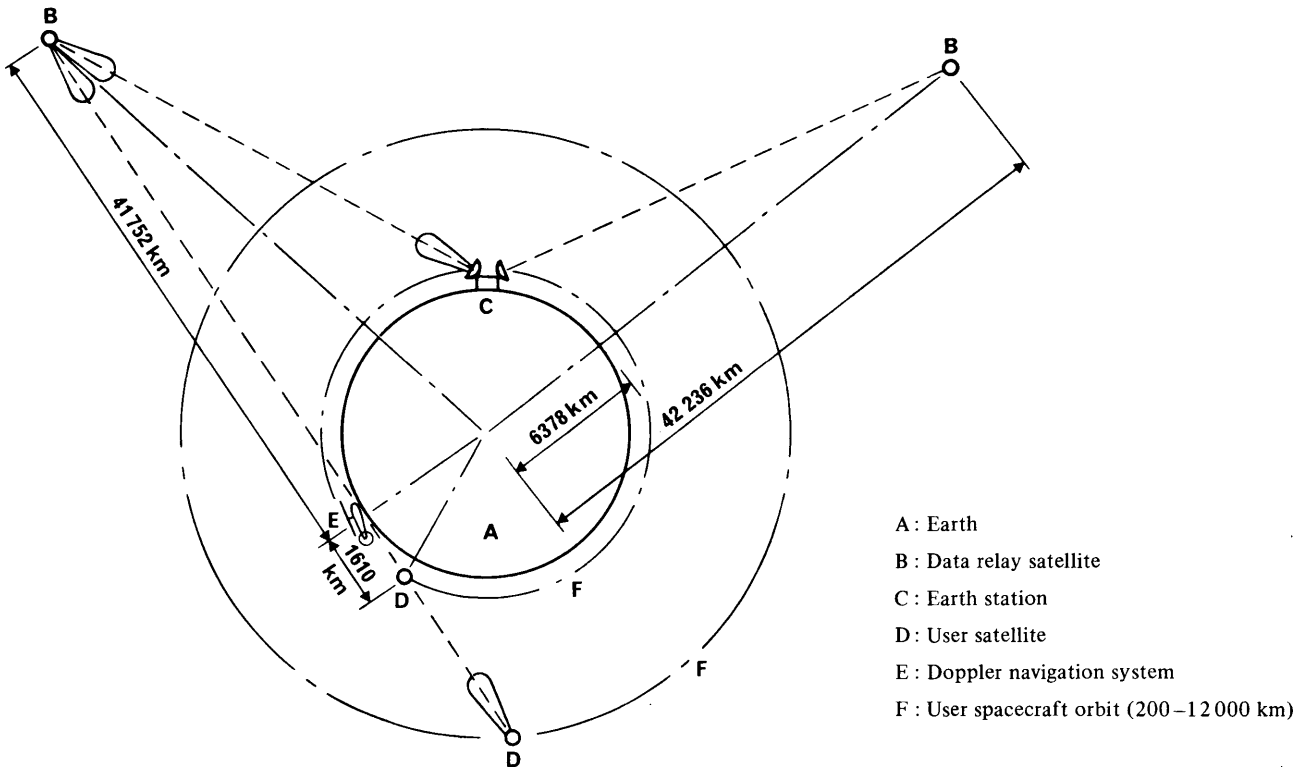

FIGURE 1 – *Data relay satellite (DSR) – user spacecraft geometry*

Possible interference paths due to transmissions from a user spacecraft to the DRS or from an earth station to the DRS are also illustrated in Fig. 1. The situations to be considered here represent the worst cases expected: interference to Doppler navigators resulting from flights in the main beam of the user-DRS return link, and interference to Doppler navigators resulting from flights in proximity to the DRS system earth station during forward link transmissions to a DRS. In both cases, Doppler transmitter/receiver antennae will be pointed toward the Earth's surface (14° to the aircraft yaw axis); the resulting interference paths are main lobe to side lobe couplings. (Fig. 2).

5. Flux-densities required to produce interference from the DRS into the Doppler radar system

The sentivity of a typical Doppler radar navigation receiver is listed in Table I as – 189 dB(W/Hz). Since the Doppler radar receiver has a relatively narrow noise bandwidth compared to DRS system transmission bandwidths, interfering signals may be treated as white noise *. As a result, if the maximum allowable interference level is assumed to be 10 dB below the receiver thermal noise, then the maximum allowable interference spectral power density at the receiver antenna is – 199 dB(W/Hz).

* See Report 537-1.

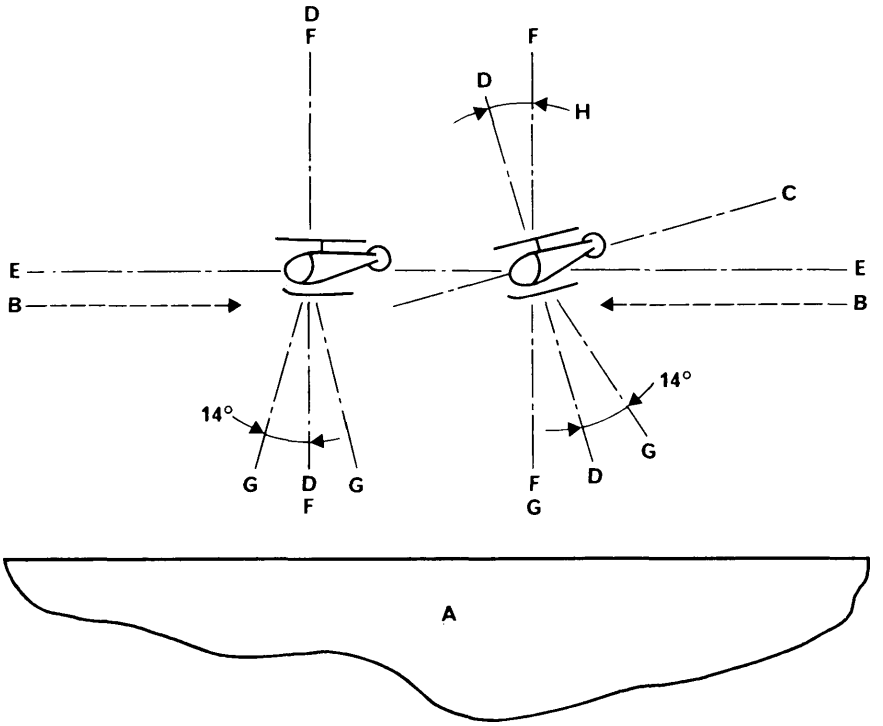

FIGURE 2 – *Doppler navigator antenna geometry*

A : Earth's surface

B : Interference path

C : Aircraft centerline

D : Yaw axis

E : Horizontal axis

F : Vertical axis

G : Antenna axis

H : Pitch angle

The spectral power flux-density at the receiver, P_r, is given by:

$$P_r = S + G_r + 10 \log (\lambda^2/4\pi) \qquad \text{dB(W/(m}^2 \cdot \text{Hz))} \tag{1}$$

where,

S: spectral power flux-density in dB(W/(m^2 · Hz)),

G_r: receiver antenna gain (dBi),

λ: wavelength in metres, and,

(G_r + 10 log $\lambda^2/4\pi$) is the effective area of the receiving antenna in dB relative to 1 m^2 (in this case, − 17 dB).

If P_r = − 199 dB(W/m^2 per Hz) and G_r = 27.0 dBi (see Table I), then at 13.25 GHz, the spectral power flux-density required at the receiver antenna main lobe to produce interference is − 182.0 dB(W/(m^2 · Hz)).

The spectral power flux-density at the receiver antenna is given by:

$$S_Q = P_t + G_t - 10 \log (4\pi R^2) \qquad \text{dB(W/(m}^2 \cdot \text{Hz))}, \tag{2}$$

where:

P_t: transmit spectral power density, dB(W/Hz),

G_t: transmitting antenna gain, dBi,

R: slant distance, metres.

Solving this for a DRS e.i.r.p. of − 26 dB(W/Hz) (see Report 691) yields a predicted spectral power flux-density at the horizon of − 189 dB(W/m^2 · Hz)), 7 dB below the level required to produce interference.

Interference coupling is very unlikely to occur through the receiver antenna main lobe. As shown in Fig. 2, receiver antennae are pointed at the Earth's surface at an angle of about 14° from the yaw axis of the aircraft. A side lobe envelope pattern of gain = 38 − 25 log φ is assumed *. This envelope reaches its lowest value (−5 dBi) at 53 degrees from the main beam axis. As a result, the antenna gain toward the horizon is at least 32 dBi below that of the main beam axis, even at aircraft pitch and roll angles up to 23°. Antenna back lobe coupling would therefore require a spectral power flux density of at least −150 dB(W/(m^2 · Hz)) to produce interference.

Back lobe coupling will always occur in straight and level flight and in manoeuvers producing aircraft attitude changes of less than 23°. Attitude changes larger than this will probably occur infrequently and be of short duration. For example, a co-ordinated standard rate (3°/s) turn of 180° can be completed in only 1 minute.

6. Maximum allowable flux-densities from the user spacecraft (under worst case conditions)

From Report 691 the radiated spectral power density of a typical user spacecraft is −28 dB(W/Hz). Solving equations (1) and (2) with this value and a range of 1610 km (distance D-E in Fig. 1) and an antenna gain of −5 dB yields an interference spectral power density of −211.7 dB(W/Hz) into the Doppler receiver. The corresponding interference-to-noise power ratio is −22.7 dB, a more than adequate margin.

7. Earth station-DRS forward link

Report 691 gives a radiated spectral power density for a DRS system earth station of 4 dB(W/Hz), assuming a transmitter antenna gain of 60 dBi. Solving for the resulting main beam interference spectral power density gives:

$$P_r = -50.7 - 20 \log R + G_r \quad (3)$$

If a Doppler navigator equipped aircraft in level flight passes directly through the earth station transmitter main beam (elevated to approximately 27° to illuminate a DRS; a value typical of that planned for use at a DRS earth station in the central United States), the receiver antenna gain at the crossing will be approximately −4 dB, or less. Therefore, the interference spectral power density is:

$$P_r = -54.7 - 20 \log R \quad (4)$$

As an example, if the aircraft were 1 km distant, the resulting interference spectral power density would be −114.7 dB(W/Hz) giving an interference-to-noise ratio of +74 dB. Thus some criterion must be established for aircraft attitude and distance to avoid interference.

An aircraft can use both off-beam discrimination and distance to limit the interference power received by its Doppler navigator. An evaluation of the previously stated relationship for interference power density (corrected for off-beam gain using G_l −(38 − 25 log φ)) shows that an aircraft, while operating the Doppler navigation system, can maintain an interference-to-noise margin of −10 dB or less by staying at least 20 km from the earth station for altitudes below 1 km above ground level.

If the DRS earth stations are permitted to use elevation angles as low as 10°, the distance at which operations of Doppler radar receivers are affected increases to about 50 km for operational altitudes of 1 km. Such operational constraints would require the development of co-ordination procedures between the two affected radio services in areas around DRS earth stations. This is not considered to be a serious handicap to either service since there is not likely to be a great number of such earth stations and they are usually sited in uncongested land areas.

8. Power flux-density restrictions on the DRS-to-Earth transmissions

The maximum levels assumed for the allowable flux-density at the Earth's surface due to emissions from a DRS are plotted in Fig. 3, derived from Recommendation 358-3, for the frequency band from 12.5 to 15.4 GHz. The values in any 4 kHz band have been normalized to 1 Hz along the ordinate axis. If these limits are assumed to apply to any space-to-Earth transmissions in the space research service, the highest spectral power flux-density allowable is −174 dB(W/(m^2 · Hz)) (corresponding to −138 dB(W/m^2 in 4 kHz)) which is 24 dB less than that level required to produce interference to a Doppler navigation system on an aircraft in level flight.

From Table I, the gain of the Doppler navigation antenna is 27 dBi, and the side lobe and back lobe response is assumed to be −5 dBi. Since the maximum allowable power spectral flux-density is equivalent to −174 dB(W/(m^2 · Hz)), main beam to main beam coupling could give rise to interference 8 dB above threshold. Main beam to main beam coupling is unlikely for all normal aircraft flight attitudes; in fact a coupling of any kind by the DRS main beam to a Doppler navigation system receiver is unlikely, as shown in detail by the following probability analysis. The maximum time which an aircraft could expect to spend within the half-power beamwidth, given that the DRS antenna main lobe scans across the aircraft position, can be estimated as described below.

* Reference pattern for small antenna.

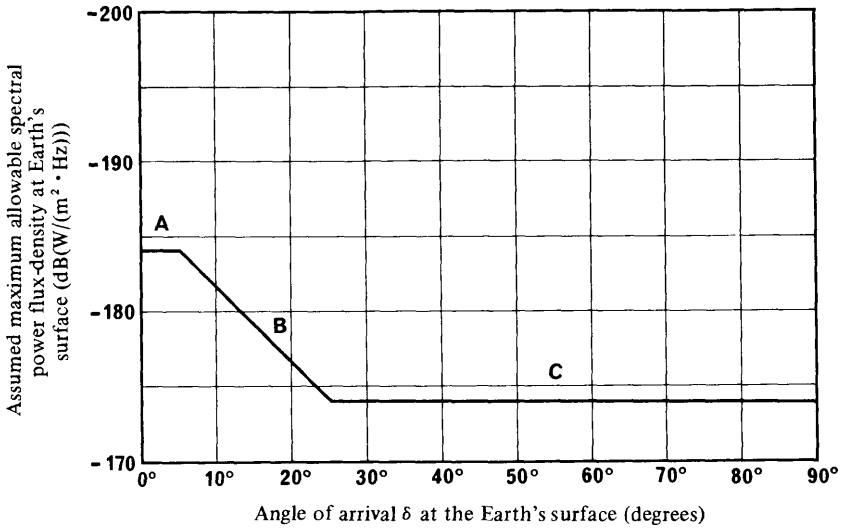

FIGURE 3 – *Flux-density restrictions on DRS transmissions*

A: –148 dB(W/m²) in any 4 kHz band for $\delta \leq 5°$

B: $-148 + (\delta - 5) / 2$ dB(W/m²) in any 4 kHz band for $5° < \delta \leq 25°$

C: –138 dB(W/m²) in any 4 kHz band for $25° < \delta \leq 90°$

9. DRS antenna scanning

The DRS, the data relay earth station and the user spacecraft all employ highly directive antennae and tracking servo systems to provide high gain telecommunications links with low transmitter power levels and low flux-densities at the antennae of other systems sharing the same frequencies (see Fig. 2). The maximum time which an aircraft could expect to spend within the half-power beamdwidth, given that the DRS antenna main lobe scans across the aircraft position, can be estimated as described below.

Fig. 4 shows the beam from the DRS tracking user spacecraft at maximum and minimum orbital altitudes (12 000 km and 200 km). For simplicity, the DRS is shown in the orbital plane of the user satellite, although this is not usually the case. The distance from DRS to user spacecraft is given by:

$$L = \sqrt{[d - (a + h) \cos \beta]^2 + [(a + h) \sin \beta]^2} \tag{5}$$

The orbital sector subtended by the beamwidth α at distance L also subtends the Earth central angle, θ_β, where,

$$\theta_\beta \approx \frac{\theta L}{(a + h) \cos (\alpha + \beta)} \tag{6}$$

and,

$$\alpha = \tan^{-1} \frac{(a + h) \sin \beta}{d - (a + h) \cos \beta} \tag{7}$$

The time for the beam to scan past a stationary (or nearly stationary) object on the Earth's surface will be given by:

$$t = \theta_\beta / \theta \tag{8}$$

where,

$\theta = 2\pi / P$,

P : period $= 2\pi r^{3/2} \mu^{-1/2} = 2\pi (a + h)^{3/2} \mu^{-1/2}$,

r : mean orbital radius,

μ : GM = constant ($3.985 \times 10^{14} m^3/s^2$),

a : mean radius of the Earth,

h : mean orbital altitude of user spacecraft.

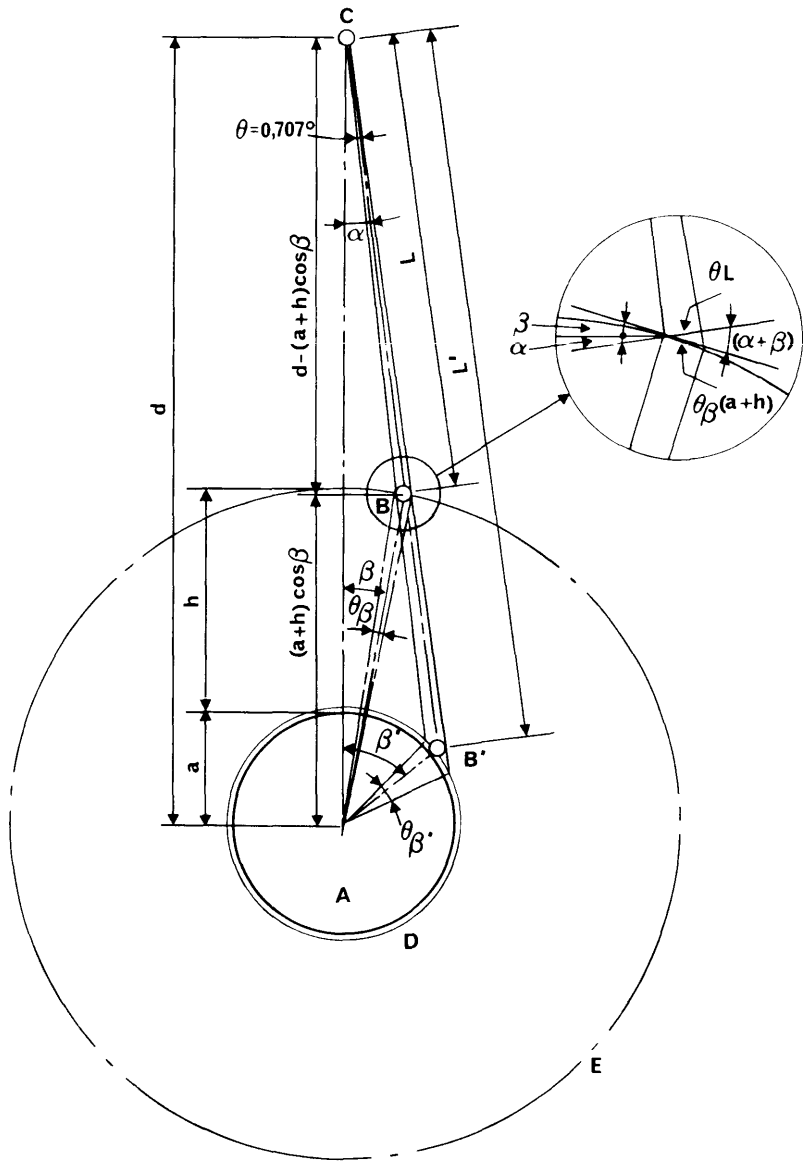

FIGURE 4 – *Data relay satellite antenna scan geometry – orbital plane*

A : Earth

B : User satellite

C : Data relay satellite

D : User satellite orbit = 200 km

E : User satellite orbit = 12 000 km

The above equations for t and α have been solved in terms of the parameter, β, and plotted in Fig. 5. This curve shows the maximum time required for the DRS main lobe to scan past a fixed or slowly moving object near the Earth's surface as a function of the angular displacement from the axis through the DRS and the Earth's centre. The peak value of 7 min is reached when the propagation path is tangent to the Earth. The values drop abruptly to zero as the beam scans beyond the altitude band which aircraft are physically able to reach (i.e. about 15 km). The majority of positions in view of the DRS will be swept by the beam in well under 5 min. This is not likely to disrupt operation of the typical Doppler system.

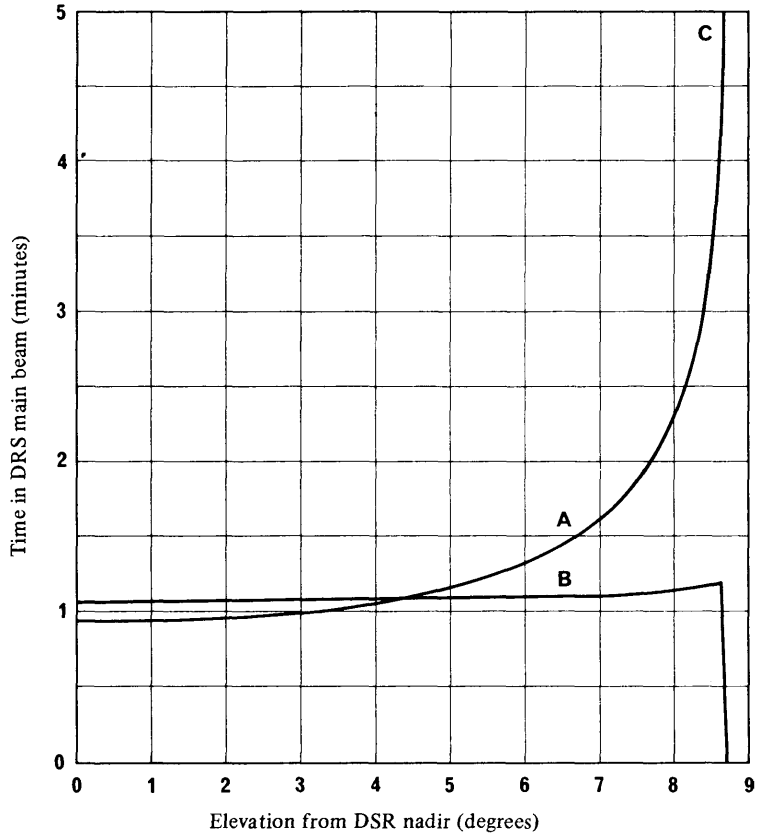

FIGURE 5 – *Time in DRS main beam versus angle from nadir*

A : User satellite altitude = 200 km

B : User satellite altitude = 12 000 km

C : ~ 7.0 minutes maximum

10. Antenna coupling

For a direct coupling to occur, the antenna of the interfered receiver must be within the zone of visibility of one or both the data relay satellites. The visible zone is within the spherical segment above the DRS horizon – symmetrical about the DRS-Earth centreline axis. The dimensions of the zone are shown in Fig. 6. The motion of the DRS antenna beam sweeps a track across the Earth's surface in the visible zone. Antennae of the interfered with receiver which lie within this DRS antenna beam track can experience interference coupling.

The area within the DRS antenna beam track can be estimated from:

$$A = Ba(h_1 - h_2) \tag{9}$$

where,

a: radius of Earth,

B: angular dimension of spherical belt segment within zone of visibility, in radians,

h: height of spherical segment (see Figure 6).

$$B = 2 \cos^{-1}\left(\frac{\left(\frac{a \cos C}{\cos I}\right) + (a \sin L \tan I)}{a \cos L}\right) \tag{10}$$

The inclination of the user orbital plane with respect to the DRS-Earth axis, I, varies with orbital parameters. However, a worst case can be evaluated by setting $I = 0$ and evaluating the maximum expected area of the antenna beam ground track. In this case,

$$B = 2 \cos^{-1}\left(\frac{\cos C}{\cos L}\right)$$

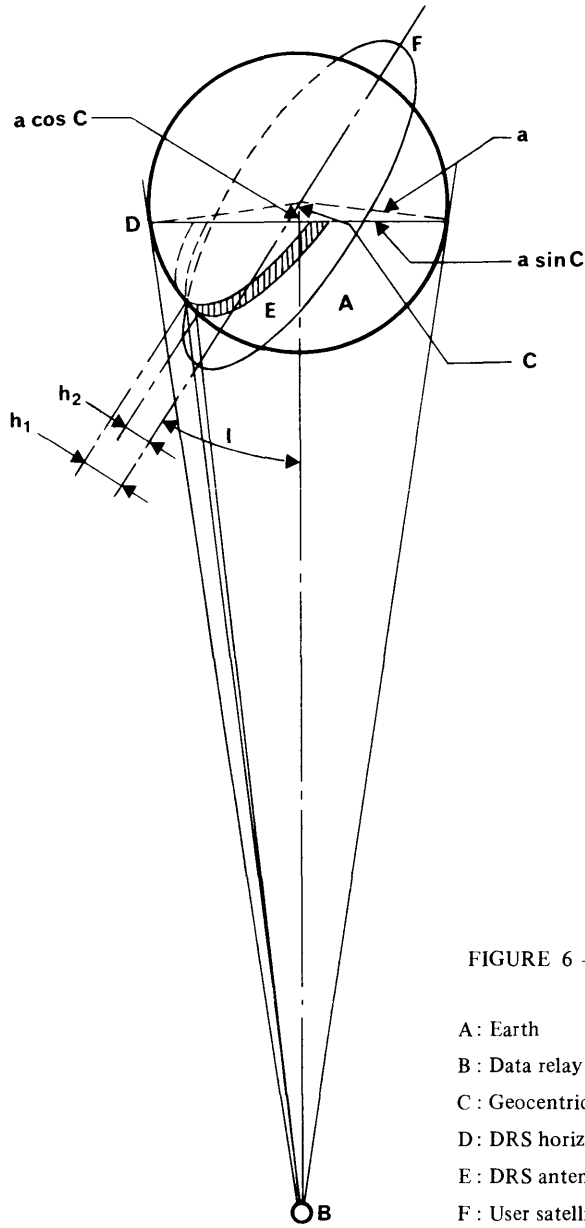

FIGURE 6 – *Data relay satellite antenna beam scan pattern – equatorial plane*

A : Earth

B : Data relay satellite (DRS)

C : Geocentric angle between DRS nadir and DRS horizon

D : DRS horizon

E : DRS antenna beam track

F : User satellite orbital plane

11. Antenna coupling rate

If the number of operating Doppler-navigator-equipped helicopters is N and they are assumed to be randomly distributed over the Earth's surface, then the mean number of operating Doppler-navigator-equipped helicopters per unit area is given by:

$$N/E \tag{11}$$

where,

$E = 4\pi a^2 = 5.112 \times 10^8$ km^2.

The number of unintentional antenna couplings per DRS within a one hour period, C, is then:

$$C = \sum_{i=1}^{i=s} \frac{A_i N}{P_i E} \tag{12}$$

where,

P_i: period of the ith user satellite (hours),

s: total number of user satellites.

The foregoing expression for coupling rate has been evaluated using six user satellites of typical parameters and plotted in Fig. 7 as a function of Earth-central angle from the DRS-Earth axis. The peak value of coupling rate can be seen to be just under 3 per hour for beam tracks which are a small angular displacement from the DRS-Earth axis.

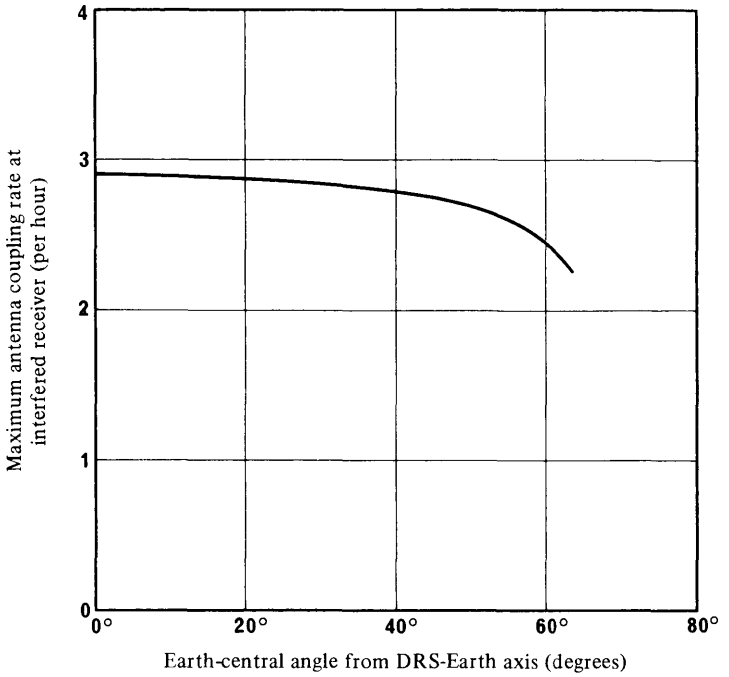

FIGURE 7 – *Antenna coupling rate versus angle from DRS-Earth axis*

12. Interference probability

If the average duration of each coupling is 5 min, then a maximum of 15 min of unintentional antenna coupling between DRS and Doppler navigation systems will occur for each 2520 min of flight operation. This will result in a probability of interference of less than 0.6% given that a flux-density level exists which could be detected by the receiver. Stated conversely, the probability of interference free operation as a result of frequency sharing with space research services would be greater than 99.4%.

13. Conclusions

The DRS system can operate in the 13 GHz region of the spectrum with the following pfd limits, in any 4 kHz band, at the Earth's surface:

$$\begin{aligned} &-148 && \text{dB}(\text{W/m}^2) && \text{for} && \delta \leqslant 5^\circ \\ &-148 + (\delta - 5)/2 && \text{dB}(\text{W/m}^2) && \text{for} && 5^\circ < \delta \leqslant 25^\circ \\ &-138 && \text{dB}(\text{W/m}^2) && \text{for} && 25^\circ < \delta \leqslant 90^\circ \end{aligned}$$

where δ is the angle of arrival of the radio frequency wave measured in degrees above horizontal.

A typical Doppler radar navigation system having the characteristics listed in Table I would not suffer harmful interference from such DRS transmissions unless direct main beam to main beam coupling occurred. The probability of such coupling in operational environments is less than 0.6%.

A typical low altitude spacecraft, when in the beam of a Doppler radar navigation antenna will produce a pfd at that antenna at least 20 dB below the Doppler receiver noise level.

Interference to Doppler radar navigation receivers from DRS earth stations will not occur if the Doppler equipped aircraft remains an appropriate distance from the earth station depending on the elevation angle of that station. This distance may be as much as 50 km for elevation angles of 10°. Closer operation between the two systems is probably feasible if appropriate co-ordination procedures are established for each earth station site including possible limitations on the minimum elevation angle.

From these considerations it appears that frequency sharing between DRS transmitters and Doppler receivers should be technically feasible, but may necessitate some operational restrictions on the aircraft service; in particular, studies are needed as regards the potential interference to radionavigation systems operating in the band 13.25 to 13.4 GHz at present allocated to the Aeronautical Radionavigation Service, with its safety-of-life implications.

TABLE I – *Typical Doppler navigation system characteristics*

Installation:	Helicopters
Extent of use:	Operation is continuous during the aircraft mission (up to 4 hours duration)
Transmitter:	
Tuning range:	13.25–13.40 GHz
Average power:	20 mW
Type emission:	F9
Emission bandwidth:	–3 dB 100 kHz –20 dB 280 kHz –60 dB 600 kHz
Filter bandwidth:	–3 dB 400 kHz
Stability:	350 PPM
Modulation:	Highest modulating frequency 30 kHz sinusoidally modulated
Harmonic attenuation:	–60 dB minimum
Spurious attenuation:	–60 dB minimum
Receiver:	
Tuning range:	13.25–13.40 GHz
Stability:	350 PPM
RF bandwidth:	–3 dB 250 kHz –20 dB 504 kHz –60 dB 785 kHz
Sensitivity	–189 dB(W/Hz) for minimum detectable signal (assumed to be unity *S/N* ratio)
Antenna:	
Polarization:	Linear
Scan:	Four narrow beams sequentially switched to positions in the four quadrants at 7.3 Hz rate
Gain:	27.0 dB
Azimuth beamwidth:	7.8° max
Elevation beamwidth:	5.8° max
Spurious response:	–40 dB

RECOMMENDATION 511 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE RESEARCH SERVICE AND THE AERONAUTICAL RADIONAVIGATION SERVICE NEAR 13 GHz

Potential interference from data relay satellite systems

(Question 11-1/2)

(1978)

The CCIR,

CONSIDERING

(a) that Report 690 indicates the feasibility of frequency sharing between the Space Research Service (transmitting stations in the Data Relay Satellite system) and the Aeronautical Radionavigation Service (Doppler Radar) near 13 GHz;

(b) that space research systems share frequency bands with the Aeronautical Radionavigation Service on a secondary basis for Earth-to-space transmissions in the 13 to 15 GHz range (No. 407A of the Radio Regulations);

(c) that interference from space research systems must not be allowed to endanger the functions of aeronautical radionavigation systems,

* This Recommendation is brought to the attention of Study Group 8.

UNANIMOUSLY RECOMMENDS

1. that frequency sharing between the Aeronautical Radionavigation Service and transmitters in the Space Research Service should be feasible near 13 GHz provided that coordination is effected when aeronautical radionavigation stations operate within 50 km of earth stations;

2. that, in frequency bands near 13 GHz shared between systems in the Space Research Service and the Aeronautical Radionavigation Service, the space research data relay satellite systems can operate within the following power flux-density limits produced at the surface of the Earth for all conditions and methods of modulation, in any 4 kHz band:

-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).

These limits relate to the power flux-density and angles of arrival which would be obtained under free-space propagation conditions.

REPORT 691

FEASIBILITY OF FREQUENCY SHARING BETWEEN THE SPACE RESEARCH SERVICE AND THE RADIOLOCATION SERVICE NEAR 14 GHz

Potential interference to radiolocation receivers by transmitters in a data relay satellite system

(Question 11-1/2)

(1978)

1. Introduction

This Report examines the potential for frequency sharing between the space research service (data relay satellites) and the radiolocation service in frequency bands near 14 GHz. An evaluation is made of co-channel operation of a data relay satellite (DRS) system and a radiolocation system. Since, at the present time, no radiolocation equipment is planned in this region of the spectrum, the parameters of a hypothetical radiolocation system have been used for this analysis. Only interference into the radiolocation receiver is considered. Interference to the DRS system is not examined.

2. Data relay satellite (DRS) system

In this analysis it is assumed that the DRS system will use two geostationary satellites for relaying data acquired from research spacecraft to DRS system users, and for tracking other spacecraft. The two spacecraft are assumed to be positioned so that only a minimal area on the Earth's surface is above the horizon (i.e., in view) of both simultaneously. Each DRS will provide two links between the DRS system ground station and user spacecraft; the forward link, from the earth station to the user spacecraft, and the return link, from the user spacecraft to the Earth. The DRS forward link and the radar system are assumed to use the same centre frequency. The characteristics of the DRS are shown in Table I.

3. The hypothetical sensitive radiolocation system

The hypothetical sensitive radiolocation system is a fixed, primary radar system designed for monitoring and controlling airport surface traffic during periods of low visibility. Since the system must display fixed targets (which would ordinarily be treated as clutter); as well as moving targets, moving target indication (MTI) is not used. Furthermore, echoes from beyond the airport boundaries or from airborne targets are rejected by limiting the vertical beamwidth, setting receiver thresholds, etc. The characteristics of such a radar system are shown in Table II.

4. Interference level

The noise power of a typical radar system receiver is approximately -117 dBW in a noise bandwidth of about 40 MHz, or -193 dB(W/Hz). If the maximum allowable interference level is assumed to be 10 dB below receiver thermal noise, the maximum allowable interference spectral power density at the receiver is -203 dB(W/Hz).

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* This Report is brought to the attention of Study Group 8.

TABLE I – *DRS system characteristics*
(Obtained from Report 537-1)

Characteristics	Forward link		Return link	
	Earth-to-DRS	DRS-to-user	User-to-DRS	DRS-to-Earth
Maximum RF bandwidth (MHz)	330	50	225	500
Earth Station				
e.i.r.p. density (dB(W/Hz))	4			
Receiver noise temperature (K)				420
Antenna gain (dBi)	60			60
DRS spacecraft				
e.i.r.p. density (dB(W/Hz))		−26		−26
Receiving antenna gain (dB)	50		50	
Receiver noise temperature (K)	2300		2300	
User spacecraft				
e.i.r.p. density (dB(W/Hz))			−28	
Receiver noise temperature (K)		2050		
Antenna gain (dBi)		40 to 50		

TABLE II – *Hypothetic sensitive radiolocation system*
Operating characteristics

Peak pulse power	25 kW
Pulse width	32 ns
Pulse rise time	12 ns
PRF	15 kHz
Average power	12 W
Frequency (carrier)	14 GHz
Receiver sensitivity	−85 dBm
Receiver noise figure	11 dB (Ts ≈ 3400 K)
Signal-to-noise ratio (required for operation)	12 dB
Receiver IF bandwidth	40 MHz
Antenna gain	35 dBi
Antenna pattern	fan beam
Side lobes	25 dB below main lobe
Antenna tilt	0°
Antenna scan rate	135 RPM
Antenna pattern	10° vertical beamwidth 0.34° horizontal beamwidth
Polarization	Circular

The spectral power density at the receiver is given by:

$$P_r = S + G_r + 10 \log (\lambda^2/4\pi) \quad (1)$$

where:

P_r: spectral power density (dB(W/Hz));

S: spectral flux-density (dB(W/(m^2 · Hz)));

G_r: receiver antenna gain (dBi) and,

λ: wavelength (m).

Solving this equation for S yields a spectral flux-density of approximately -193.6 dB(W/(m^2 · Hz)) required to produce interference through the DRS main lobe to the radar system main lobe antenna couplings. (Effective area is approximately 0.1 m^2). Furthermore, since the radar system side lobes are about 25 dB below main beam gain, -168.6 dB(W/(m^2 · Hz)) is required to produce interference through a DRS main lobe and a radar side lobe.

5. Flux-density restrictions

Fig. 1 illustrates recommended flux-density limits for the Fixed Satellite Service as contained in Recommendation 358-2, for the frequency band from 12.5 to 15.4 GHz. If these restrictions are applied to any space-to-Earth transmissions in the space research service, the highest flux-density allowable at small grazing angles is -184 dB(W/(m^2 · Hz)), (-148 dB(W/m^2) in the worst 4 kHz band). This value is almost 10 dB greater than that level required to produce interference to a radar system via a main lobe to main lobe path. The highest flux-density allowable at high arrival angles is -174 dB(W/(m^2 · Hz)); more than 5 dB below that required for the DRS transmitter antenna main lobe to produce interference through the radar receiver side lobe. The highest potential for harmful interference is seen to result from main lobe to main lobe couplings.

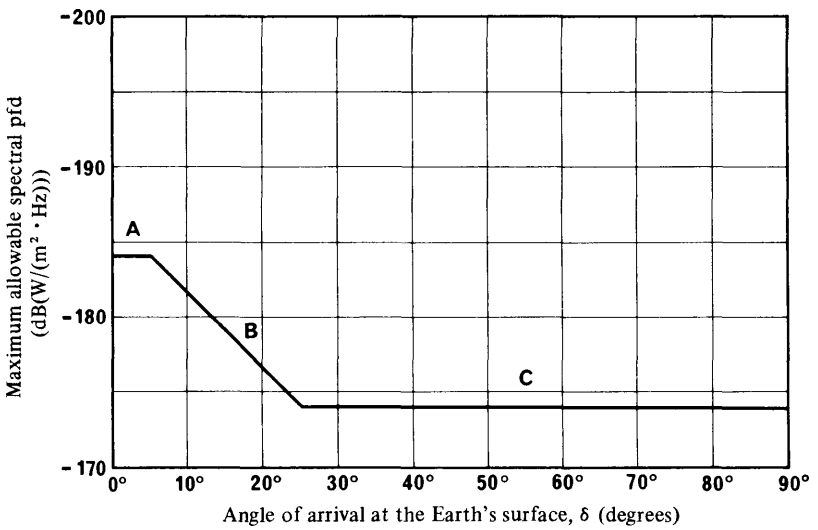

FIGURE 1 – *Flux-density restrictions for fixed satellite transmitters (Recommendation 358-2)*

A: -148 dB(W/m^2) in any 4 kHz band for $\delta \leqslant 5°$

B: $-148 + (\delta - 5) / 2$ dB(W/m^2) in any 4 kHz band for $5° < \delta \leqslant 25°$

C: -138 dB(W/m^2) in any 4 kHz band for $25° < \delta \leqslant 90°$

6. Interference paths

Possible interference paths between DRS system components and a radiolocation system are illustrated in Fig. 2. It is to be noted that a main beam to main beam interference path between near-Earth research spacecraft and a radiolocation system can exist only if the radiolocation equipment is located within a narrow spherical cap centered at the DRS-user spacecraft horizon for a grazing sightline. The geocentric angular width of this interference cap, measured about the angular DRS-user horizon point is equal to the main lobe dimension of the user spacecraft transmission beam. For main lobe interference to occur, the radiolocation system must be located within this cap along the line between the DRS and research satellite centres while all systems are operating.

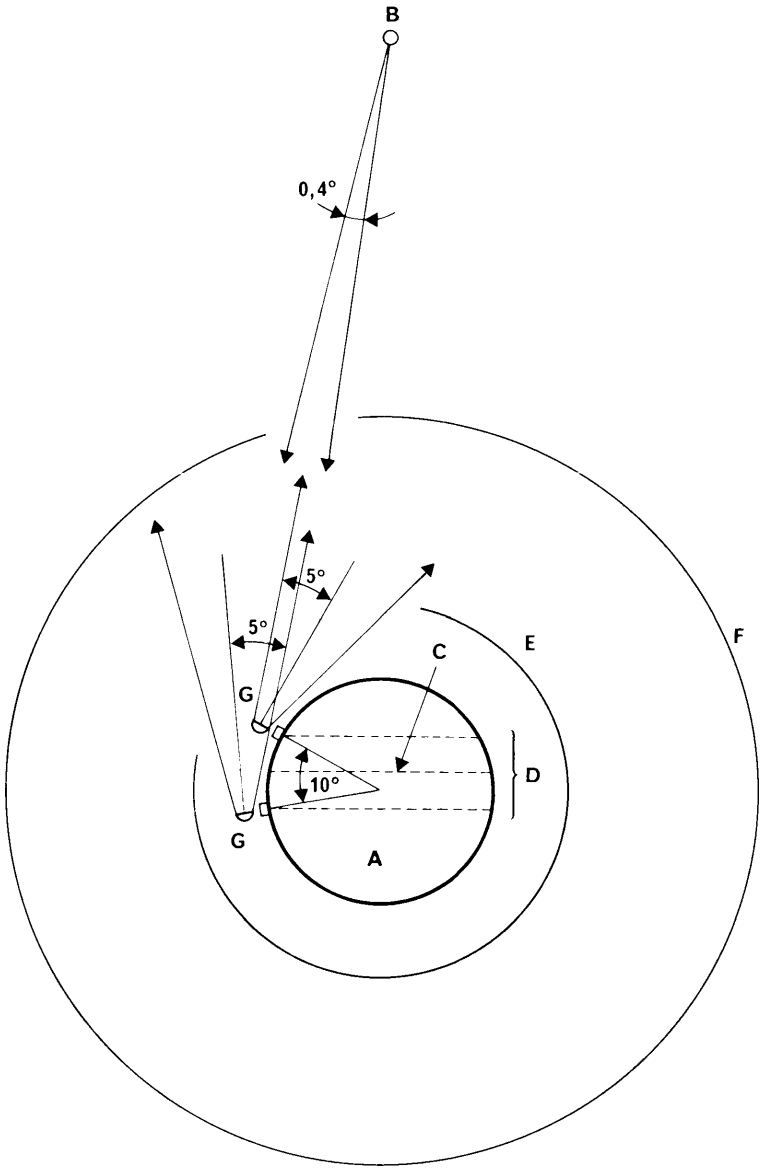

FIGURE 2 – *Radiolocation system – data relay satellite – user spacecraft geometry*

A : Earth

B : Data relay satellite

C : Horizon

D : Radiolocation system interference belt

E : DRS user spacecraft minimum orbit (200 km)

F : DRS user spacecraft maximum orbit (12 000 km)

G : Radiolocation system antenna

Interference to radiolocation equipment will result from DRS earth station emissions if the two stations are within view of each other; i.e., if the radiolocation system antenna is above the earth station horizon, *and* if the angular orientation of the two antennae allows sufficient interference power to be coupled into the radiolocation system antenna to cause harmful interference.

7. Interference from the DRS to the radiolocation system

7.1 *DRS main beam irradiation*

Any location within the DRS horizon will be irradiated by the DRS main beam only if some part of the area within the DRS antenna beam scans across a radiolocation site while tracking a user satellite. Fig. 3 is a view of the Earth and the user satellite orbital sphere as seen from the DRS. If a single user satellite is assumed to have a uniformly distributed probability of passing through any point in the upper orbital hemisphere during a large

number of tracking and data transfer sequences, the probability of main lobe illumination of any given fixed site on the visible Earth hemisphere, is given by the ratio of the projected area within one beamwidth radius to the projected area of the user orbital sphere (see Fig. 4); i.e.:

$$P_l = \frac{2\pi r_s h}{2\pi r_s H} = \frac{1 - \cos\theta}{1 - \sqrt{1 - \dfrac{(a + h_u)^2}{r_s^2}}} \tag{2}$$

where:

P_l: probability of DRS main lobe irradiation of the hypothetical sensitive radiolocation system;

h: height of spherical segment at geosynchronous radius subtended by DRS beam;

H: height of spherical segment at geosynchronous radius subtended by user spacecraft orbital sphere;

r_s: synchronous orbital radius (km);

θ: DRS antenna half-power beamwidth, (radians);

a: mean earth radium (km);

h_u: mean user satellite altitude (km).

This relationship has been plotted for a single user satellite in Fig. 5 as a function of user orbital altitude.

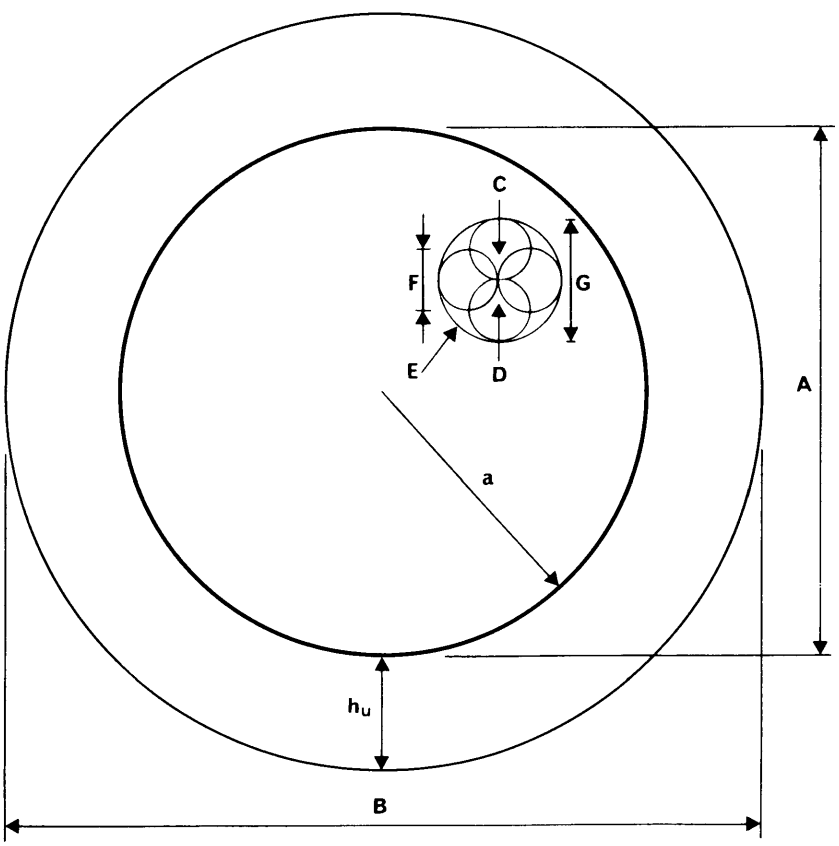

FIGURE 3 – *Cross-sectional view of Earth and envelope of user satellite positions*

A : Earth cross-section

a : Earth radius (6378 km)

B : Envelope of user satellite positions

C : Radiolocation system position

D : Beam cross-section of DRS antenna

E : Envelope of DRS positions producing irradiation of radiolocation system

F : One beamwidth

G : Two beamwidths

h_u : User spacecraft orbital altitude

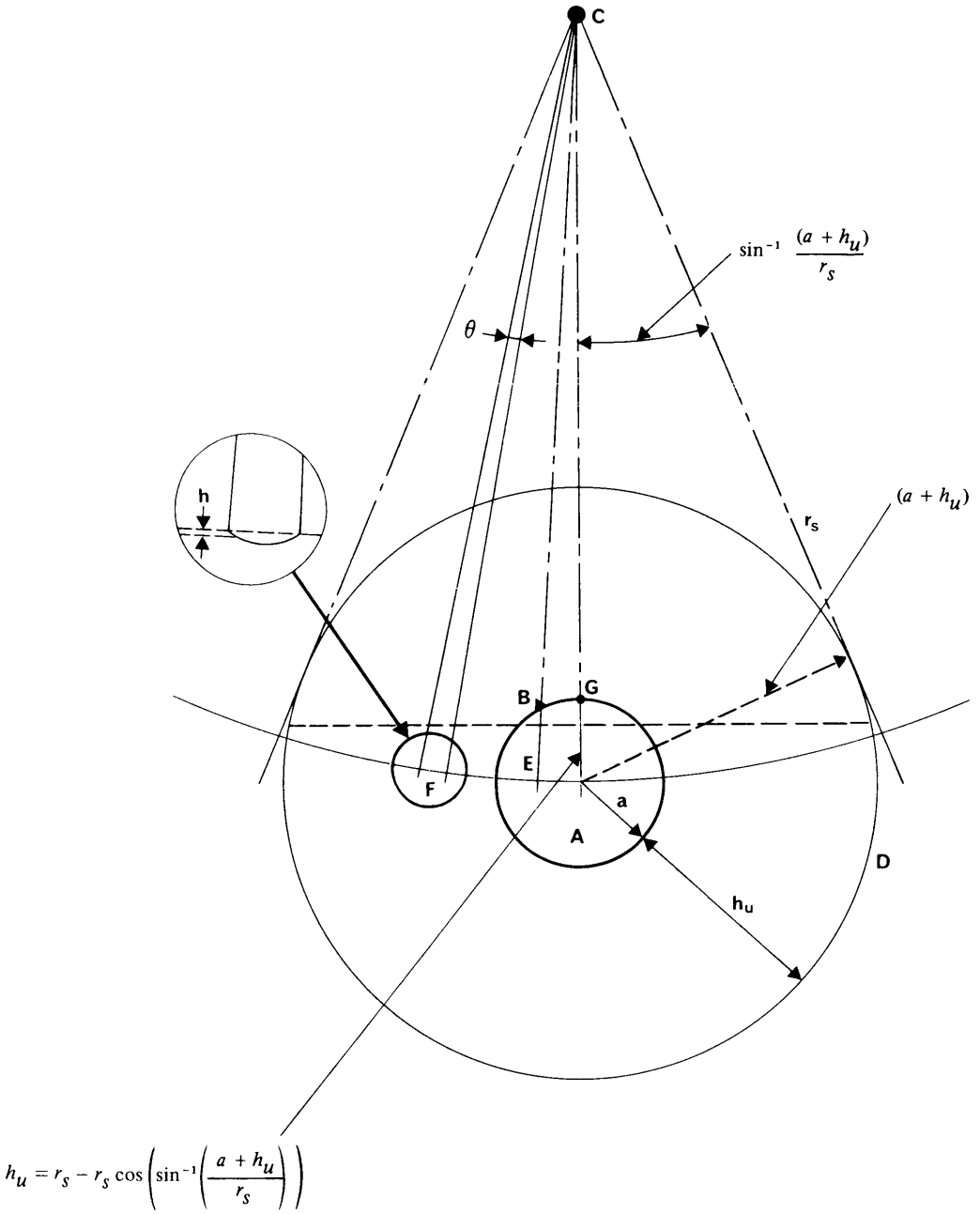

FIGURE 4 – *Probability geometry – DRS main lobe irradiation of radiolocation system*

A : Earth

a : Earth radius (6378 km)

B : Radiolocation system

C : Data relay satellite (DRS)

D : User spacecraft orbital sphere

E : Projected radiolocation system position

F : Projected beam

G : DRS nadir

h_u : User spacecraft orbital altitude

r_s : Geostationary orbital radius (42 236 km)

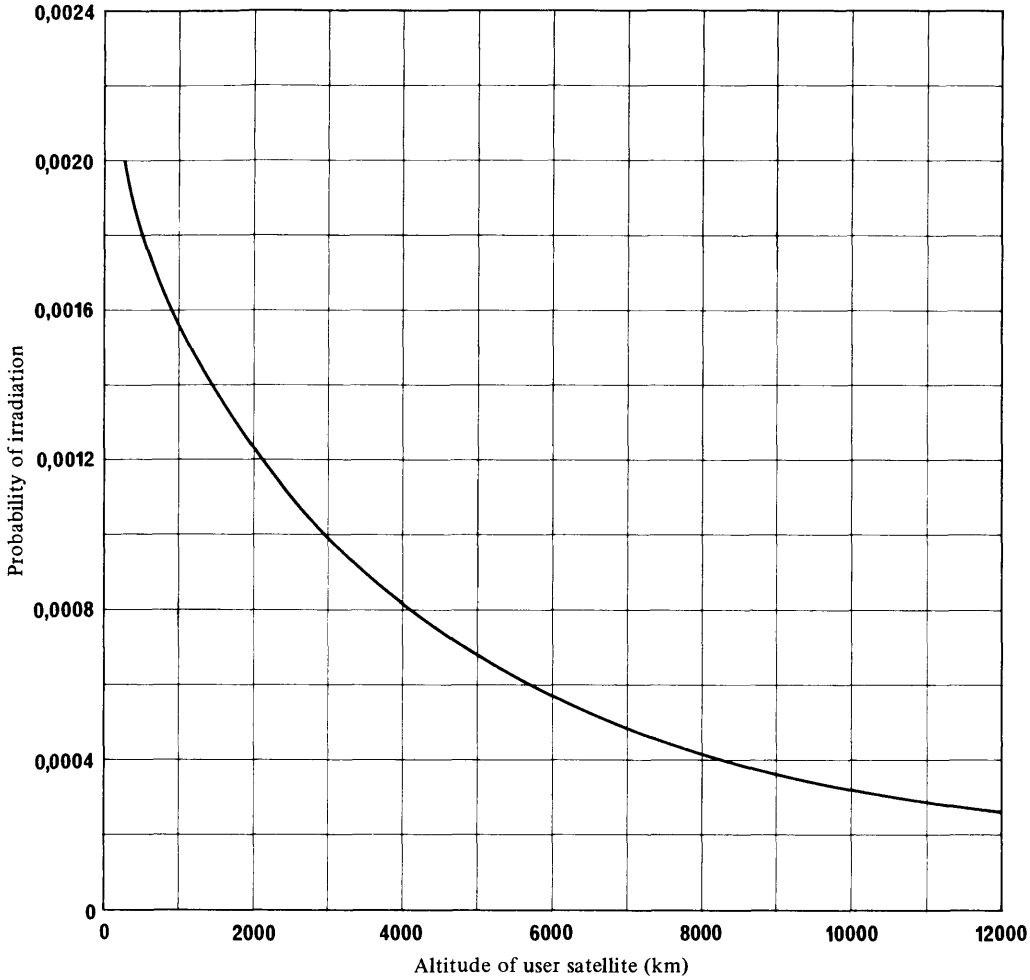

FIGURE 5 – *Probability of radiolocation system irradiation – one user satellite*

7.2 *Multiple satellite operations*

The previous sections have described simultaneous operations of a DRS, a radiolocation system and a single user satellite. For multiple user satellites, the maximum probability that a single fixed radar system site will be irradiated by at least one scan of the DRS beam per orbital period can be estimated from:

$$P_I(k) = \left(\frac{n!}{k!\,(n-k)!}\right) p^k (1-p)^{n-k} \tag{3}$$

where:

n: number of user satellites,

k: number of couplings per orbital period,

p: probability of coupling in one scan.

The probability of radar irradiation by at least one scan per orbital period, i.e.

$$P_I(k \geqslant 1) = 1 - P_I(0) \tag{4}$$

has been plotted in Fig. 6 with n as a parameter. This value varies directly with the number of users, and inversely with orbital altitudes. The value for n user satellites at different altitudes will always be less than the value plotted for n satellites, all at the lowest altitude.

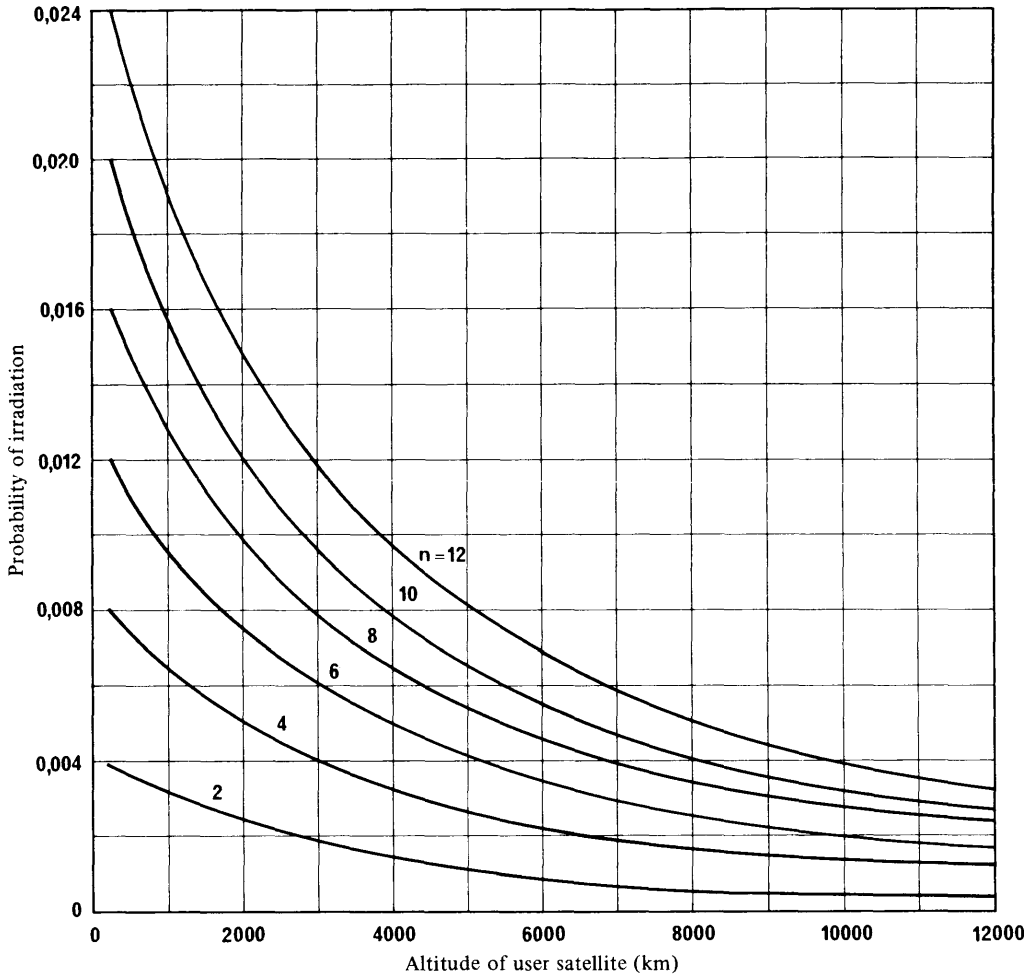

FIGURE 6 – *Probability of radiolocation system irradiation by at least one DRS scan per user satellite orbit – multiple user satellites*

parameter, *n*: number of user satellites

7.3 *Main beam to main beam paths*

Irradiation of a radiolocation system site located within the belt of highest susceptibility (see Fig. 2), results in main beam to main beam antenna couplings only during those times when the radar antenna main lobe is pointed toward the DRS. Since the typical radar beam scans at a much higher rate (135 RPM) than the DRS (a maximum of 0.634 degrees per minute), the fraction of operating time during which the two are nearly aligned is given by the ratio of the radar system horizontal beamwidth to total scan angle, i.e.

$$P_{D/I} \leqslant \frac{\theta_A}{2\pi} \leqslant 0.000944 \tag{5}$$

where:

θ_A: radiolocation system horizontal beamwidth (radian),

$P_{D/I}$: probability of a detectable interference-to-noise ratio, given that a radar system in the interference belt is irradiated.

Thus, although direct coupling can occur on every scan, it only lasts 419.7 μs per 7.407 ms scan, or 3.398 seconds per hour of operation.

7.4 *Combined probability of interference*

A combined probability of interference can be estimated by multiplying the appropriate values of the conditional probabilities, i.e.:

$$P_D = P_I \times P_{D/I} \tag{6}$$

Thus, for a radar system located in the interference zone, the probability of a detectable interference-to-noise ratio appearing within its receiver output circuit is a maximum of:

$$P_D = 0.000\,944 \times 0.012 = 0{,}000\,011\,3 \quad \text{or} \quad 1.13 \times 10^{-5}$$

for 6 user satellites. The probability of a detectable interference-to-noise ratio appearing via a side-lobe path is negligibly small, based on the interference criterion assumed in § 4.

7.5 *Summary*

Frequency sharing between a transmitting DRS and radiolocation services in the 14 GHz region seems to be feasible. Co-channel operation would probably not result in harmful interference to a hypothetical sensitive radiolocation system provided that the radiolocation system receiver sensitivities are of the order of −189 dB(W/Hz), when the DRS e.i.r.p. density is −26 dB(W/Hz). If the pfd from the DRS approaches the suggested limit, or if the receivers are more sensitive than, for example those quoted in § 4, they may detect DRS emissions; provided the receiver antenna is located within a narrow belt centered on the DRS horizon with an angular dimension at the Earth's centre equal to the vertical beamwidth of the radar system antenna (10° in the example). The duration of interfering emissions in such a case is principally determined by the horizontal beamwidth of the radar. For the example considered, these emissions would last no more than 420 μs per radar scan, or less than 0.0944% of the total operating time.

8. Interference from the user-to-DRS link to the radiolocation system

8.1 *Interference-to-noise ratio*

From Table I the e.i.r.p. density of a typical user spacecraft is −28 dB(W/Hz). Solving equation 1 with this value, a range of 1610 km, and an antenna gain of 35 dB yields an interference power density of −172 dB(W/Hz). For a noise power density of −193 dB(W/Hz) the interference power density yields an interference-to-noise ratio of 21 dB which is 31 dB above the maximum allowable level. Thus, the relative frequency (probability) of the occurrence of interference has to be estimated.

8.2 *Probability of main beam to main beam interference paths*

A near-Earth research satellite in the minimum postulated orbit (200 km altitude) circles the Earth once each 88.5 min approximately. Thus the angular rate in the orbital plane is 0.071 rad/min. The time required to traverse the assumed maximum beamwidth of the research satellite (1.86°) is approximately 0.46 min. During this half minute interval the radiolocation system scans its horizon at an angular rate of 135 rpm or a maximum of 62 total scans per 88.5 min. period. The horizontal beamwidth of the radiolocation antenna determines the fraction of each scan during which main lobe to main lobe radiolocation system coupling can exist. In this case the horizontal beamwidth is 0.34° and the user spacecraft is within this main beam for a maximum of 0.000 944 of the time per scan.

For the high orbit (for example 12 000 km), research satellite, the period is 420 min (7 h). The satellite angular rate in the orbital plane is, therefore, 0.015 rad/min. The time needed to cross the 1.86° beam of the research spacecraft is, therefore, approximately 2.2 min. During this 2.2 min. period the radiolocation antenna sweeps its horizon at 135 rpm for a maximum of 292 scans. The user spacecraft is within this main beam 0.000 944 of the time per scan, as for the low orbit case.

If we are given the fact that on one particular orbit, the DRS, the radiolocation system and the user spacecraft will align themselves, main lobe to main lobe coupling can exist for 0.000 944 of a time period varying between 0.46 and 2.2 minutes. This condition will occur on a maximum of 0.005 17 of the total number of orbits in any given time period. Thus, in a year (8760 hours) of operation, a low orbit (200 km) research spacecraft will circle the Earth 5939 times. A maximum of 31 of these orbits will be capable of producing main lobe to main lobe couplings at a single radiolocation system site. These couplings will exist for, at most, 0.000 944 × 0.46 min per coupled orbit. The resulting probability (relative frequency) of interference can be no greater than:

$$P_I \leqslant \frac{0.000944 \times 0.46 \times 31}{8760 \times 60} = 2.56 \times 10^{-8}$$

This means that in 8760 h of operation, a maximum of 810 ms of main lobe to main lobe coupling can be expected.

For the higher altitude case (12 000 km), one year of operation will produce 1251 orbits. Main lobe couplings can occur on 7 of these orbits. These couplings can exist for 0.0021 min per coupled orbit, at most. The resulting probability of interference can not be greater than:

$$P_I \leqslant \frac{0.000944 \times 2.2 \times 7}{8760 \times 60} = 2.76 \times 10^{-8}$$

Thus, in 8760 h of operation, a maximum of 870 ms of main lobe to main lobe coupling can exist. The precise interference times can be predicted in advance in every case.

8.3 *Summary*

Co-channel operation of radiolocation equipment and a DRS user spacecraft return link transmitter will result in the possibility of harmful interference to the radiolocation station during less than 2.76×10^{-8} times the total operating time of the period under consideration.

9. Interference from the earth station-to-DRS link into the radiolocation system

9.1 *Separation distance* *

The interference signal power density at the radiolocation receiver can be estimated from:

$$P_r = P_t + G_t - L_b \tag{7}$$

where,

P_r : maximum allowable interference signal power density in dB (W/Hz),

P_t : transmitting power density of DRS earth station in dB (W/Hz),

G_t : gain of transmitting antenna of DRS earth station in the direction of the horizon in dB,

G_r : gain of receiving antenna of radiolocation station in dB,

L_b : basic transmission loss between the transmitting and receiving antenna in dB.

Here, we assume that P_r, P_t and G_r are -203 dB (W/Hz), -56 dB (W/Hz) and 35 dBi, respectively.

If two geostationary DRSs separated by 130° of longitude, share an earth station at 35° North latitude, which is equidistant from the two, the directive antennae at the earth station must be elevated approximately 17° above the horizontal plane through the earth station, for maximum signal-to-noise ratio at the DRS. Thus, the maximum antenna gain near the earth station's horizon will be:

$$G_t = 32 - 25 \log 17 \approx 1.2 \text{ dBi.}$$

Then, the basic transmission loss, L_b is calculated as:

$$L_b = 183.2 \text{ dB.}$$

In order to find the separation distance which corresponds to the above basic transmission loss, we will use the methods shown in Report 382-3.

Firstly, assuming that the radio-climate zone is of type "A" and also that the time probability at which the basic transmission loss is less than 183.2 dB is 0.01%, the maximum separation distance R in a great circle propagation mode is estimated as

$$R = 220 \text{ km.}$$

In the next place, assuming that propagation mode is of scattering from hydrometeors, the normalized transmission loss at the time probability of 0.01%, L' dB, is calculated from:

$$L' = P_t + \Delta G - P_r$$

where,

$$\Delta G = G_r - 42 = -7,$$

Therefore, we have

$$L' = -56 - 7 + 203 = 140 \text{ dB.}$$

Here, assuming that the rain-climate zone is of type "2" or "5", the separation distance, R', which corresponds to the above normalized transmission loss L' is calculated, respectively,

$$R' = 250 \text{ km or } 220 \text{ km.}$$

9.2 *Summary*

Referring to the above results, it can be concluded that, if frequencies are shared between the radiolocation service and space research service (using DRSs), coordination will be necessary when the radiolocation station and the DRS earth station are not separated by at least 250 km.

10. Discussion

This Report deals with present and proposed sharing of this region of the spectrum by radiolocation and space research. Future use and sharing by these systems will satisfy this analysis if the characteristics are similar to those assumed in this Report.

Although interference to the DRS system from radiolocation transmitters was not analysed, it is unlikely to be considered a serious problem. However, further studies are required.

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* For a complete discussion of propagation factors including radiometeorological aspects, see Reports 563-1, 564-1 and 569-1 of Study Group 5.

11. Conclusions

11.1 *Interference from a satellite in the DRS system to a radiolocation system*

A DRS system can operate in such a way that if the maximum power flux-density produced at the surface of the Earth by emissions from a satellite in the space research service for all conditions and methods of modulation does not exceed, in any 4 kHz band:

-148	$dB(W/m^2)$	for	$\delta \leq 5°$
$-148 + (\delta - 5)/2$	$dB(W/m^2)$	for	$5° < \delta \leq 25°$
-138	$dB(W/m^2)$	for	$25° < \delta \leq 90°$

where δ is the angle of arrival of the radio-frequency wave (degrees above the horizontal). Interference to a radiolocation receiver should then be acceptably small.

11.2 *Interference from an earth station to a radiolocation system*

If frequencies are shared between a DRS system and a radiolocation system then co-ordination will be required in all cases when the separation distance is less than 250 km.

RECOMMENDATION 512 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH SERVICE AND RADIOLOCATION SERVICE NEAR 14 GHz

Potential interference from data relay satellite systems

(Question 11-1/2)

(1978)

The CCIR,

CONSIDERING

(a) that Report 691 indicates the feasibility of frequency sharing between the Space Research Service (transmitters of a data relay satellite system) and the Radiolocation Service near 14 GHz;

(b) that space research systems share frequency bands with radiolocation services near 14 GHz on a secondary basis (Earth-to-space) (No. 407A of the Radio Regulations);

(c) that it is desirable to limit the power radiated from space research systems so as not to degrade the functions of radiolocation systems,

UNANIMOUSLY RECOMMENDS

1. that frequency sharing between the Radiolocation Service and Space Research Service using data relay systems, is feasible near 14 GHz provided that appropriate power flux-density limits are specified for the Space Research Service;

2. that, in frequency bands near 14 GHz shared between systems in the Space Research Service and Radiolocation Service, the space research data relay satellite systems can operate within 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:

-148	$dB(W/m^2)$	for	$0° < \delta \leq 5°$
$-148 + (\delta - 5)/2$	$dB(W/m^2)$	for	$5° < \delta \leq 25°$
-138	$dB(W/m^2)$	for	$25° < \delta \leq 90°$

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;

3. that if frequencies are shared between the Radiolocation and Space Research Service (using data relay satellites) coordination may be necessary when the radiolocation station and the earth station are not separated by at least 250 km.

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* This Recommendation is brought to the attention of Study Group 8.

REPORT 686 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN FIXED-SATELLITE AND NEAR-EARTH SPACE RESEARCH SERVICES NEAR 15 GHz

Analysis of potential interference from a data-relay system

(Question 11-1/2)

(1978)

1. Introduction

This Report examines the potential for frequency sharing between the Space Research Service (data relay system) and the Fixed Satellite Service in frequency bands near 15 GHz. Considering a data relay satellite (DRS) system with the characteristics in Table I, the following links are analyzed in this Report:

Forward links: Earth to data-relay-satellite (DRS) (Earth-to-space)
DRS to user (space-to-space)

Return link: user to DRS (space-to-space)

The Report investigates interference into receivers in the Fixed Satellite Service from transmitters in the DRS system.

2. Interference criterion and assumptions

The method of Appendix 29 of the Radio Regulations establishes a criterion of 2% increase in equivalent satellite link noise temperature, as a basis for determining interference potential between two satellite systems. The method of Appendix 29 has been used in this analysis to establish a criterion for interference between the space research and Fixed Satellite Services. (The Appendix 29 method is independent of modulation characteristics of the satellite systems involved). Accordingly, an input I/N (interference to noise) ratio of -17 dB (10 log 0.02) at the receiving system is used as the interference criterion for link calculations. The number of entries of simultaneously interfering satellite networks are assumed to be included in the establishment of this margin.

The analysis is developed for the worst case and the following assumptions are made:

- free space loss is the only power loss in transmission for all links,
- there is no improvement from antenna polarization discrimination,
- there is co-channel carrier operation for signals of both equal and unequal bandwidths in the band, and
- there is accurate satellite station-keeping.

The antennae in all systems are assumed to be parabolic reflector type or equivalent. The reference radiation pattern is obtained from Recommendation 465-1, except for satellite antennae in fixed-satellite services, which use the pattern given in Report 558-1.

TABLE I – *DRS system characteristics*

Characteristics	Forward link		Return link	
	Earth-to-DRS	DRS-to-user	User-to-DRS	DRS-to-Earth
Earth station				
e.i.r.p. density (dB(W/Hz))	4			
Antenna gain (dB)	60			60
DRS spacecraft				
e.i.r.p. density (dB(W/Hz))		−26		−26
Antenna gain (dB)	50		50	
User spacecraft				
e.i.r.p. density (dB(W/Hz))			−28	
Antenna gain (dB)		≈40 to 50		

* This Report is brought to the attention of Study Groups 1 and 4.

3. Interference from Earth-to-DRS forward link to up-links of Fixed Satellite Services

An appropriate minimum satellite separation in the geostationary satellite orbit can prevent a satellite from receiving excessive interference due to signals transmitted from fixed earth stations of other systems. At the earth station receiver of a fixed satellite system, the interference (I) and total link noise (N), both in dB(W/Hz), can be expressed as:

$$I = (\text{e.i.r.p.})' - \Delta G(\theta) + G_s(\psi) - L + \gamma \quad (1)$$

$$N = k + T + \gamma + R \quad (2)$$

where,

(e.i.r.p.)' = DRS earth station e.i.r.p. density (dB(W/Hz))

$\Delta G(\theta) = G(0) - G(\theta)$: minimum antenna discrimination at DRS earth station required to meet the interference criterion, $G(\theta)$ being the antenna gain at off-main beam axis angle θ (dBi)

$G_s(\psi)$: fixed satellite space station antenna gain at off-axis angle ψ (dBi)

L : transmission loss of interference path $\approx$ 208 dB

γ : transmission gain, i.e., the ratio of received signal power density at the earth station, to that at the space station in the fixed satellite system (dB)

k: Boltzmann's constant = -228.6 dB($WK^{-1}Hz^{-1}$)

T: up-link system noise temperature of the fixed satellite system (dBK)

R: total link to up-link thermal noise ratio of the fixed satellite system (dB)

Assuming that the DRS earth station is located in the main-beam coverage of the fixed satellite receiving antenna, i.e., $G_s(\psi) = G_s(0) \equiv G_s$, the above equations yield:

$$\Delta G(\theta) = -(I/N) + (\text{e.i.r.p.})' + G_s - L - k - T - R \quad (3)$$

The system parameters of fixed-satellite services involved in equation (3) are G_s, T, and R. Their values are determined below and are used throughout this Report. The satellite antenna gain (G_s) can be as high as 40 dB for a 1.5° spot beam, and this value is employed since it gives a large required discrimination $\Delta G(\theta)$. A typical value of 1000 K is considered appropriate as the up-link system noise temperature, and its contribution is not expected to be more than one third of total link noise. (In a frequency division multiplex telephony system, for example, 2700 pW0p is allocated for up-link thermal noise in the 8000 pW0p budget for total internal noise arising in an overall satellite link). The ratio R of 5 dB is thus assumed.

The required separation angle θ, seen from the DRS earth station, is calculated from the antenna gain obtained from equation (3), and equals 5.7°. Since the topocentric angle θ is always greater than the geocentric separation between two satellites, 5.7° is a conservative approximation of the latter.

Furthermore, the above analysis is much the same as that for sharing between two different fixed-satellite systems. Since the fixed Earth-to-DRS link and Fixed Satellite Service up-links are compatible with each other in system characteristics, their sharing of the same band is feasible and efficient orbit utilization can be accomplished in non-congested parts of the geostationary satellite orbit.

Alternatively, in order not to affect the orbital sharing possibilities within the Fixed Satellite Service at congested orbital positions, the DRS earth station could be located outside the main-beam coverage of the fixed satellite receive spot-beam antenna. This would enable the DRS to be located nearer the fixed satellite. For example, if the location of the DRS earth station were restricted to outside the -3 dB contour of the fixed satellite spot beam antenna (amounting to some 500-600 km – a not impractical proposition) the satellite separation angle could be reduced to about 4° as seen from the DRS earth station.

4. Interference from user-to-DRS return link to up-links of the Fixed Satellite Service

As in the previous case, interference is most likely to occur when the DRS and the satellite in the Fixed Satellite Service are adjacent in orbit. The return link signal transmitted from the DRS user satellite up to a DRS in geostationary satellite orbit may result in an unacceptable interference entry into the Fixed Satellite Service up-links. The worst case occurs when a DRS user is in the main lobe of a satellite receiving antenna of the Fixed Satellite Service, as shown in Fig. 1. A minimum separation between satellites is thus required and can be evaluated from the following equation:

$$\Delta G_u(\theta) = -(I/N) + (\text{e.i.r.p.})_u + G_s - L' - k - T - R \quad (4)$$

If the DRS user spacecraft antenna pattern gives $(\text{e.i.r.p.})_u$, as its e.i.r.p. density, $\Delta G_u(\theta) = G_u(0) - G_u(\theta)$ is the required antenna discrimination at the user spacecraft, L' is the free space loss of the interference path, and the other parameters are as given in Equation (3). It can be shown that the variation of transmission loss with various user altitudes is negligible compared with that of $\Delta G_u(\theta)$, and that for a value of θ the largest required geocentric separation angle occurs at the lowest orbital altitude. Therefore, the worst case occurs at the lowest user orbit of 200 km, and results in a transmission loss of 207 dB. For $G_u(0)$ = 40 dB, the off-main beam axis angle θ is 2.7° and conservatively equals the required satellite separation. This demonstrates that the required separation of 5.7° in the previous case is large enough to avoid the occurrence of harmful interference in the present case.

It is to be noted that if the separation angle between DRS and fixed satellites is reduced to the order of 3°, as could follow from § 3 above, the user-to-DRS link may have to be restricted so that it lies outside a cone around the axis of the fixed satellite spot beam.

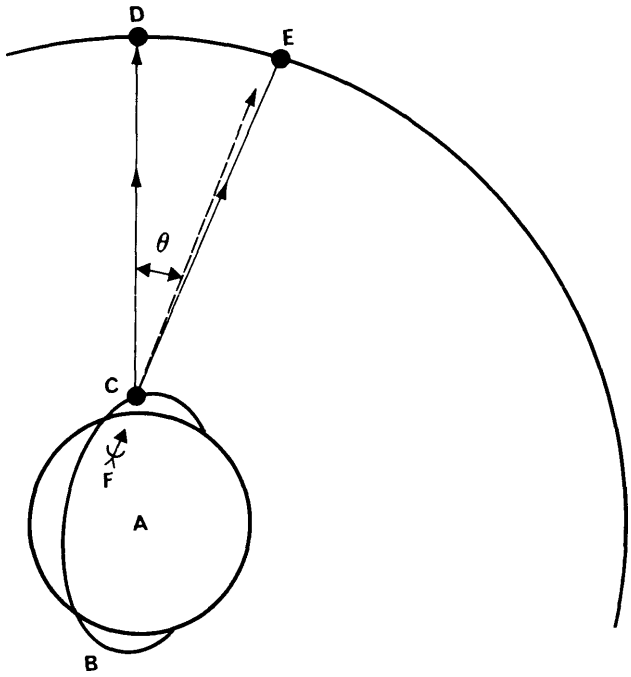

FIGURE 1 – *Configuration relevant to interference from user-to-DRS link to up-links of the fixed-satellite service*

A : Earth

B : User orbit

C : DRS system user

D : DRS

E, F : Space and earth station of fixed-satellite service

5. Interference from DRS-to-user forward link to up-links of Fixed Satellite Services

Fig. 2 shows the geometry of this interference case for a single DRS spacecraft. The worst case is when the user is orbiting on the equatorial plane, or at a very low inclination. The DRS transmit antenna main beam (0.4°) tracks the user, and simultaneously illuminates portions of the geostationary orbit. The fixed satellite system which has spacecraft near antipodal locations may thus receive excessive interference. These two orbital segments (I and II) can be determined from required antenna discrimination at the spacecraft:

$$\Delta G_s(\psi) = -(I/N) + (\text{e.i.r.p.})_{DRS} + G_s - L'' - k - T - R \qquad (5)$$

where $(\text{e.i.r.p.})_{DRS}$ is the DRS e.i.r.p. density, L'' the transmission loss from the DRS to the fixed satellite (214 dB), and other parameters as previously given. Calculations show $\Delta G_s(\psi) = 7.6$ dB. Using the antenna pattern of Report 558-1, the minimum off-main beam axis angle (ψ) is 1.3° for the 40 dB gain antenna. If the satellite is at the minimum elevation of 15° from its earth station, the receiving antenna is pointed 0.3° inward from the edge of the Earth. The angle Ω in Fig. 2 for satellites on segments I and II then ranges from 0° to 1°, and the measure of each segment is approximately 2.3°. The worst case calculation indicates that the fixed satellite system could experience up-link interference for 10% of time, which is considerable. However, the narrowness of the two segments makes the co-ordination of satellite positioning possible, so that this constraint does not lead to poor orbit utilization.

In addition, it should be observed that the above constraint of 7.6 dB antenna discrimination can be totally or partially offset by varying other parameters in Equation (5). The following arrangements may be made:

- locating satellites with lower gain antenna on the segments,
- locating satellites with lenient interference margin on the segments, and
- decreasing the DRS e.i.r.p. density by using carrier energy dispersal techniques.

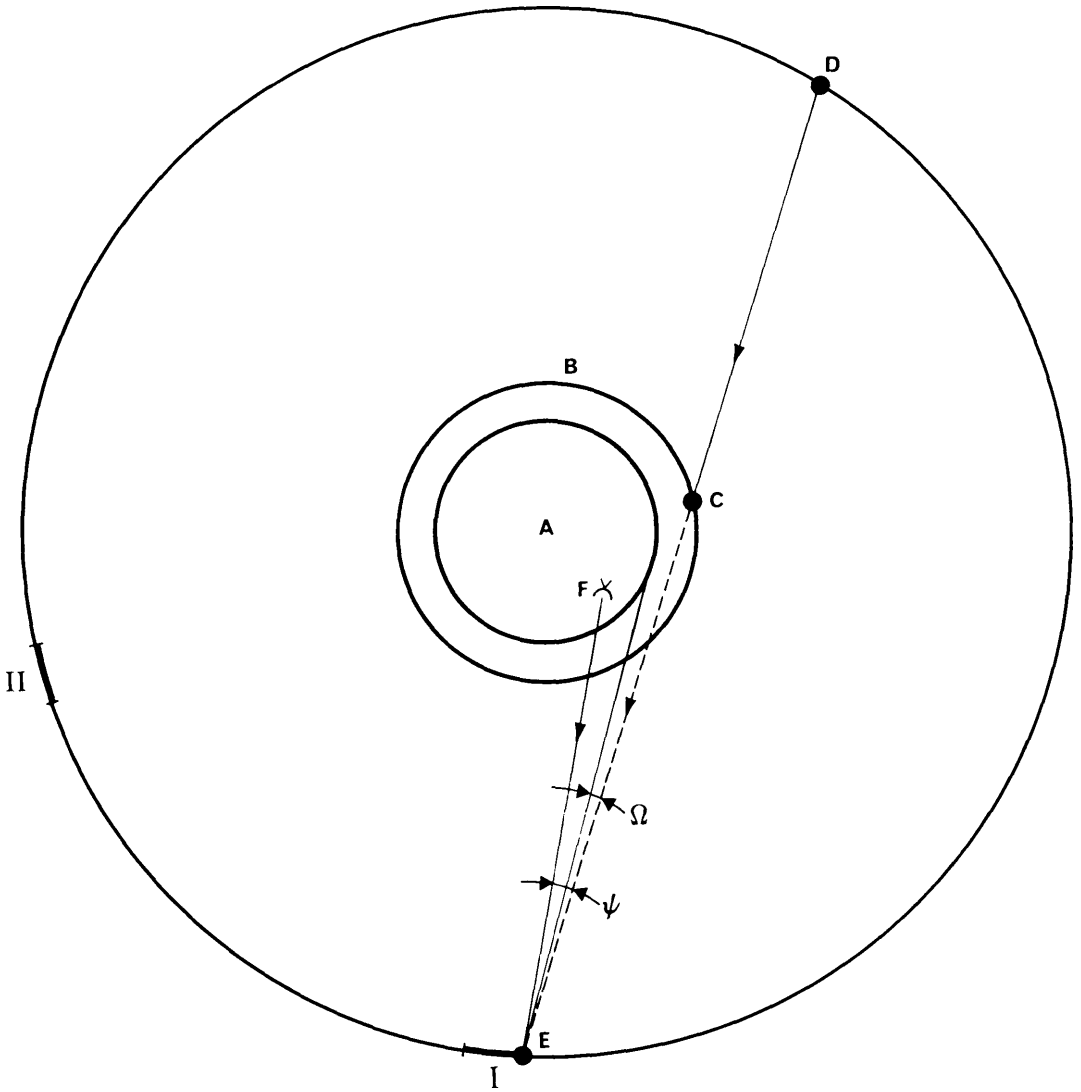

FIGURE 2 – *Configuration of interference from DRS-to-user to up-links of fixed-satellite services*

A to F : same as in Fig. 1

For practical purposes, specific system characteristics are desirable on further sharing studies dealing with this case.

In the case of a Fixed Satellite Service space station located near orbital segments I and II, when the fixed-satellite earth station is located near the Equator and on the limb of the Earth as seen from the DRS, some constraints may need to be placed on the DRS-to-user operations.

6. Conclusions

This analysis of potential interference to the Fixed Satellite Service demonstrates that, at the frequencies in the vicinity of 15 GHz:

- the sharing of Earth-to-DRS and user-to-DRS links with up-links of Fixed Satellite Services is feasible for satellites in non-congested parts of the geostationary satellite orbit, while in other parts of the geostationary satellite orbit there may need to be restrictions on DRS earth station locations and/or positions from which the user-to-DRS links can be used;
- and the sharing of DRS-to-user link with up-links of Fixed Satellite Services is also feasible, provided that co-ordination of satellite positioning and system implementation is performed.

REPORT 456-2 *

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(Question 10-1/2)

(1970 - 1974 - 1978)

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 and for geodetic measurements with scientific objectives, such as the measurement of the shape of the Earth or variations in the distances between points located on its surface. Other applications of beacons are described in Report 538-1 and [CCIR, 1974-78].

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 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, geodesy and 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.

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* This Report is brought to the attention of Study Groups 5 and 6.

3. Ionospheric research

Ionospheric beacon satellites transmitting at harmonically related frequencies have proved to be powerful tools for the investigaton of iono- spheric 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 205-4):

- 15 to 20 GHz range
- 30 GHz
- 90 GHz
- 150 GHz.

5. Geodesy

The general problem in the geodetic work envisaged is to establish accurately the relative locations of a satellite and one or more points on Earth, at various known times. This information can then be used to calculate the separations of the earth terminals or to use the satellite motions to calculate the shape of the Earth.

Geodetic beacons are used to determine, by the Doppler effect, the radial speed of a satellite as seen from an earth station, and the need to exploit this technique is likely to continue indefinitely. The variable received frequency is measured in given time intervals (seconds for example), and then compared with the transmitted frequency, which must be known accurately so that the difference in frequency can be calculated. Ionospheric (and tropospheric) refraction is a perturbing influence. In view of the high accuracy required, correction must be made for refraction effects and this is so, even in the case of transmissions at rather high frequencies when these effects are slight. The most important ionospheric correction can be obtained with the differential Doppler technique, using harmonically-related frequencies as explained above.

At least two sets of frequencies have been used. One system based on multiples of 54 MHz has often been applied; for example, in the GEOS series with 162, 324 and 972 MHz [Hayes, 1964]. It has been reported that interference from other transmitters often occurs on the lowest of these frequencies and that fully satisfactory operations are uncommon. A second system is based upon the primary frequency allocations for radio navigational satellites, at 150 and 400 MHz; these are used by some TRANSIT satellites [Newton, 1967]. The frequency ratio 3/8 leads to complication of the ground equipment and from this point of view it would be preferable for the geodetic application to be based on a simpler frequency ratio, for example 1/2, 1/3 or perhaps 1/4 or 2/3.

Techniques similar to those needed for geodesy are of interest for the location of platforms on which meteorological or other environmental measurements are made. These requirements are discussed in Report 538-1.

6. 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 (Recommendations 364-3 and 365-3).

7. Conclusion

A continuing need, for many years, is envisaged for space research experiments involving Doppler and Faraday rotation techniques, for geodetic measurements based on the Doppler effect, and 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.

Geodetic work can be carried out to some extent by using the allocated bands for radio-navigation satellites, but a pair of frequency bands more simply related than are the present 150 and 400 MHz bands could lead to a simplification of equipment. Furthermore, for work of the highest accuracy an additional frequency, higher than and harmonically related to 400 MHz, is required.

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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CCIR Document

[1974-78]: 2/52 (USA).

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 antennae 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 antennae except on board geostationary satellites. However, even in the case of these satellites, the technical expense of installing directional antennae is prohibitve 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 antennae 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.

RECOMMENDATION 513

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(Question 10-1/2)

(1978)

The CCIR,

CONSIDERING

(a) that a continuing need is envisaged for space research experiments involving Doppler and Faraday rotation techniques, for geodetic measurements based on the Doppler effect, and for measurement of atmospheric transmission characteristics above 10 GHz;

(b) that the conclusions drawn in Report 456-2 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 the atmospheric attenuation curve, frequencies near 15, 20, 30, 90 and 150 GHz are technically suitable for atmospheric measurements;

(f) that use of frequencies which are not in simple harmonic relation for geodetic applications leads to the complication of ground equipment;

(g) that for work of the highest accuracy, an additional frequency, higher than and harmonically related to 400 MHz is a technical requirement for geodetic measurements;

(h) 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 (by Radio Regulation No. 236 A);

3. that frequencies near 15, 20, 30, 90 and 150 GHz are desirable for atmospheric measurements;

4. that a pair of frequencies in more simple relation to each other than 150 and 400 MHz is desirable for geodetic measurements;

5. that frequencies higher than and harmonically related to 400 MHz are also desirable for geodetic measurements.

REPORT 700

RADIOCOMMUNICATION REQUIREMENTS FOR SYSTEMS TO SEARCH FOR EXTRA-TERRESTRIAL LIFE (SETI)

(Question 17/2)

(1978)

1. Introduction

Question 17/2 on Radiocommunication Requirements for Systems to Search for Extra-terrestrial Life 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 develop 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 on nearby 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).

There are at present several SETI programmes in progress [Sagan and Drake, 1975]. These include the following:

1.1.1 Bridle and Feldman, at Algonquin Radio Observatory in Canada, are searching nearby stars at 22.2 GHz, near the H_2O line.

1.1.2 Dixon and Cole, at Ohio State University Radio Observatory, are making an all-sky survey near the 1.4 GHz hydrogen line [Dixon and Cole, 1977]. This survey has been in progress continuously for three years.

1.1.3 Drake and Sagan, using the Arecibo Observatory in Puerto Rico, are observing several nearby galaxies at 1420, 1653, and 2380 MHz [Ponnamperuma and Cameron, 1974].

1.1.4 The Soviet Union SETI programme [U.S.S.R., 1974; U.S.S.R., 1975].

1.1.5 Kardashev, using the Eurasian Network, in the U.S.S.R., is searching for pulsed signals, with hemispherical coverage [Kardashev, 1976].

1.1.6 Troitsky, using the Eurasian Network, is 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, are 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 is currently 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 stated that an average life of communicating civilizations would be of the order of 10^7 years. It is concluded therefore, that the other civilizations 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 comes 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 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 564-1). When rain is taken into account, attenuation becomes more significant at frequencies greater than 3 GHz. Atmospheric attenuation is shown in Fig. 1, based on data from Report 564-1.

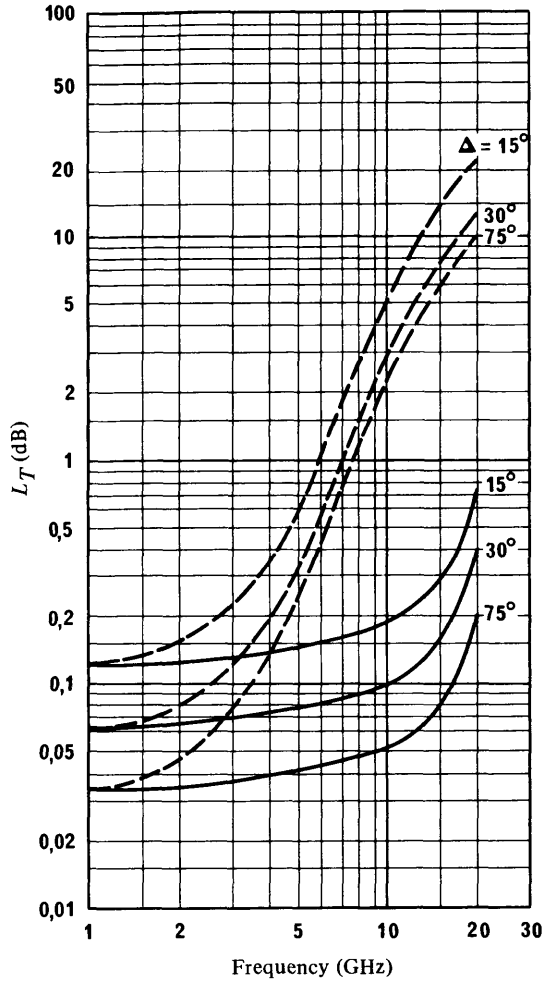

FIGURE 1 – *Space-to-Earth attenuation (L_T)*

——— clear weather, atmosphere only

– – – – – rain and atmosphere

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 and galactic noise and quantum noise (caused by fluctuations in the rate of arrival of RF quanta at the receiver), [Oliver, 1973a]. These noise contributors are shown in Fig. 2.

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 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.

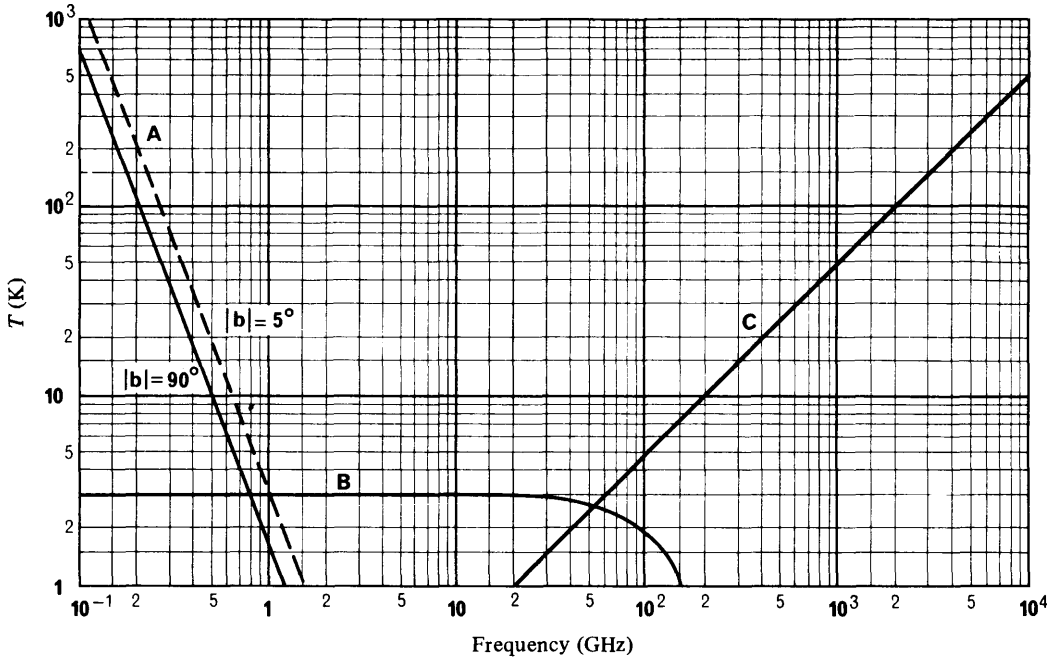

FIGURE 2 – *Background noise temperature (T) contributors outside the atmosphere of the Earth*

A : Galactic

B : Black body

C : Quantum effect

parameter | *b* | : Absolute value of galactic latitude

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.

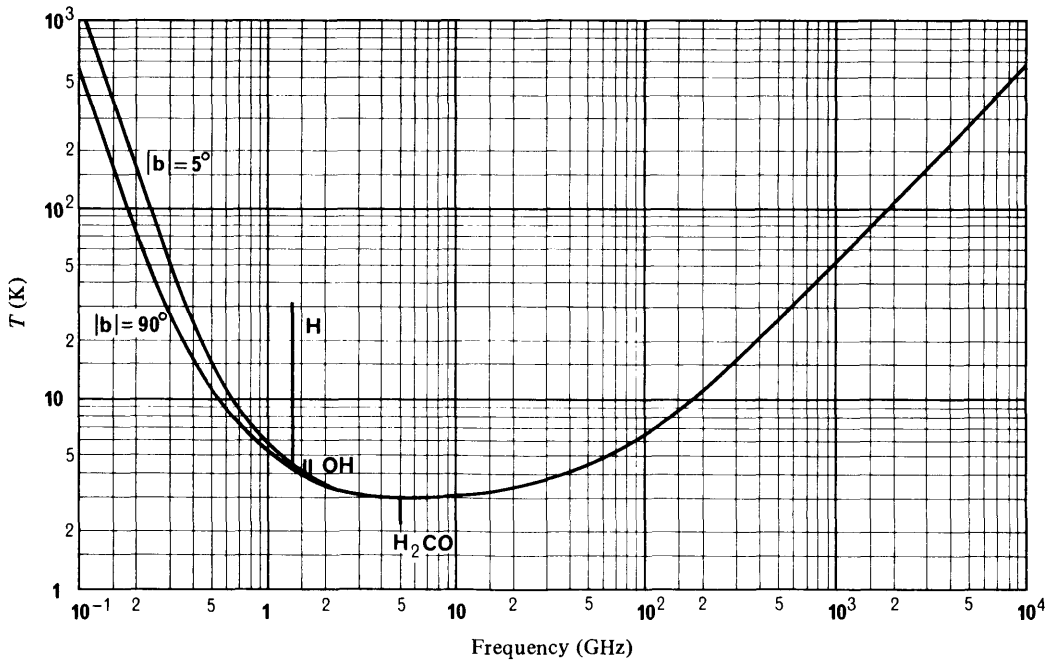

FIGURE 3 – *Total sky noise temperature (T) outside the atmosphere of the Earth*

parameter | *b* | : the absolute value of the galactic latitude

2.3.1.2 *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 564-1. The effect of the atmosphere is to reduce the frequency range of the sky noise temperature minimum.

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). The resultant total sky noise temperature is shown in Fig. 4.

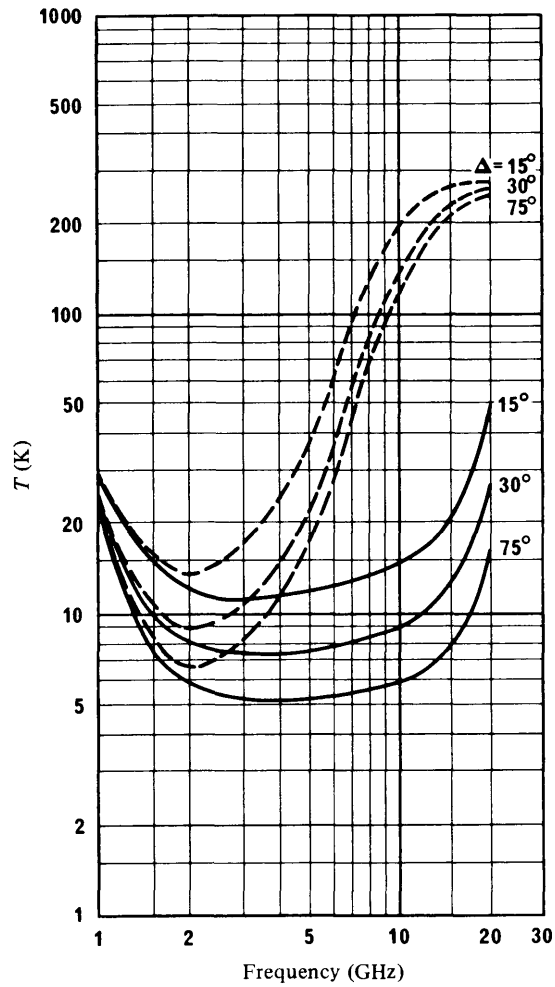

FIGURE 4 – *Total sky noise temperature (T) seen from the surface of the Earth*

——— clear weather, atmosphere only

– – – – – rain and atmosphere

parameter Δ: elevation of earth station antenna

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.

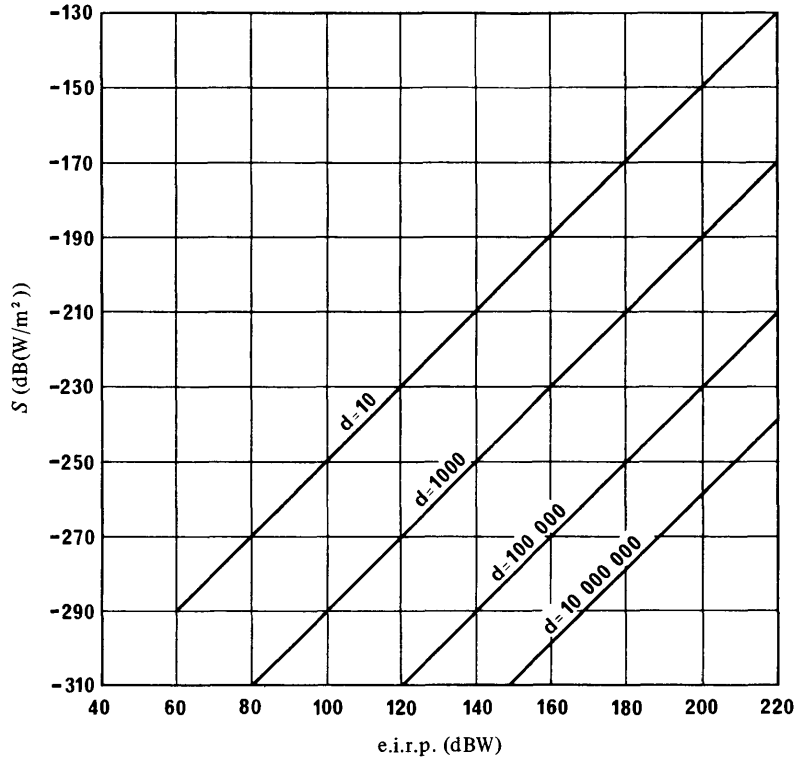

FIGURE 5 – *Received flux-density(s) versus effective isotropically radiated power for unattenuated sources at various distances*

parameter d : distance in 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.

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.

3. Preferred frequency bands

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 1.3 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.

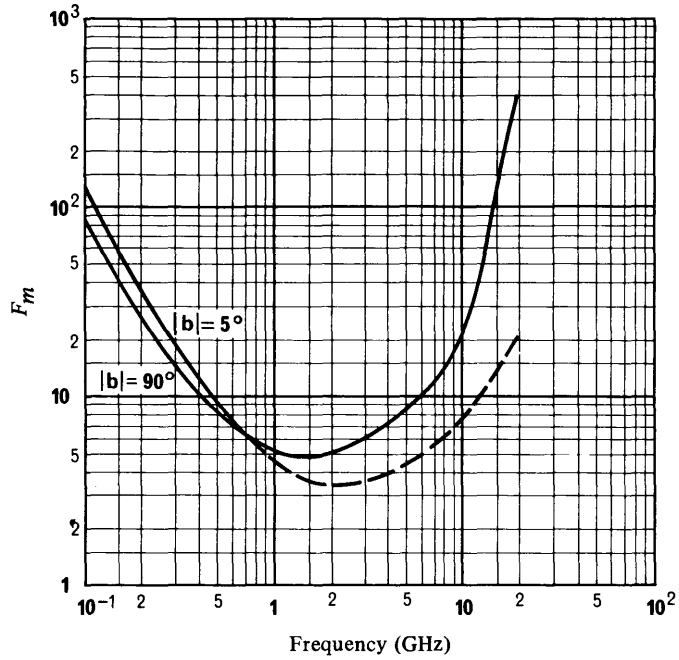

FIGURE 6 – *Combined noise and Doppler drift system sensitivity figure of merit, F_m*

——— Including zenith atmosphere noise

— — — Extraterrestrial noise only

parameter | *b* |: The absolute value of the galactic latitude

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.* 1977].

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.

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*

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.

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, 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 antennae 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 colinear 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.

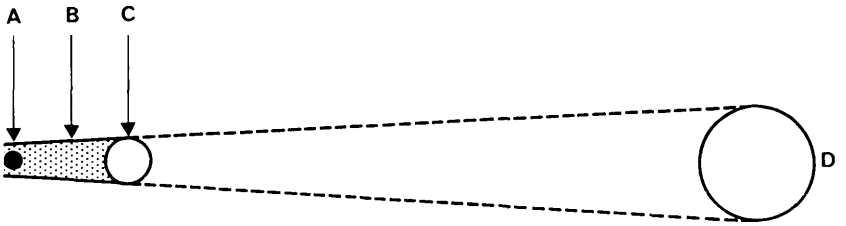

FIGURE 7 – *Lagrangian collinear equilibrium point*

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 antennae dedicated to SETI. They will examine many more targets and directions; will search much wider bandwidths; and will be considerably more sensitive than 1977 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 antennae.

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*

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 (1950) (4)	Declination (5)
+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

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
Tuneable 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. 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, antennae 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.

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 envision 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 used for SETI are considering 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 548-1 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 dBW 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*

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 bandwith 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.

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 224-4 would be adequate for their protection.

As the SETI systems and frequencies become better defined, additional protection criteria will emerge.

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SECTION 2C: EARTH EXPLORATION SATELLITE SERVICE

Recommendations and Report

REPORT 692

PREFERRED FREQUENCY BANDS AND POWER FLUX-DENSITY CONSIDERATIONS FOR EARTH EXPLORATION SATELLITES

(Question 12-2/2)

(1978)

1. Introduction

In recognition of the potential usefulness of Earth exploration satellites, the 1971 WARC-ST allocated frequency bands for telemetering data from Earth exploration satellites in Band 10 (8025 to 8400 MHz and 21.2 to 22.0 GHz). Further study of Earth exploration satellites under consideration in the United States indicates that these bands may be inadequate to satisfy requirements of future satellite systems.

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 currently under development include a thematic mapper which produces data at a rate of 84 Mbit/s. This sensor is planned for use in the LANDSAT programme beginning with LANDSAT-D.

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 antennae. In addition to the economic advantage of using existing data acquisition antennae, there are technical reasons why 9 m diameter antennae 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 the 21.2 to 22 GHz Earth exploration satellite allocation, 9 m approaches the limiting size for an 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 in the 21.2 to 22 GHz Earth exploration satellite allocation because of the required data rates. At low elevation angles, link losses under moderate rain conditions are about 28 dB greater in the 21.2 to 22 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 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 the 21.2 to 22 GHz allocation were used for data communications. One of the sensors developed by earth resources scientists is a microwave radiometer which utilises 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. 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 rates of 10^{-5} are required.

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 minimised 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) is being designed by the United States to provide two-way radiocommunications to and from experimental Earth exploration satellites and other research Earth satellites. The system will relay these communications and data to one or more fixed earth stations within view of the relay satellites. At the same time, the Earth orbiting 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 Annex I.

The design of the TDRS is such, that user satellite data rates up to 300 Mbit/s will be accommodated. Effective 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, $32 - 25 \log \Psi$, 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 and 21.2 to 22 GHz as well as in the vicinity of 20 GHz.

TABLE I – *Radiocommunication link parameters*

Radiocommunication link	Frequency bands					
	8025 to 8400 MHz Major facility	8025 to 8400 MHz Low-cost facility	21.2 to 22.0 GHz Major facility	21.2 to 22.0 GHz Low-cost facility	20 GHz Region Major facility	20 GHz Region Low-cost facility
System temperature (K)	266	292	484	445	477	420
System noise (dBm)	−93.6	−100.9	−91.0	−99.1	−91.1	−99.4
System margin (dB)	−3.0	−6.0	−3.0	−6.0	−3.0	−6.0
Required *S/N* (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required receive signal (dBm)	−78.6	−82.9	−76.0	−81.1	−76.1	−81.4
Nominal ground antenna gain (dB)	55.5	26.0	63.7	34.2	63.1	33.2
Antenna surface tolerance loss (dB)	−0.3	–	−2.0	–	−1.8	–
Antenna pointing loss (dB)	−0.5	−0.5	−3.0	−3.0	−2.6	−2.6
Receive circuit loss (dB)	−0.5	−1.0	−1.0	−2.0	−0.9	−1.7
Free space loss (dB)(1)	−181.0	−174.7	−189.3	−183.5	−188.8	−181.9
O_2/H_2O absorption loss (dB)	−0.6	−0.4	−6.0	−1.2	−3.2	−0.5
Precipitation loss (4 mm/h) (dB)	−0.8	–	−9.5	−2.7	−8.1	−2.1
Cloud loss (dB)	−1.9	−0.3	−10.0	−1.8	−8.1	−1.7
Satellite antenna pointing loss (dB)	−3.0	−3.0	−3.0	−3.0	−3.0	−3.0
Satellite required e.i.r.p. (dBm)	53.9	71.2	84.1	81.9	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°.

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 rate 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.

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:

$$\text{pfd}_{max} = 10 \log (4 \text{ kHz}) + \text{e.i.r.p.} - 10 \log BR/2 - 10 \log 4\pi D^2 \quad (1)$$

for quadriphase modulation, and

$$\text{pfd}_{max} = 10 \log (4 \text{ kHz}) + \text{e.i.r.p.} - 10 \log BR - 10 \log 4\pi D^2 \quad (2)$$

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	21.2 to 22.0 GHz	In the region of 20 GHz
pfd max (major data facility)	−145.8 dB(W/(m² · 4 kHz)) (at 90°)	−91.7 dB(W/(m² · MHz)) (at 90°)	−98.9 dB(W/(m² · MHz)) (at 90°)
pfd max (low cost facility)	−123.8 dB(W/(m² · 4 kHz)) (at 90°)	−89.1 dB(W/(m² · MHz)) (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°)	−105 dB(W/(m² · MHz)) (25° to 90°)

Due to increased path length attenuation at low elevation angles from low orbiting 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 358-3, and discussed in Report 387-3, are derived from detailed analyses of interference to the fixed service, based essentially on the use by the fixed satellite service of satellites in the geostationary orbit. Further detailed examination may be required to verify an extension of their applicability to include systems in non-geostationary orbit.

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, the transmission path to TDRS will not come closer to the surface of the Earth than 50 km. The worst pfd which would occur in this case, would be −124.2 dB(W/(m² · MHz)).

* 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.

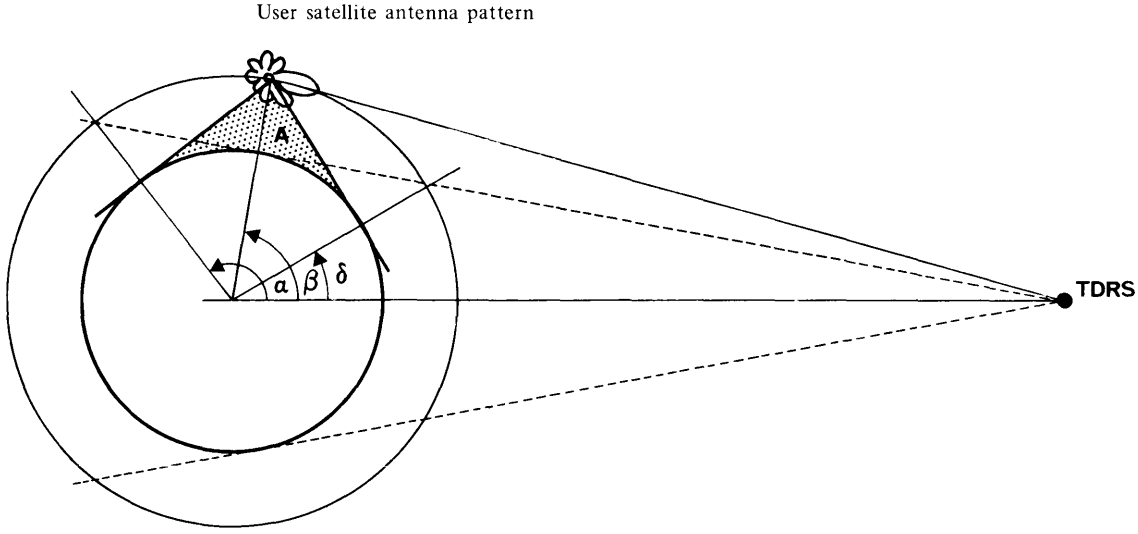

FIGURE 1 – *Earth, user satellite, TDRS geometry*

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 21.2 to 22.0 GHz band, the limit is exceeded on the link to the major data acquisition facility by 13.3 dB and on the link to the low cost data acquisition facility by 15.9 dB. 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 12.2 dB.

6. Conclusion

Future applications planned for Earth exploration satellites cannot be satisfactorily carried out in the two band 10 allocations available for telemetering data.

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.

Increased atmospheric and precipitation losses at the 21.2 to 22 GHz allocation 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 in the 21.2 to 22 GHz band.

The 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 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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ANNEX I

OPERATIONAL GEOSTATIONARY RELAY SATELLITES FOR EARTH EXPLORATION SATELLITE SERVICE

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 extremely 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 simultaneously relay 600 Mbit/s data links from two low orbiting 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 Annex 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. 2. 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 utilise the high gain pointable antennae required on board the EES and relay satellite spacecraft for data transmission.

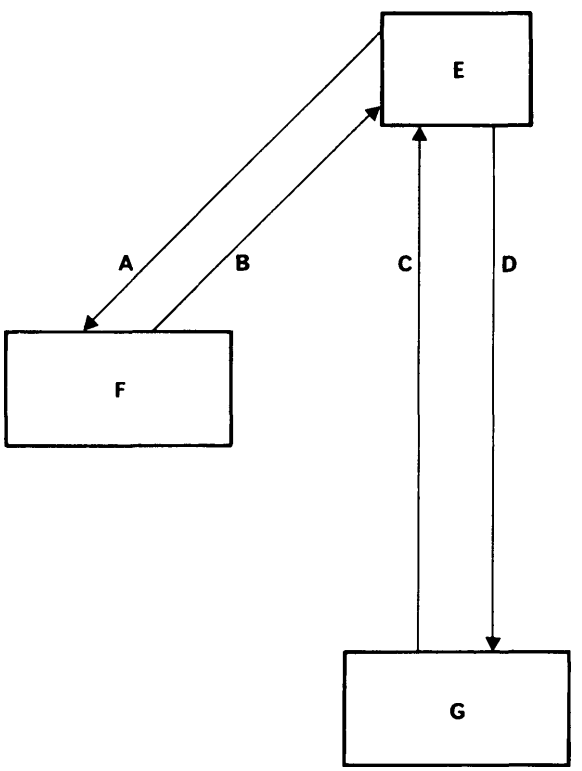

FIGURE 2 – *Operational EES relay satellite data transfer system*

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

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 II 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}.

TABLE II – *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 3m)	52.5
E.i.r.p. (dBW)	64.8
Spreading loss (40 600 km, 10° elevation (dB/m^2)	–163.7
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 density (dB(W/Hz))	–180.7
Receiver system noise density (T = 400 K) (dB(W/Hz))	–200.6
C/N down path (dB)	20.9
Margin (dB)	3.0
Required C/N down path (dB)	17.9

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 RF 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 III 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.

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 antennae 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 IV.

TABLE III – *EES-to-relay satellite (space-to-space) link parameters*

EES transmit power (dBW)	20.5
EES antenna gain (1.5m 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

TABLE IV – *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 Annex.

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 V gives the pfd calculation for the relay satellite-to-Earth data link and indicates that the pfd is 13.9 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 561-1 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 V – *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
Spreading loss (40 000 km, 10° elevation)	−163.7
Power flux-density (dB(W/(m²·MHz)))	−128.9
Allowable pfd limit (Earth's limb) (dB(W/(m²·MHz)))	−115.0
Margin (dB)	−13.9

5.2 *EES to relay satellite data link*

The 25.25 to 27.5 GHz frequency band is at present allocated only to the fixed and mobile services and no sharing criteria exist for space systems. The closest band, for which a pfd limit has been adopted, is the 21.2 to 22.0 GHz band – with a limit of -115 dB(W/(m^2 · MHz)) at the Earth's limb, 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 θ (off-axis angle)). This does not impose any operational constraints on an EES system.

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 IV. 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 co-ordination 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 · MHz)) at low elevation angles is obtained. The following calculation presents the anticipated pfd produced on the Earth from relay satellite emissions arriving at low elevation angles:

TABLE VI

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
Spreading loss (to Earth's limb) (dB/m²)	−163.2
Power flux-density (dB(W/(m²·Hz)))	−173.2
or (dB(W/(m²·MHz)))	−113.2

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 orbit is -179.6 dB(W/(m^2 · 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.

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 below (Table VII). None of the required constraints would materially affect the operational capabilities of an EES system.

TABLE VII

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 for 21.2 to 22 GHz region
25 to 30 (command link)	Earth station-to relay satellite	Fixed Satellite	Standard FSS(1) spacing
		Fixed/ Mobile	Appendix 28 of the Radio Regulations
	Relay satellite-to-ESS	Fixed Satellite	Antipodal transmission constraint (see text)
		Fixed/Mobile	Appropriate pfd limits

(1) FSS: Fixed Satellite Service

RECOMMENDATION 514

TELECOMMUNICATION LINKS FOR EARTH EXPLORATION SATELLITES

Frequencies, bandwidths and criteria for protection from interference

(Question 12-2/2)

(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 100K, 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 600K (-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 535-1

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR THE EARTH EXPLORATION SATELLITE SERVICE

(Study Programme 12A-1/2)

(1974 - 1978)

1. Introduction

At the World Administrative Radio Conference for Space Telecommunications (WARC-ST), Geneva, 1971, a new satellite service, the Earth Exploration Satellite Service, was defined * as:

"A radiocommunication service between earth stations and one or more space stations in which:

- information relating to the characteristics of the Earth and its natural phenomena is obtained from instruments on earth satellites;
- similar information is collected from airborne or earth-based platforms;
- such information may be distributed to earth stations within the systems concerned;
- platform interrogation may be included."

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 under consideration in the United States of America.

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,
- 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.

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* See No. 84ASA of the Radio Regulations.

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 references. In the years to come, many different types of systems will come into use [Univ. Mich., 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 therefore only to be considered representative of earth exploration satellites now existing or envisaged, within the United States.

The application of satellite techniques to the geosciences (i.e., earth and ocean physics) can provide a more precise determination of the size, shape, gravity and magnetic fields, land movement, and ocean phenomena of the Earth.

3. Present and near future Earth exploration systems

3.1 *Earth exploration systems*

Earth exploration satellite systems being considered by the United States include systems to be flown both in low earth orbits and in the geostationary satellite orbit.

The low-orbit systems comprise the two experimental satellites LANDSAT-1 and LANDSAT-2, launched respectively in 1972 and 1975, and LANDSAT-C scheduled for launching in 1977. A later series of experimental multi-disciplinary spacecraft would perform environmental quality, meteorological, oceanographic and Earth resources surveying, by advanced remote sensing techniques beginning with LANDSAT-D in about 1980. An operational satellite system, the Earth Resource Survey Operational System (ERSOS) may be developed, which would utilize sensors and techniques developed in the LANDSAT programme.

The Synchronous Earth Observatory Satellite (SEOS) contemplated for launching in the mid 1980's, would be used to investigate and develop remote sensing techniques from the geostationary satellite altitude. The SEOS experimental spacecraft would be followed by a series of Operational Synchronous Earth Observatory Satellites (OSEOS) in the late 1980's.

The major objectives of the US geodetic satellites have been to obtain a more precise description of the Earth's surface, together with a refined mathematical model of its gravitational field. The following satellites have been launched: EXPLORER-22, EXPLORER-27, GEOS-1, PAGEOS-1, GEOS-2, GEOS-3. Satellites with geodetic objectives currently planned for launching include SEASAT-A and LAGEOS.

A geodetic satellite under consideration for possible launching in 1982 is GEOPAUSE, which could provide more precise determinations of earth and ocean-dynamics.

Most of these future satellites will be designed to supply local direct read-out of sensor data and may also be capable of forwarding information to earth stations via geostationary data relay satellites.

These earth exploration satellites are described more fully in the Annexes to this Report.

3.2 *Spectrum considerations for data communications*

Earth exploration satellites are 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.

This data will be transmitted from many of the planned satellites to the Earth via three modes:

- direct to major data acquisition facilities,
- direct to local users having lesser data acquisition facilities,
- through geostationary data relay satellites which will provide a continuous real-time data readout capability.

The earth exploration satellites being considered by the United States and discussed in the Annexes to this Report are listed in Table II, with anticipated bandwidth requirements and proposed frequency for data communication from spacecraft to Earth. Several of these near-term spacecraft will operate with sensor systems and ground data handling systems capable of generating and processing upwards of 84 Mbit/s of data. Because of the high data rate requirements, the LANDSAT programme plans to transmit to Earth in the 8025 to 8400 MHz frequency band for LANDSAT-D and follow-on satellites. Experimental data will also be transmitted in the 14.4 to 15.35 GHz band in order to achieve compatibility with the tracking and data relay satellite, (TDRS).

The WARC-71 allocated frequency bands for telemetering data from earth exploration satellites in band 10 (8025 to 8400 MHz and 21.2 to 22.0 GHz). Further study indicates that future requirements cannot be met within the two allocated bands.

The earth station configuration, together with the high data-collector data rates, the expected number of earth exploration satellites and 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.

3.2.1 *Power flux-densities*

Power-flux density limits which are at present in effect may restrict the applications planned for earth exploration satellites. Specifically:

- studies show that the achievement of a satisfactory communications link is difficult in the 21.2 to 22 GHz allocation with the present power flux-density limits and present technology;
- 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. In order to minimize costs, small antennae must be used for those terminals which require 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 prescribed limits.

As low orbiting satellites provide an inherent method for time sharing, and as studies show that sharing may be feasible between services for 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.

3.2.2 *Passive sensors*

Passive sensors obtain data on surface or atmospheric phenomena by sensing time/temperature variations, using 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.

Another recent finding is that profiles of soil moisture content obtained in the frequency range 0.5 to 3 GHz are more significant than those obtained at shorter wavelengths due to the greater depth of penetration at the longer wavelengths.

Passive earth exploration sensors may utilize bands allocated for radioastronomy and/or for space research (passive). However, it may be found that for certain functions the optimum frequency for a passive sensor does not coincide with allocations for radioastronomy or space research (passive). Therefore, studies are being 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.

3.2.3 *Active sensors*

Active microwave sensors have two unique features not found in passive microwave sensors. These are:

- topological features of land and sea surface can be determined, and
- greater spatial resolutions can be obtained by utilizing a synthetic aperture radar.

As an example of the first feature, petroleum exploration and mineral deposit mapping are two applications for which the unique capability of active microwave sensors to penetrate surface vegetation could be extremely valuable.

As for the second feature, the best resolution expected from the best passive microwave imaging radiometer is of the order of 320 metres, while the synthetic aperture radar to be carried on SEASAT is expected to have a resolution capability of 25 metres. (See Annex V).

Active microwave sensors have shown promise at frequencies ranging from 1.4 GHz to above 30 GHz. However, experiments have not yet advanced to the point where specific frequency bands can be identified for specific functions.

It appears that frequency bands allocated to the Radiolocation Service may be shared with active microwave sensors without disruptive interference to either the Radiolocation Service or to the active sensor. Design frequencies and bandwidths of active sensors currently under development are contained in Report 693.

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TABLE I – *Sensors and parameters for Earth exploration satellites*

Instrument	Swath width (km)	Resolution	Data rate (bit/s)
Television imagers	185	30 m	2×10^7
Multi-spectral scanners	185	30 m	1.2×10^8
High resolution pointable imagers	48	10 m	1.2×10^8
Infra-red radiometers	2870	2 km	3.3×10^5
Radar scatterometer	641 (dual)	20 km	600
Microwave radiometer	1300	20 – 60 km	3×10^3
Synthetic aperture radar	100	25 m	5×10^7
Radar altimeter	2	10 m(2)	100
Large earth survey telescope	200	100 m	3×10^7
AASIR(1)	variable	1.5 – 9 km	7×10^6

(1) Advanced atmospheric sounder and imaging radiometer (AASIR)

(2) Vertical resolution

TABLE II – *Earth observation spacecraft under consideration by the United Sates*

Spacecraft	Year of launch	Anticipated bandwidth requirements(1) (MHz)		Technically preferred HDR frequency region
		LDR	HDR	
LANDSAT-C	1977	(0.5)	(20)	2200 to 2290 MHz
SEASAT-A	1978	(0.03 ; 1)	(20)	2200 to 2290 MHz
ERSOS-A	1980	(0.5)	(40)	Band 10
LANDSAT-D	1980	(0.05 ; 0.5)		2200 to 2290 MHz
			(40)	8025 to 8400 MHz
			(100)	14.4 to 15.35 GHz
ERSOS-B	1982	(0.5)	(40)	Band 10
LANDSAT-D'	1981	(0.05)	(20)	8025 to 8400 MHz
			(100)	14.4 to 15.35 GHz
LANDSAT-E	1982	(0.05 ; 0.5)	(20)	8025 to 8400 MHz
			(100)	14.4 to 15.35 GHz
ERSOS-C	1984	(0.5)	(40)	Band 10
SEOS-A	1982	(0.5)	(50)	8025 to 8400 MHz
				14.4 to 15.35 GHz
SEASAT-B	1982	(0.03 ; 1)	(20)	2200 to 2290 MHz
LANDSAT-E'	1983	(0.05 ; 0.5)	(20)	8025 to 8400 MHz
			(100)	14.4 to 15.35 GHz
LANDSAT-F	1984	(0.05 ; 0.5)	(20)	8025 to 8400 MHz
			(350)	14.4 to 15.35 GHz
ERSOS-D	1986	(0.5)	(50)	Band 10
LANDSAT-F'	1985	(0.05 ; 0.5)	(20)	8025 to 8400 MHz
			(350)	14.4 to 15.35 GHz
SEOS-B	1985	(0.5)		8025 to 8400 MHz
			(200)	14.4 to 15.35 GHz
ERSOS-E	1988	To be determined	To be determined	Band 10

(1) LDR – Low data rate; HDR – High data rate; Numbers given in parentheses are approximate bandwidth requirements in MHz.

ANNEX I

LANDSAT-1, 2, C

1. Introduction

The United States LANDSAT-1, 2, C Satellite programme (formerly known as the Earth Resource Technology Satellite) has been 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 will point the way towards development of fully operational and more effective systems for earth resources management. LANDSAT-1 was launched in July 1972 and LANDSAT-2 was launched in January 1975. LANDSAT-C is planned for launching in 1977.

To achieve their broad objectives, the missions of LANDSAT-1, 2, and C provide for the repetitive acquisition of high resolution multi-spectral data of the surface of the Earth on a global basis. Two sensor systems have been selected for this purpose: a four channel multi-spectral scanner (MSS) for LANDSAT-1 and 2 (five channels for LANDSAT-C), and a three-camera return beam vidicon (RBV) system. In addition, the satellites will be utilized as a relay system to gather data from remote, earth-based sensor platforms equipped by individual investigators. The data acquired by the total LANDSAT system will permit quantitative measurements to be made of surface characteristics of the Earth on a spectral, spatial, and temporal basis.

2. Satellite design and construction

The spacecraft (Fig. 1) is designed so that the payload equipment is centrally located in the circular structure at the base of the spacecraft, providing close proximity to the payload sensors, their associated electronic apparatus and the wide-band communications equipment. To maintain accurate alignment, the three return beam vidicon camera heads are mounted on a common baseplate, structurally isolated from the spacecraft.

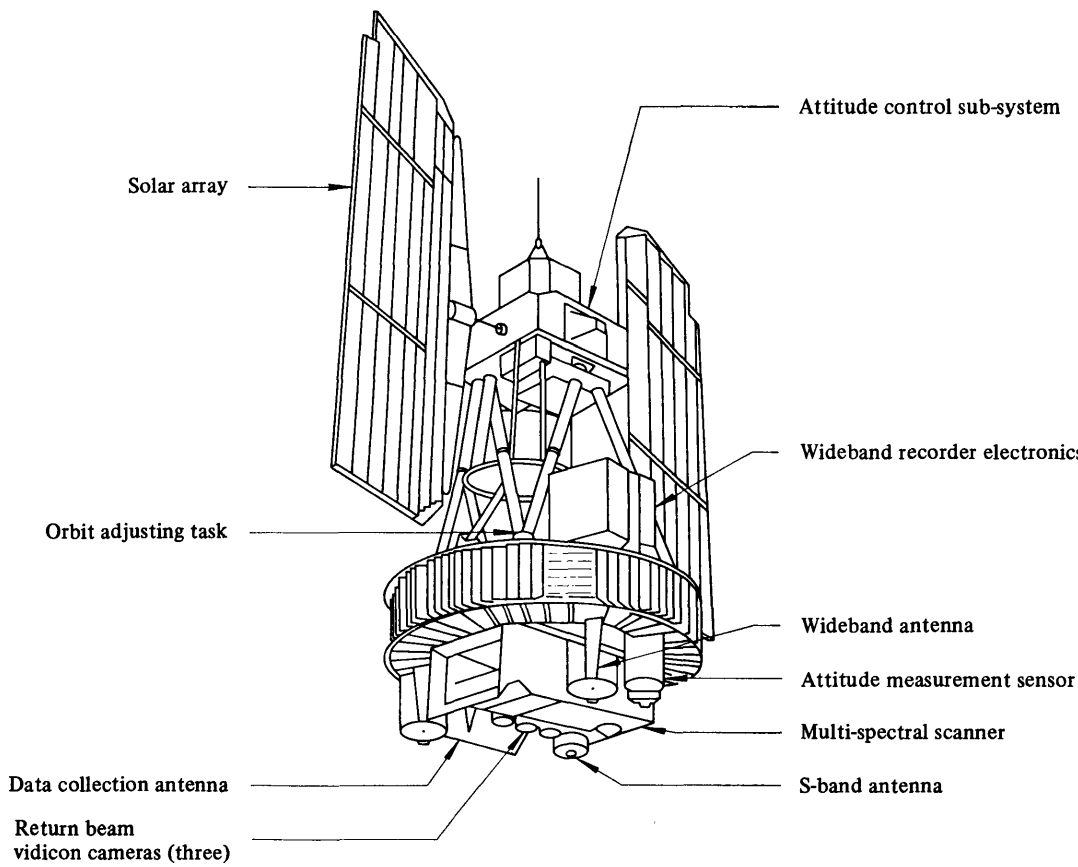

FIGURE 1 – *LANDSAT-1, 2, C spacecraft configuration*

3. Orbital considerations and attitude control

Systematic, repetitive Earth coverage under nearly constant observational conditions is provided, so that the utility of the multi-spectral images collected by LANDSAT-1, 2, and C will be a maximum. The spacecraft will operate in a circular, sun-synchronous, near-polar orbit at an altitude of about 900 km. It will circle the Earth every 103 min, completing an entire Earth scan every 18 days.

Control of spacecraft attitude to the local vertical and orbit velocity vectors, within 0.7° of each axis, is achieved by a three-axis active attitude control sub-system. It uses horizon scanners for pitch and roll control, and a gyro-compassing mode for yaw orientation. An independent passive attitude measuring sub-system (AMS), operating over a narrow range of about 2°, provides pitch and roll attitude data, accurate to within 0.07°, to aid in image location.

4. Communications and data handling sub-system

A sub-system for communications and data handling provides for all spacecraft information flow and is composed of the sub-systems for wide-band telemetering, narrow-band telemetering, tracking and command, and wide-band video tape recorders, (WBVTR).

4.1 *Wide-band telemetering sub-system*

The wide-band telemetering sub-system accepts and processes data from the return beam vidicon, the multi-spectral scanner and the wide-band video tape recorders and transmits them to the ground-receiving sites. This sub-system consists of two 20 W, band 9, frequency-modulated transmitters and their associated components. The sub-system permits transmission of any two data sources simultaneously. Commandable power level travelling wave tube (TWT) amplifiers and shaped beam antennae provide maximum fidelity of the sensor data at minimum power. The assigned carrier frequencies for this experimental system are in band 9, with 20 MHz bandwidth per channel. The return beam vidicon baseband signal is a 3.2 MHz video signal. The multi-spectral scanner baseband is 15 Mbit/s pulse code modulated (PCM), non-return to zero-level (NRZ-L). Both basebands frequency-modulate the carriers directly.

4.2 *Telemetering, tracking and command sub-systems*

The telemetering, tracking and command sub-systems collect and transmit spacecraft and sensor maintenance telemetering data to the ground sites, provide tracking aids, receive commands from earth stations, and implement those commands on board the spacecraft.

The maintenance telemetering data is pulse-code modulated (PCM) and can be either transmitted in real-time at a rate of 1 kbit/s, or it can be stored up to 210 min, on each of two narrow-band tape recorders (NBTR) for subsequent playback at a rate of 24 kbit/s. Playback data from either of the NBTRs can be transmitted at any time over the band 8 equipment.

Command can be exercised either at VHF or in band 9 by the use of reserve receivers on the spacecraft. These commands can be any of the 512 possible commands executable by the command/clock or any of the 8 commands recognizable by a separate "command integrator unit". A total of 30 command/clock commands can be "stored" for execution outside the range of the ground stations.

The LANDSAT uses a pseudo-random ranging technique.

4.3 *Wide-band video tape recorder sub-system*

Two wide-band video type recorders (WBVTR) record and reproduce the data outputs from either the return beam vidicon (RBV) or multi-spectral scanner (MSS) during remote sensing operations. Each recorder can record 30 min of either 3.2 MHz video analogue data from the vidicon, or 15 Mbit/s digital data from the scanner.

The MSS digital video data is received as a NRZ-L (non-return to zero, type L) 15 Mbit/s data stream. In the WBVTR, the data stream frequency-modulates a carrier. The resulting frequency-shift keyed (FSK) signal is recorded. The MSS data are recorded asynchronously; that is, the data stream and recorder are not synchronized. In playback, the MSS signal is read out sequentially, with switching and demodulation producing a continuous, NRZ-L, stream of data at 15 Mbit/s.

ANNEX II

EARTH RESOURCES SURVEY OPERATIONAL SYSTEM

1. Introduction

The Earth Resources Survey (ERS) operational system, envisaged for launching in the early 1980's, would be an operational system based upon spacecraft and sensors developed in the LANDSAT programme. The initial ERS operational system may be composed of two spacecraft whose payload will be similar to the LANDSAT-C.

These spacecraft would be flown concurrently in order to provide more frequent coverage than is possible with the experimental LANDSAT spacecraft.

2. Frequency allocation requirements

As in the present LANDSAT spacecraft, each of the ERS spacecraft would have wide-band telemetering, narrow-band telemetering, tracking, command, and data collection requirements. The ERS operational system would operate in bands 9 and 10.

The technical characteristics of the ERS satellites are expected to be similar to those of the LANDSAT.

ANNEX III

LANDSAT-D AND FOLLOW-ON PROGRAMME

1. Introduction

The United States LANDSAT-D and follow-on satellite programme (formerly known as the Earth Observatory Satellite) is intended to continue the research initiated by the LANDSAT-1, 2, C series. The objectives of the programme are, firstly, to define advanced remote sensing instrumentation, Earth observations 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.

To achieve these objectives a multi-mission programme would include the development and operation of advanced space-borne sensors with increased resolution and spectral performance, development of spacecraft systems and sub-systems which would fully support sensor operation and development of improved information processing and distribution systems. The latter would include direct data transmission from the spacecraft to regional and local users (domestic and foreign). This communications approach provides the advantages of immediate availability of data to interested users.

2. Initial mission payloads

The initial mission, LANDSAT-D would have application to the disciplines of earth resources survey and pollution measurement. Sensors for this spacecraft will include a six-channel thematic mapper (TM) scanning a 185 km swath with 30 m resolution, and a five channel MSS (Fig. 2). Coverage of the Earth survey function would be real-time, direct data transmission only, with no on-board recording capability planned for this type of high data rate.

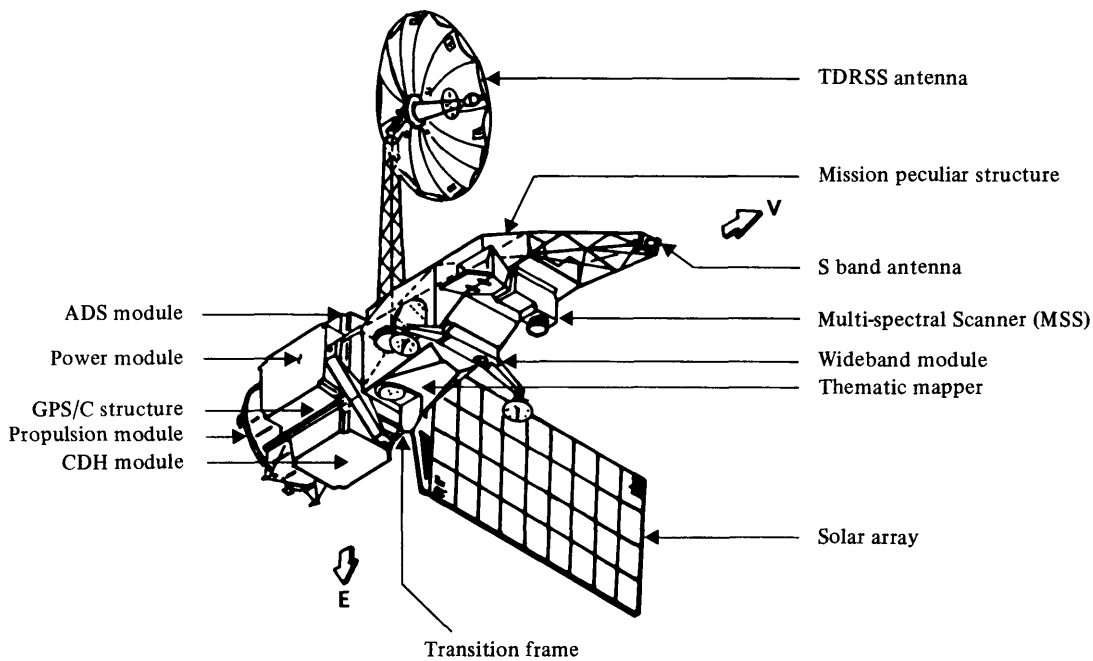

FIGURE 2 – *LANDSAT-D spacecraft*

3. Orbital consideration and attitude control for LANDSAT-D

Systematic, repetitive Earth coverage is required to maximize the utility of the multi-spectral images collected by the different LANDSAT-D sensors. The spacecraft would operate in a circular, sun-synchronous, near-polar orbit at a planned altitude of 705 km. It would circle the Earth every 99 min, completing an entire Earth scan every 16 days.

During normal operation, the attitude control sub-system (ACS) would be capable of pointing the observatory continuously to the Earth's centroid to an accuracy of better than 0.01°. Attitude perturbation would be less than 2 arc seconds and the rate of attitude drift would be less than 2×10^{-6} degrees/s.

4. High data rate communications for LANDSAT-D

The thematic mapper (TM) and the multi-spectral scanner (MSS) sensors planned for LANDSAT-D will produce a composite data rate of approximately 84 Mbit/s.

Three wideband data communications links are planned for LANDSAT-D:

4.1 The primary wideband data link from LANDSAT-D to the ground will be via the TDRS. The composite data rate of 84 Mbit/s will be transmitted from LANDSAT-D to the TDRS on a frequency in the 14.4 to 15.35 GHz band.

4.2 The 84 Mbit/s TM data will be transmitted directly to Earth in the 8025 to 8400 MHz band. Quadriphase modulation will be utlized 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 will be used to maximize data acquisition by participating earth stations.

The usage of a common frequency band with anticipated operational programmes is considered very important because a major aspect of the LANDSAT programme is the development of both space and ground-based systems that can be directly applied to operational programmes with a minimum of conversion cost. This is of particular importance, as several of the regional and local user terminals, capable of receiving direct data transmissions, would probably be phased into operational facilities.

4.3 MSS data may be transmitted directly to Earth at a rate of 15 Mbit/s. This sub-system operates in band 9 and would be identical to the wideband telemetering sub-system utilized on LANDSAT-1, 2 and C. This data link is being considered for LANDSAT-D in order to provide continuity of data for existing earth stations that are currently acquiring MSS data from LANDSAT. This link will probably not be included on spacecraft in the LANDSAT programme beyond LANDSAT-D.

5. Communications and data handling (CDH) sub-system

The CDH sub-system provides means for ground and onboard 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 onboard computer. Redundant band 9 transponders compatible with both the TDRS and tracking network stations will be used for command reception, low-rate telemetry transmission and precision tracking.

ANNEX IV

SYNCHRONOUS EARTH OBSERVATORY SATELLITE

1. Introduction

The Synchronous Earth Observatory Satellite (SEOS) programme would be a research and development tool to demonstrate the feasibility of monitoring and/or predicting environmental phenomena with lifetimes shorter than 24 hours or with significant variability within a 24 hour period from a remote sensing platform in synchronous orbit. Such short-lived and variable phenomena include hurricanes, tornadoes, forest fires, floods, frost, and fish location and movement. The utility and feasibility of a SEOS system to provide useful and important data for use by other government agencies and individuals would be demonstrated by conducting various types of operational experiments with SEOS. The ground data processing system would be capable of registering successive images, detecting changes, flagging critical regions for human interpretation on interactive cathode-ray tube (CRT) displays with time sequence imaging, and, within minutes, distributing the results of these analyses via SEOS and other communication circuits to observers (including sending images using photo-facsimile techniques).

The phenomena to be studied extend over large areas but are either short-lived, undergo rapid changes, must be detected nearly instantly, or are detectable only against a time variable background (e.g., cloud cover). They therefore require nearly continuous monitoring of large regions. In general, the size of these regions range from about 100 to about 1000 km in diameter. They must be observed with dwell times up to several hours and at a periodicity, over the entire area, ranging from every few minutes to every few hours. Considering the geographical extent of the phenomena, the requirements for long dwell times and rapid repetition rates of the observations, the most effective monitoring can be conducted by remote sensing techniques from a space-borne platform in geostationary satellite orbit, combined with in-situ and other measurements from strategically placed automatic sensors.

2. Sensor payload

The types of phenomena to be studied determine the instrumentation required. Spatial resolutions approaching those of LANDSAT, namely, about 100 m in the visible and near infra-red spectra and 800 m in the thermal infra-red spectrum, are desired for terrain and inland water monitoring. For storm and ocean observations, coarser resolutions of the order of 1 km are acceptable.

Many of the problems will require a close coupling of the space-based observations with measurements made from ground, aircraft and balloon platforms. This will mean that data from all sources required for a particular problem must be available promptly and in a meaningful form at one location.

The primary sensor of the SEOS would be a Large Earth Survey Telescope (LEST) with a large mirror, 1.5 m in diameter. The LEST would contain a "push-broom" scanner, and possibly an image plane scanner. The push-broom scanner will generate high resolution (100 m) images in the visible and in the near infra-red spectra by focusing a 200 km wide portion of the field of view onto an array of diode detectors. Single-line composite arrays of 3000 of these detectors are needed for each of four spectral bands in order to obtain the necessary spatial resolution. No scanning mechanism is employed; motion of the spacecraft around the pitch or roll axis would move the sensor over the desired length of coverage of the Earth's surface (nominally, 1000 km). The image plane scatter will be used to collect lower resolution visible and infra-red data.

A synchronous orbit microwave sounder with a 2 m aperture is also being considered as part of the SEOS payload.

3. Spectrum considerations

The approximate data rates of the various SEOS sensors are given below:

- LEST: 50 Mbit/s
- Microwave sounder, infra-red sounder and housekeeping data: 25 kbit/s

Due to the high data rates generated by the SEOS sensors, band 10 will be used for transmission of this data.

The data collection system, ranging, command and maintenance telemetry will probably make use of appropriate allocations in band 9.

The retransmission of narrow bandwidth data to low cost mobile remote stations via SEOS may be required for rapid data distribution to some users.

ANNEX V

GEODETIC SATELLITES

1. Introduction

A series of United States geodetic satellites was launched in the 1960's to provide information leading to a more precise description of the Earth's surface and its gravitational field. These satellites included:

- EXPLORER-22, launched 10 October 1964.
- EXPLORER-27, launched 29 April 1965.
- GEOS-1; launched 6 November 1965. This mission made use of a Doppler navigation system, an electronic ranging system, optical beacons, laser reflectors, and a range and range-rate system. This combination of instruments permitted the examination of various modes of satellite tracking as well as obtaining gravitational field information.
- PAGEOS-1, launched 1 July 1966.

More recently, two more GEOS satellites have been launched.

GEOS-2 was launched 11 January 1968. This mission is nearly identical to GEOS-1 with the addition of a band 10 transponder and reflector, and a CW laser detector. The retrograde orbit provided a better distribution of inclinations to separate the coefficients of the mathematical representation of the gravity field.

The third geodetic Earth orbiting satellite (GEOS-3) was launched in April 1975. Its mission is to demonstrate the utility of satellite altimeters for measuring the geometry of the ocean surface and to contribute to the calibration of ground-based and satellite-borne tracking systems.

SEASAT spacecraft are dedicated to ocean dynamics applications. SEASAT-A is planned for launching in 1978 and will provide data for the development and evaluation of models for prediction of sea state and ocean circulation.

LAGEOS is a completely passive 411 kg, 60 cm sphere equipped with laser retro-reflectors for the calibration of ground based optical tracking systems. Its high density and simple geometry will allow mathematical models to be developed for the orbital motion, in which uncertainties due to atmospheric drag and solar radiation pressure will not exceed the goal precisions in determining geodynamic parameters. LAGEOS was launched in May 1976.

In addition to these planned satellites, consideration has been given to a gravity-gradiometer satellite to provide data which could be used to describe the Earth's gravity field more precisely.

Gravity gradiometers provide a gravity mapping technique as an alternative to that provided by perturbation analyses of satellite trajectories.

The perturbation analyses are based on position measurement, which is obtained by integrating the acceleration twice, thus being relatively insensitive to high frequency effects of the gravity field. Doppler techniques measure a relative velocity, which is a single integral of acceleration. A gravity gradiometer measures the second derivative of the gravity field, and can detect higher frequency effects so that higher order (up to 75th) terms of the harmonic expansion of the gravity field can be calculated.

An enhanced gravity map could be used to improve orbit-determination accuracies for future Earth-satellite missions. In addition, density changes in the Earth's mantle would be accentuated.

The gravity gradiometer satellite being considered for possible launching in 1982, is named GEOPAUSE.

2. Satellite descriptions

2.1 *Geodetic Earth Satellite (GEOS-3)*

The mission objectives of the Geodetic Earth Orbiting Satellite (GEOS-3) flight in support of the geosciences are to:

- determine the feasibility of a space-borne radar altimeter to map the topography of the ocean surface;
- measure deflection of the vertical at sea and measure wave height;
- support calibration of ground based (band 10) radar systems;
- perform a satellite-to-satellite experiment with ATS-6 using a band 9 transponder to measure directly the short period accelerations imparted to the spacecraft by the gravity field, and to determine the position of the spacecraft;
- support intercomparison of new and established geodetic and geophysical measuring systems including:
  - a radar altimeter,
  - satellite-to-satellite tracking, and
  - band 10, band 9, laser, and Doppler tracking.
- investigate solid-earth dynamic phenomena (i.e., polar motion, fault motion, Earth rotation);
- further define orbit determination techniques, the determination of interdatum ties, and gravity models; and
- furnish a space-borne Unified (band 9) transponder to assist in positioning the network stations in the world-reference tracking system.

The GEOS-3 structural configuration consists of a rigid octahedron box topped by a truncated pyramid with dimensions calculated to minimize the daily average fluctuation in solar power resulting from orbital precession. This satellite was launched into a 843 km mean altitude orbit with an inclination of 115°. The elliptical orbit (0.006 eccentricity) has a period of 101.8 min.

The stabilization requirements of the radar altimeter, laser retro-reflectors, and the satellite-to-satellite experiment system are provided by a gravity gradient stabilization system, which is augmented by a constant-speed angular momentum wheel. (The momentum wheel is intended to reduce the attitude variations about the roll axis). In orbit, the system is stabilized in yaw so that the pitch axis is normal to the orbit plane. This system maintains the spacecraft to within ± 1° of nadir pointing 98% of the time.

The telemetry sub-system consists of band 8 (136 to 137 MHz) and band 9 (2200 MHz) systems. The band 8 telemetry sub-system operates in three modes:

- maintenance telemetry (1562 bit/s, 0.25 W),
- low data rate (real time altimeter data and selected engineering parameters telemetered at 1562 bit/s, 0.25 W),
- high data rate (real time altimeter data and selected engineering parameters telemetered at 15.6 kbit/s, 1.5 W).

The band 9 transponder is modulated with the same type of radar altimeter data as the band 8 transponder, and supplements the real-time data readout capability of GEOS-3.

The command sub-system operates in band 8 (148.98 MHz), and can process real-time commands at 64 bit/s (PCM/FSK – AM/AM). In addition, the command sub-system can store and execute up to 28 time-delayed command functions.

The experiment sub-system onboard GEOS-3 consists of five instruments. The areas of contribution of these instruments to the overall mission goals are discussed briefly below.

Radar altimeter

The GEOS-3 radar altimeter will demonstrate the ability to operate over extended areas of the world with a high degree of accuracy. The design characteristics are shown in Table III.

TABLE III – *Radar altimeter design characteristics*

Characteristics	Mode I Long pulse altimeter	Mode II Short pulse altimeter
Frequency (GHz)	13.9	13.9
Antenna type	Parabolic	Parabolic
Diameter (cm)	58.5	58.5
Gain (dB)	36	36
Beamwidth (degrees)	2.7°	2.7°
Instrument altitude error (m)	±2	±0.5
Altitude granularity (m)	±0.2	±0.2
Altitude data rate (s^{-1})	2	6
Maximum range acquisition time (s)	6	6
Average transmitter power (W)	0.64	0.3
Receiver sensitivity (dBm)	–80	–80

C-band transponder experiment

The C-band transponder experiment system consists of separate coherent and noncoherent transponders. Those transponders may operate separately or simultaneously, and transmit one pulse for each coded group of pulses received from a ground tracking band 10 radar. The noncoherent transponder provides range and angle measurements; the coherent transponder, operating in conjunction with ground radar systems, provides range, range-rate and angle measurements. Both transponders operate in band 10 (5700 MHz).

Band 9 transponder

The band 9 transponder sub-system provides tracking range and range-rate data using satellite-to-satellite tracking links as well as ground radar. Up-link frequency is 2069.1125 MHz, while the down-link is 2247 MHz, with a peak power of 100 W.

Laser retro-reflector

The laser retro-reflector array consists of 264 35-mm corner reflectors placed on a lateral surface at 45° from the Earth-oriented surface of the spacecraft. The array used in conjunction with ground laser systems provides satellite tracking information.

Radar Doppler beacon

This sub-system consists of two transmitters: one at 162 MHz, the other at 334 MHz. The use of two frequencies provides a method for removal of ionospheric effects from the range rate data.

2.2 *SEASAT-A*

The SEASAT-A satellite is the first major step in developing and demonstrating a global ocean dynamics monitoring system using relevant measurement techniques from a space platform. SEASAT-A will carry an experimental instrumentation payload intended to validate concepts for monitoring and measuring ocean features.

The overall objectives include the development and validation of means of predicting general ocean circulation, for synoptic monitoring and the predicting of transient surface phenomena. Also for the refinement of the global geoid, earthquake hazard prediction, mapping the ocean geoid, charting ice fields, and measuring precise sea-surface topography as well as the global monitoring of wave height, directional spectra, surface wind speed and direction, ocean current patterns and ocean surface temperature.

The mission configuration includes the observatory satellite and a ground-based tracking, data collection and mission control network.

The satellite instrument complement includes three active radars: a radar altimeter, a wind field scatterometer and a synthetic aperture radar, all of which normally operate full-time over the ocean and are switched off over land.

The functions of the radar altimeter are to measure the spacecraft height above the mean sea level, to measure significant wave height of the ocean surface beneath the spacecraft and to measure the ocean backscatter coefficient of the ocean surface beneath the spacecraft. The instrument uses a 1.5° beamwidth nadir-looking parabolic antenna. A linear-FM waveform will be transmitted in 3 μs duration pulses, at a pulse repetition frequency of 1050 per second in the middle of band 10. High resolution is required to achieve 10 cm altitude precision for wave heights between 1 and 20 m, and the high pulse rate is required to reduce the sampling variability of the altitude and wave height measurements.

The function of the scatterometer is to measure the wind speed and direction over dual swaths 750 km wide commencing 200 km on either side of the sub-satellite track. Backscattered signal strength is measured along ± 45° and ± 135° azimuth angles by sequencing between four 1/2° × 25° fanbeam "stick" antennae. Doppler filter bands resolve the fanbeam footprints into the equivalent of 50 km cells at earth incidence angles between 25° and 55°. The operating frequency will be in the middle of band 10.

The imaging radar uses the synthetic aperture technique, commonly called "side looking". This imaging radar will produce images of the open ocean, coastal regions, and will map sea ice with resolutions of 25 m for a swath of 100 km in range width, centered at points 290 km to the right of the spacecraft track. A second imaging mode has a resolution of 100 m for a swath of 200 km range width. The system will operate in the middle of band 9.

A scanning radiometer will operate in the visible and infra-red regions of the spectrum.

SEASAT-A sensors and associated parameters are summarized in Table IV.

The SEASAT-A will be placed into a nearly circular orbit at an altitude of approximately 800 km. The orbit will be inclined 108° to the Equator with a period of 6045 s, resulting in about 14 1/3 orbits per day. The orbit is non-sun-synchronous and will precess during a day/night cycle in approximately 3.5 to 5.5 months.

The capability to maintain the satellite pointed to within 0.5° of the local vertical, and aligned within 0.5° of the line-of-sight constitutes the requirements on the altitude control system. In addition, the interpretation of the data requires knowledge of the actual pointing within these limits to an accuracy of about 0.2°.

The SEASAT-A satellite control, tracking and data transmission complement includes a receiver and four transmitters. The dual redundant receiver operates in band 9. Two of the transmitters, although used for tracking, are primarily utilized for data transmission. The wideband data transmitter will require a 20 MHz bandwidth in band 9 for the data stream from the synthetic aperture radar. The narrowband data transmitter will require a 5 MHz bandwidth in band 9. Real time or recorded data from the other sensors will be transmitted over this link.

Two other transmitters will operate in band 8 and band 9 and will transmit stable signals containing no modulation. The signals from these transmitters will be used for range-rate tracking measurements. The use of two separate frequencies permits compensation for ionosphere path deviation effects.

The radar altimeter will operate in band 10 and will transmit peak power of 2.5 kW.

The scatterometer will operate in band 10, separated by about 1000 MHz from the radar altimeter, with 100 W peak power.

The synthetic aperture radar will operate in the middle of band 9 with a peak power of 800 W.

The normal mode of operation for the radar altimeter and scatterometer will only be over seas. Illumination of any one spot on Earth will occur a maximum of 2.4 seconds per day and 2 minutes per day for the altimeter and scatterometer respectively.

The illumination of any one spot on Earth from the synthetic aperture radar will occur a maximum of 2 seconds per day.

The spacecraft configuration for SEASAT-A is illustrated in Fig. 3.

TABLE IV – *Sensors and parameters associated with SEASAT*

Physical Parameters	Instruments	Range	Precision	Spatial resolution	Spatial grid	Update period	Coverage
Wave height	Pulse altimeter	1 to 20 m	±0.5 m	2.5 km	2.5 km swath	36 h	Global(1)
Wave spectrum	Coherent imaging radar	Unknown amplitude 0 to 360°	θ: ±10° λ: 20 %	25 m × 25 m	100 km swath	–	Demonstration in local waters
Surface wind field	Scatterometer	4 to 20 m/s no angle	±2 m/s	50 km	750 km swath on each side	36 h	Global(1)
Sea surface topography	Pulse altimeter	10 cm to 50 km	±10 cm	2.5 km	2.5 km swath	–	Global

(1) Real time capability locally.

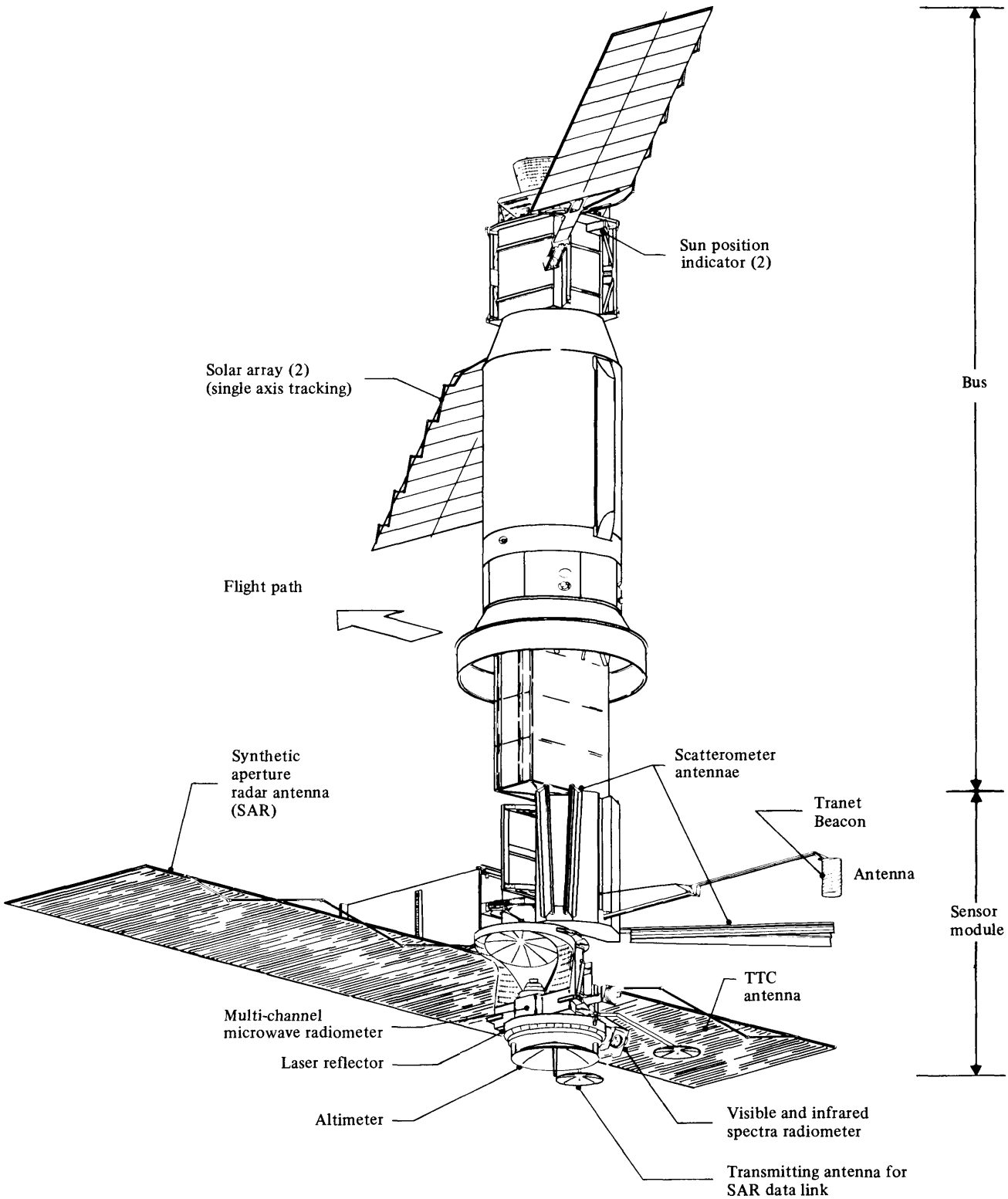

FIGURE 3 – *SEASAT-A spacecraft configuration*

REPORT 540 *

FEASIBILITY OF FREQUENCY SHARING BETWEEN AN EARTH EXPLORATION SATELLITE (EES) SYSTEM AND FIXED SATELLITE, METEOROLOGICAL SATELLITE AND TERRESTRIAL FIXED AND MOBILE SERVICES

(Study Programmes 12A-1/2)

(1974)

1. Introduction

According to the Final Acts of the World Administrative Radio Conference for Space Telecommunications (WARC-ST), Geneva, 1971, the frequency band 8025 to 8400 MHz is allocated to the Earth Exploration Satellite Service (space-to-Earth) on a shared basis. In particular, the band 8175 to 8215 MHz is shared with the following primary services, the Earth Exploration Satellite Service being primary in Region 2 and secondary in Regions 1 and 3:

- the terrestrial Fixed and Mobile, Fixed Satellite (Earth-to-space) and Meteorological Satellite Services (Earth-to-space) in Region 2.
- the Fixed and Mobile, Fixed Satellite (Earth-to-space) and Meteorological Satellite Services (Earth-to-space) in Regions 1 and 3.

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 ** 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.

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)	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.

* This Report is brought to the attention of Study Group 5, in particular as regards the need for appropriate propagation curves relative to 1% of the time.

** No. 470 of the Radio Regulations (1971).

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.

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.

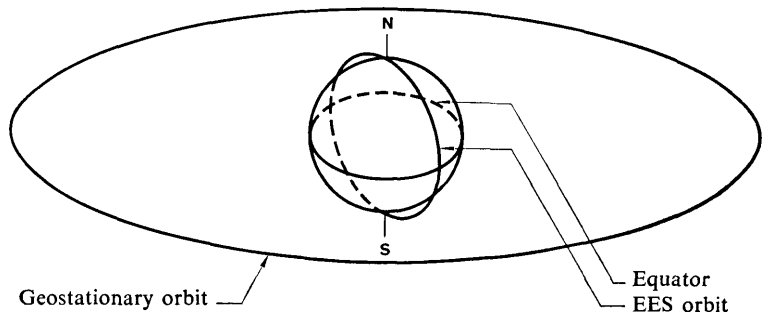

FIGURE 1 – *Geometric relationship between geostationary satellite orbit and circular-inclined orbit of altitude 1800 km, inclination 100°*

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:

$$C/I = P_{TW} + G_{TW} - (P_{TU} + G_{TU}) + \Delta L_p + 10 \log (B_U/B_W) \quad \text{dB} \qquad (1)$$

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:

$$C/I = 45 - (P_{TU} + G_{TU}) + \Delta Lp + 10 \log (B_U/0.25) \quad B_U \text{ in MHz} \qquad (2)$$

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:

$$\text{Power flux-density} = P_t + G_t - L_p - 10 \log B_U \quad \text{dB(W/(m}^2 \cdot \text{4 kHz))} \tag{3}$$

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:

$$\text{Power flux-density} = +22 - 162 - 34 = -196 + 22 = -174 \quad \text{dB(W/(m}^2 \cdot \text{4 kHz))}.$$

4. Interference from terrestrial fixed service transmitters to the 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:

$$L_b\,(1\%) = P_t + G_t - (P_i - G_R) \quad \text{dB} \tag{4}$$

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

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/m²))	−123·6
Effective area of receiving antenna, A_R (m²) 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%.

With such a low value of C/N, the maximum tolerable value of interference, P_i, at the EES earth station receiver is assumed to be 6 dB below $k\,T_sB$, 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 characterisics of an earth exploration satellite earth station are given in Table III using a frequency of 8 GHz as an example.

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 receives, 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 transmitter 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,

$$L_b\,(1\%) = P_t + G_t + 147.6 \qquad \text{dB} \tag{7}$$

REPORT 693

TECHNICAL AND OPERATIONAL CONSIDERATIONS FOR THE EARTH EXPLORATION SATELLITE SERVICE

Preferred frequency bands for active and passive microwave sensors

(Question 12-2/2)

(1978)

1. Introduction

In the area of Earth exploration for earth resources, meteorology and oceanography, new satellite programmes currently being developed in 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 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.

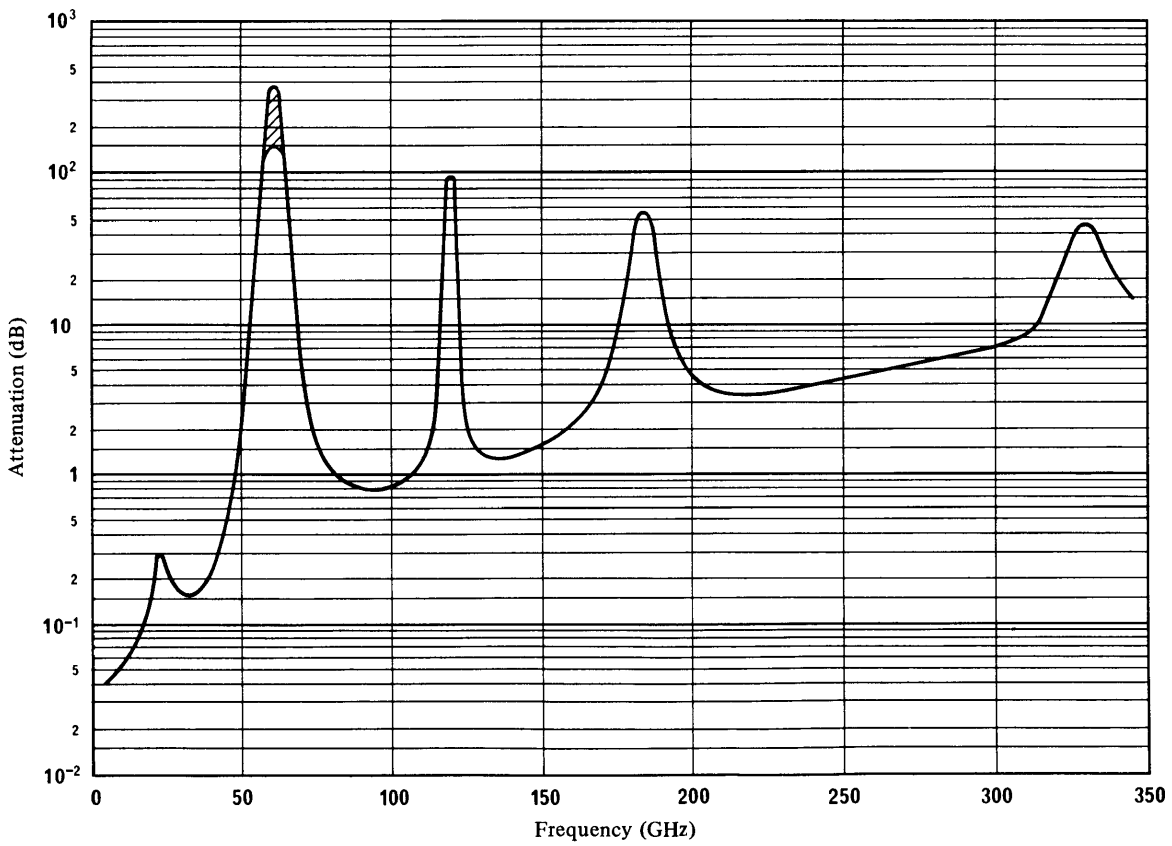

FIGURE 1 – *Zenith attenuation versus frequency (Zenith attenuation January – Mid-atitude 7.5 g/m³ surface water vapour density)*

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,

$$T_A(\nu) = \frac{P(\nu)}{kB} = \frac{1}{4\pi}\int_0^{4\pi} G(\Omega)\left[T_0(\nu)\, e^{-\tau(L)} + \int_0^L T(s)\,\beta(s)\, e^{-\tau(s)}\, ds\right] d\Omega \quad (1)$$

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:

$$\tau(s) = \int_0^s \beta(x)\, dx = \int_0^s \left(\frac{a(x)}{4.34}\right) dx = \frac{A(s)}{4.34} \quad (2)$$

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:

$$T_A(s) = T_0\, e^{-\tau(s)} + T_s(1 - e^{-\tau(s)}) \quad (3)$$

$$T_A(s) \simeq T_0(1 - \tau(s)) + T_s\,\tau(s) \quad (4)$$

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]:

$$\Delta T_e = \frac{\alpha(T_A + T_N)}{\sqrt{B\tau}} \quad (5)$$

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 focussed 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.

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. Fig. 2 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.

* See also the sections on Radiometeorology (5C), Space Telecommunications (5F) and Interference (5G) of Volume V.

TABLE I – *Passive microwave sensor parameters*

Sensor	Frequency (GHz)	Bandwidth (MHz)	Sensitivity ΔT_e (K)	Sensitivity (dBm)	Operation date
L-band radiometer	1.4135	27	1	–124	1970
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-F) 19.35 (NIMBUS-5)	250 300	1 1	–114 –114	1975 1972
Scanning multichannel microwave radiometer	6.6, 10.69, 17.96, 22.0, 37.0	250	0.9 to 1.5	–113	1978
Microwave limb sounder	CO lines – 115.271, 230.538, 345.796 H_2O lines – 183.310, 325.154, 380.196 O_3 lines – 184.749, 235.710, 237.146, 364.432 N_2O lines – 100.491, 125.613, 150.735, 175.856, 200.975, 226.094, 251.211, 276.327, 301.442 O_2 lines – 367, 118.75, 69.488, 68.960, 68.431, 67.900, 67.369, 66.836, 66.302, 65.764, 65.224, 64.679, 64.128, 63.569, 62.998, 62.411, 61.800, 61.151, 60.435, 59.591, 58.557, 56.265	600	0.3–3	–116 to –106	1978
S-band radiometer	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
Shuttle imaging microwave system	0.61 1.413 2.695 6.6 10.69 20.0 22.2 37.0 53.0 94.0 118.7	10 30 10 300 300 1000 1000 2000 500 2000 700	0.3 to 3	–134 to –101	To be determined

TABLE I *(cont.)* – *Passive microwave sensor parameters*

Sensor	Frequency (GHz)	Bandwidth (MHz)	Sensitivity ΔT_e (K)	Sensitivity (dBm)	Operation date
Low noise microwave radiometer	6.6, 10.69, 18, 21, 35	250	0.33 to 1	–120 to –115	To be determined
L-band radiometer	1.4	100	0.1	–129	1972
Swept frequency radiometer	4.5 – 7.8	100	0.1	–129	1976
Passive microwave imaging system	10.69	10	0.75 to 3.5	–129 to –123	1970
Multifrequency microwave radiometer	1.42 18.0 22.05 37.0	27 200 200 500	1 1 1 1	–124 –115 –112 –112	1970

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 X 1	–98.5	64	1978
SEASAT scatterometer	14.6	25 X 5	–128	55	1978
SEASAT altimeter	13.5	1.5	–81	75	1978
Active/passive imaging system	3.0 13.9 35.0	4.25 4 4	–97.3 –96.8 –92.05	67 63 72	1971
Coherent imaging radar	1.5	4.9	–88	49	1975
Surface profile radar	36	1.2	–70	45	1976
Radiometer/scatterometer	13.9	1.5	–90	41	1970
Radar pulse compression experiment	13.9	15	–107	21	1977
Short pulse wind/wave sensor	13.9	2.5	–80	74	To be determined
Orbiting met radar	10	0.06	–98	96	To be determined
High resolution imaging radar	1.4 and 13.9	Not yet determined	Not yet determined	Not yet determined	To be determined

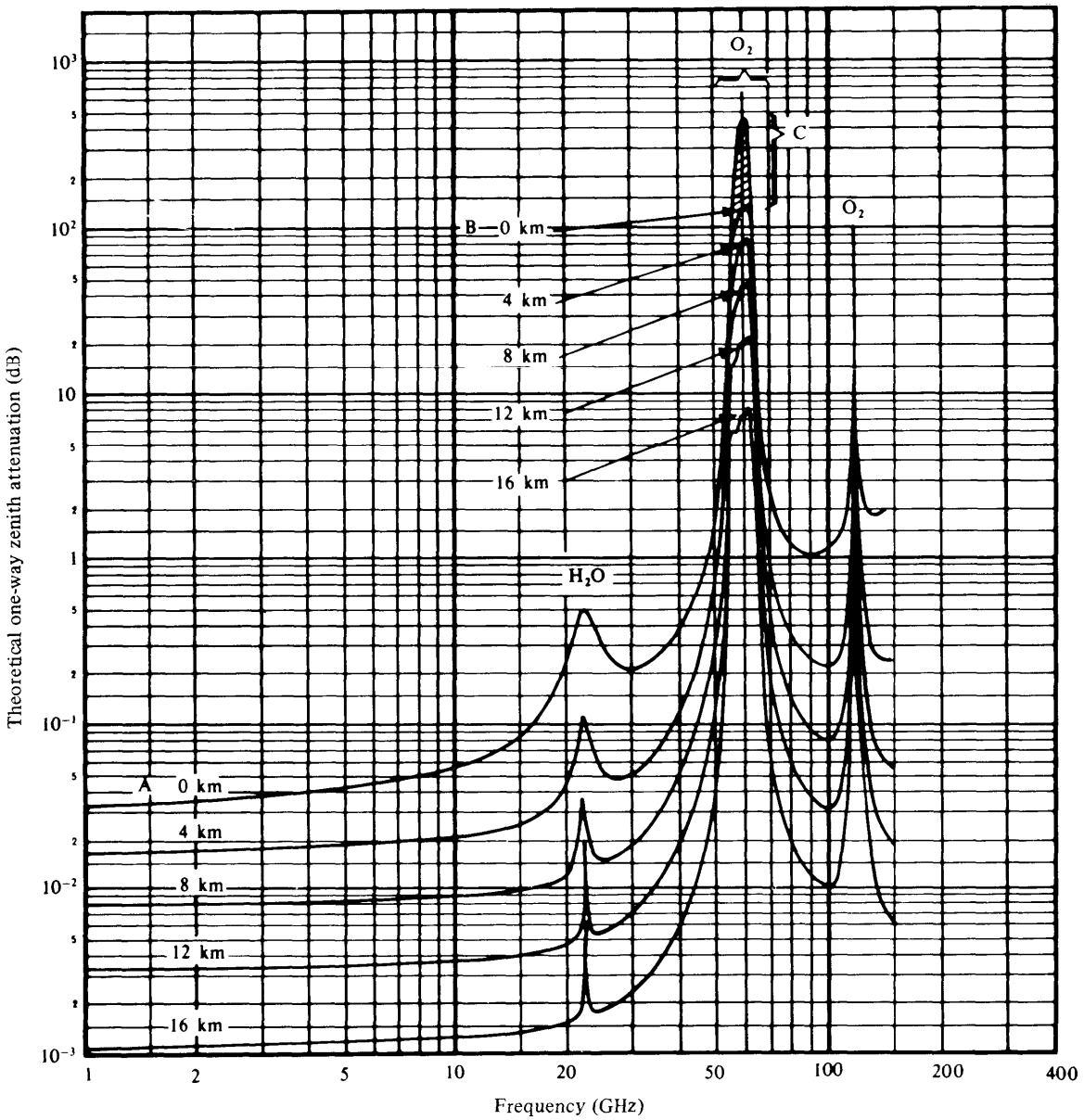

FIGURE 2 – *Theoretical vertical one-way attenuation from specified height to top of the atmosphere for a moderate humid atmosphere (7.5 g/m³ at the surface)*

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

A number of different frequencies may be chosen to provide a reasonable set of weighting functions for atmospheric temperature, water vapour, ozone, clorine 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.

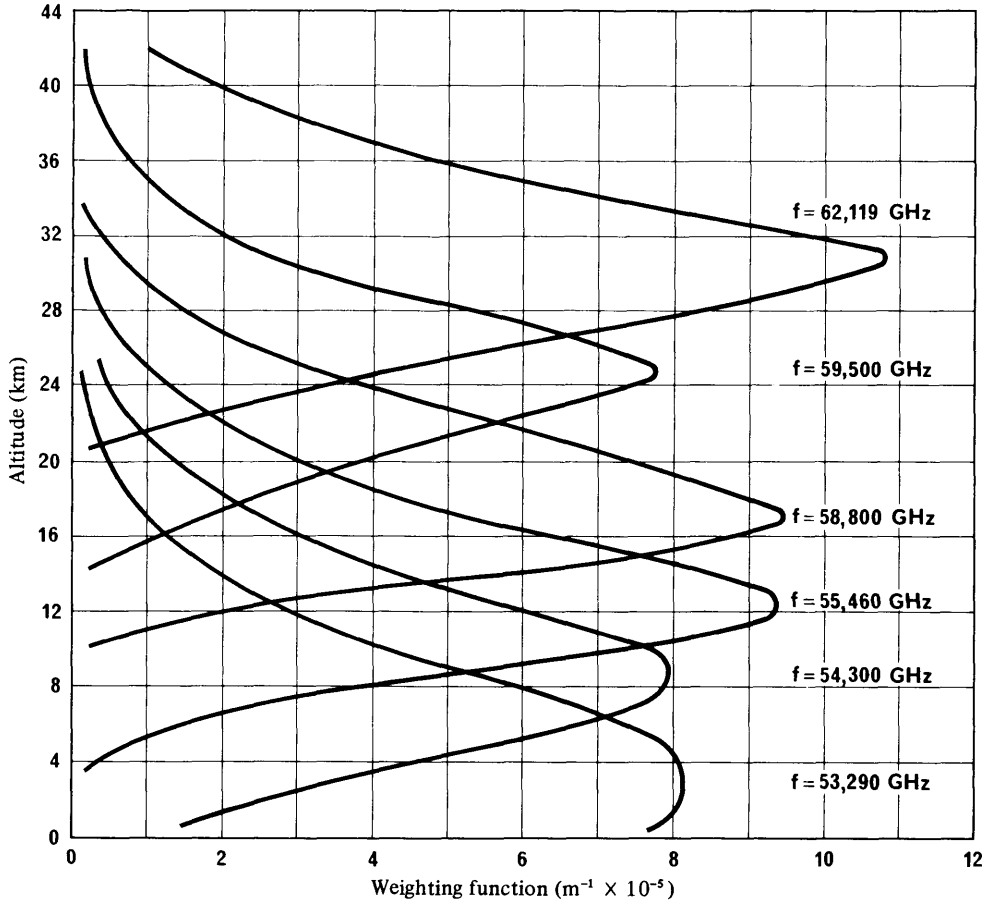

FIGURE 3 – *Temperature weighting functions (zenith $\theta = 40°$, polarization = 90°)*

(Clear sky)

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).

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. Figs. 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.

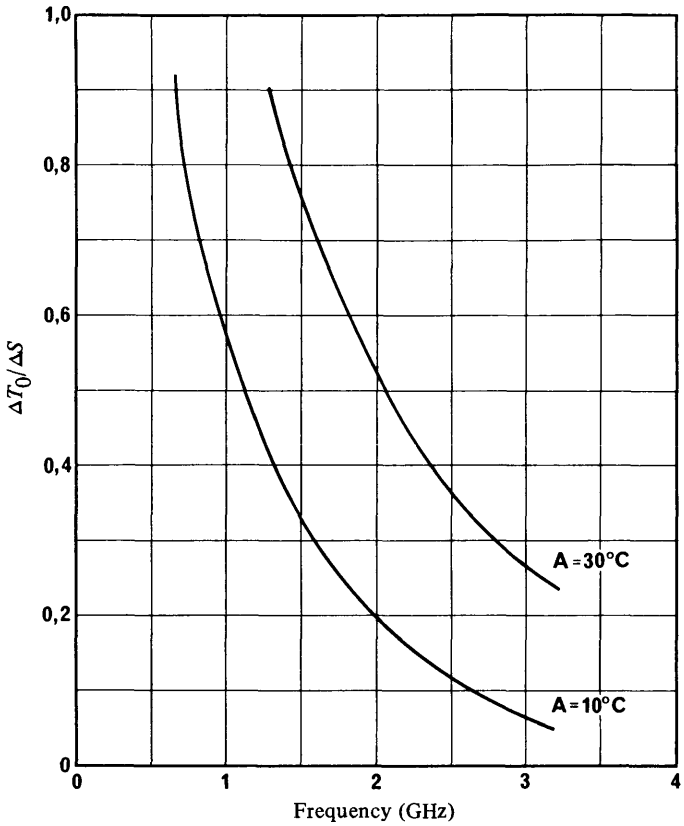

FIGURE 4 – *Change in brightness temperature with salinity*

A : Surface temperature

ΔS : Salinity change in parts per thousand (‰)

ΔT_0 : Temperature change (K)

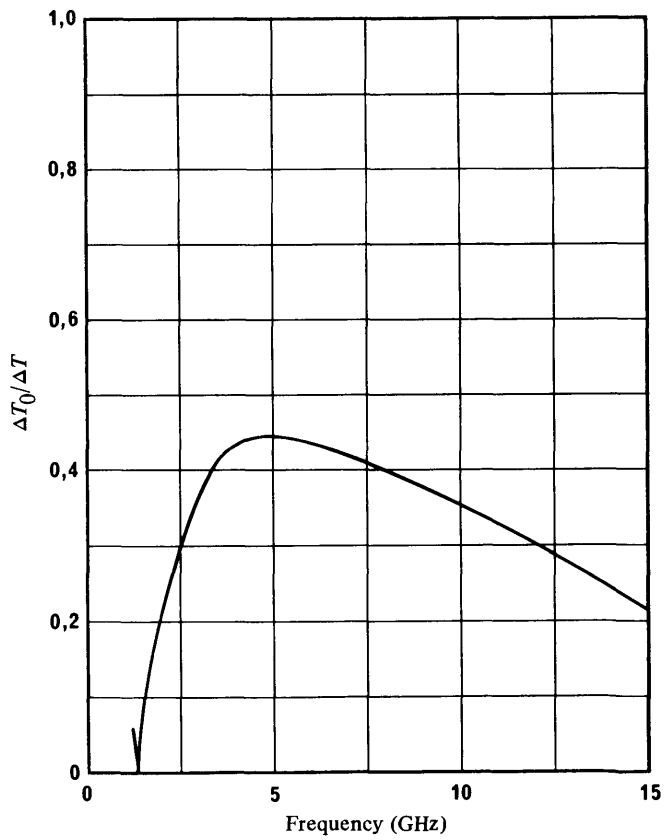

FIGURE 5 – *Change in brightness temperature with surface temperature (salinity 36 parts per thousand)*

ΔT : Physical surface temperature change (K)

ΔT_0 : Brightness temperature change (K)

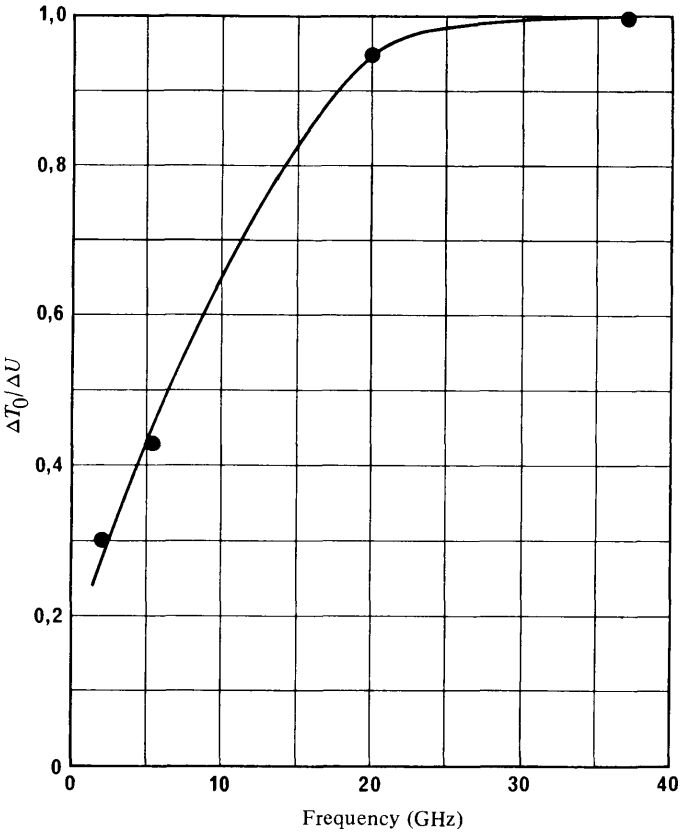

FIGURE 6 – *Change in brightness temperature with wind speed (nadir)*

ΔU : Wind speed change (m/s)

ΔT_0 : Brightness temperature change (K)

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. Figs. 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 useable areas of coverage.

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. More than every 18 days data updating is required to fully satisfy the requirements of environmental scientists and meteorologists.

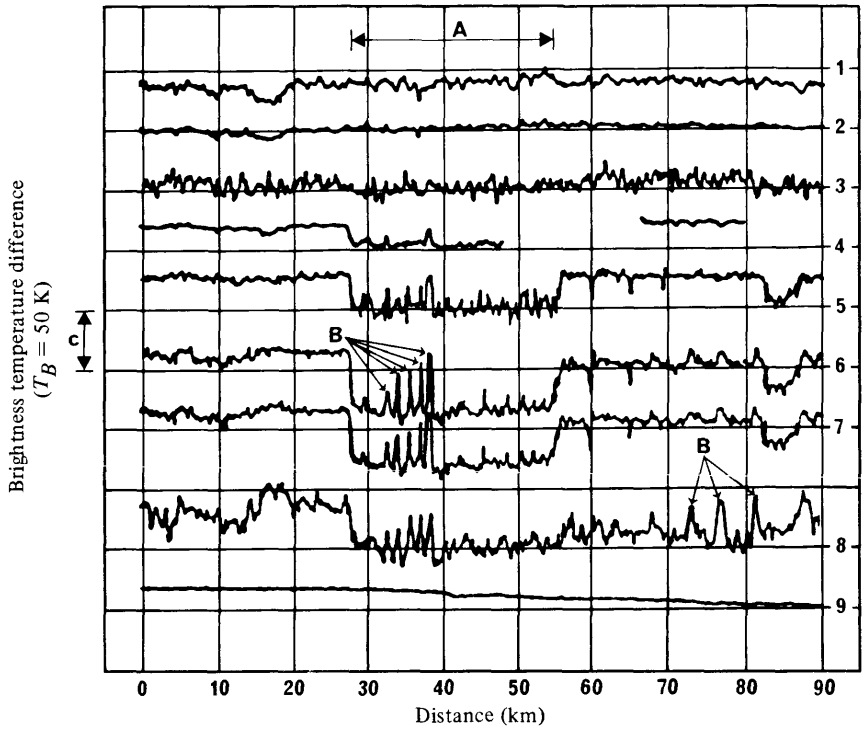

FIGURE 7 – *Brightness temperatures of ice at various wavelengths and polarizations*

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			

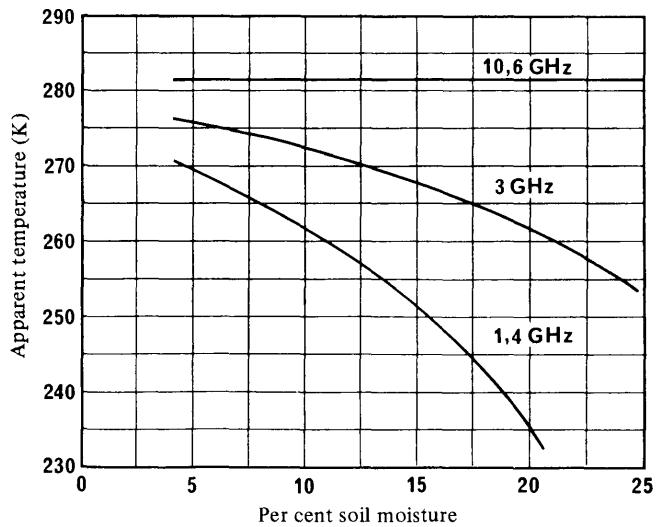

FIGURE 8 – *Apparent temperature of a smooth surface uniform vegetation for various frequencies*

40° Incidence
Vertical polarization
Density = 5.0%
Canopy height = 50 cm

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.

5.2 *Active sensors*

Unlike passive sensors, 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 transverse the atmosphere twice. As a result the electromagnetic absorption and scattering properties of the atmosphere play an important role in determining the spectral regions available to 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 larger 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.

Active microwave sensors have shown promise at frequencies from approximately 1 GHz to above 30 GHz. Although experiments have not yet advanced to the point where specific frequency bands can be verified for specific functions, some preferences for certain frequency bands are becoming apparent. Since active sensors are in general radar devices, it appears desirable to share frequency bands allocated to the radiolocation service (see Report 695). SEASAT-A, to be launched by the United States in 1978, has an active sensor complement (Table II) designed to study ocean dynamics and physical properties on global basis. The SEASAT-A results will help in determining preferred frequency bands, especially for measurement of ocean surface winds with an active microwave scatterometer. Currently, the preferred frequency band for this measurement is believed to be in the region of 10 to 15 GHz.

Other studies [NASA, 1974] conclude that active sensors could measure liquid water content, drop-size spectra, and rainfall rates on a global scale. In addition, they could map maximum echo heights and melting layer heights in rain clouds. Measurements of this type require an active sensor simultaneously operating on at least two wavelengths – preferably three. A set of optimum frequencies probably exists and studies have indicated that frequency bands near 3, 10 and 30 GHz may be the most appropriate to use for an experimental design of this instrument.

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REPORT 694

SHARING CONSIDERATIONS AND PROTECTION CRITERIA RELATING TO PASSIVE MICROWAVE SENSORS

(Question 12-2/2)

(1978)

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 224-4). This sensitivity is given by:

$$\Delta T_e = \frac{\alpha T_s}{\sqrt{2Bt}} \qquad (K) \tag{1}$$

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:

$$\Delta P = k\Delta T_e B \qquad (W) \tag{2}$$

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:

$$P_H = 0.2\ k\Delta T_e B \qquad (W) \tag{3}$$

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 [CCIR, 1974-78]. The potential for sharing between sensors and other services has been analyzed for each frequency band. Typical equipment parameters for the stations of other services were used in the analyses. For bands where equipment has not yet been developed potential systems were postulated following applicable CCIR guidelines.

3.1 *Gain-range quotient analysis*

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,

$$P_H = \frac{P_t G_t G_r}{4\pi R^2} \left(\frac{\lambda^2}{4\pi}\right) \quad (4)$$

where:

G_t: gain of transmitting antenna,

P_t: power of transmitting source (W),

G_r: gain of receiver antenna,

λ: wavelength (m),

R: range (m).

Rearranging equation (4):

$$\frac{P_H (4\pi)^2}{P_t \lambda^2} = \frac{G_t G_r}{R^2} \quad (5)$$

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 quotient 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 antennae 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 [CCIR, 1974-78] are given in Table I. Applicable bandwidths related to the interference thresholds are also given. The values for the interference thresholds are determined using equation (3), the values for ΔT_e given in Table IV of [CCIR, 1974-78], and the values for bandwidth given in Table I of this document and Table III of [CCIR, 1974-78].

The following paragraphs consider the feasibility of sharing between passive microwave sensors and stations in other services.

4.1 *Sharing between passive sensors and the Fixed and Mobile Services*

Each of the preferred frequency bands for passive sensors has been analyzed using the gain-range quotient analysis programme and the random interference analysis programme. Annex I contains details of the analysis.

Simultaneous sharing between passive sensors and Fixed and Mobile Services has been determined to be generally not feasible below 10 GHz.

Time sharing with Fixed and Mobile Services is generally not feasible since operation of these services is usually continuous. Limited exceptions might be found where Fixed and Mobile Service is limited to daytime hours. In that case, sensors could operate during the night and 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 and mobile stations. However, sensing applications cannot be performed over some major areas of interest.

Above 20 GHz frequency sharing between passive sensors and Fixed and Mobile Services appears feasible due to increased atmospheric attenuation and assumptions as to the technical characteristics of the, as yet, undeveloped Fixed and Mobile Services, which are 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.

TABLE I – *Sensor interference thresholds*

Frequency (GHz)	Interference threshold (dB(W))	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	–160	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

Frequency sharing with the Fixed and Mobile Services between 10 GHz and 20 GHz would only be feasible provided the maximum equivalent isotropically radiated power of a fixed or mobile station does not exceed 35 dBW at 10 GHz, increasing to 40 dBW at 20 GHz; and that the power delivered by a transmitter to the antenna of the fixed or mobile station does not exceed –3 dBW. Given the existence today of operating systems in the 10 GHz range which exceed the criteria by an order of magnitude, together with the expectation that further improvement of prototype, high density fixed systems around 20 GHz will incorporate parameters exceeding those on which the above sharing feasibility is predicted, suggests a serious incompatibility at the extremities of this band. There appears, however, to be mid-range possibilities around 15 GHz where the, as yet undeveloped, requirements of the fixed and mobile services might be sufficiently constrained to permit sharing.

4.2 *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 analyzed in the vicinity of 18 GHz. Details of the analysis are contained in Annex II.

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 would be 16 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 power flux-density at the Earth's surface produced by emissions from a fixed-satellite space station does not exceed -109 dB(W/m^2) in a 200 MHz reference band for all angles of arrival.

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. Applications utilising small earth stations might be limited by the imposition of decreased power flux-density limits.

4.3 *Sharing between passive sensors and the Fixed-Satellite Service (Earth-to-space)*

Sharing between passive sensor and fixed-satellite up-links was analyzed 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.

4.4 *Sharing between passive sensors and the Inter-Satellite Service*

The feasibility of frequency sharing by passive sensors and the Inter-Satellite Service has been analyzed in the region of 50 to 70 GHz and in the vicinity of 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-orbiting satellite,
- pointing (for a limb sounder) directly at the geostationary satellite.

Cumulative side lobe interference from multiple inter-satellites 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 III.

4.4.1 *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.

4.4.2 *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%.

4.4.3 *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.

4.4.4 *Conclusion*

Sharing on a simultaneous operational basis between passive sensors and the Inter-Satellite Service is feasible.

4.5 *Sharing between passive sensors and the Aeronautical Radionavigation and Radiolocation Services*

Sharing between passive sensors and the Aeronautical Radionavigation and Radiolocation Services has been analyzed for frequency bands near 1.4 GHz, 15 GHz, and above 100 GHz. Annex IV contains details of methods of this analysis.

Transmitters in the Aeronautical Radionavigation and Radiolocation Services are typically pulse type radars.

The gain-range quotient analysis programme was used to simulate couplings between the passive sensor and transmitter antennae. 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 analyzed 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 § 4.8.

4.6 *Sharing between passive sensors and the Broadcast-Satellite Service*

Sharing between passive sensors and the Broadcast-Satellite Service near 2.6 GHz was analyzed.

There are two possible interference paths from a broadcasting-satellite to a low orbiting 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 the interference to the passive sensor would be 22 to 33 dB above the sensor interference threshold.

Calculations for a broadcast-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 Broadcast-Satellite Service is not considered feasible either on a simultaneous operation or on a time sharing basis. Improved side lobe discrimination of the broadcast-satellite could possibly permit time sharing on a limited scale.

4.7 *Sharing between passive sensors and the Mobile-Satellite Service*

Sharing between passive sensors and Mobile-Satellite Services has been analyzed for frequency bands near 20 GHz, 37 GHz, and 50 GHz.

4.7.1 *Space-to-Earth mobile-satellite links*

Sharing calculations were based on a hypothetical model of a mobile-satellite system, using spread spectrum techniques as presented in Annex II.

Interference levels were determined to be below the sensor interference threshold as 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.

4.7.2 *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.

A gain-range quotient analysis 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.

4.8 *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 analyzed.

Both CW and pulsed type altimeters operate in the 4.2 to 4.4 GHz 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.

The passive sensor interference threshold would not be exceeded unless an excess of 3000 aircraft were simultaneously in view of the sensor. This is well above the predicted number in view over coastal and ocean areas.

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.

4.9 *Sharing between passive 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 224-4, 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 antennae (Recommendation 314-4).

5. Conclusions

Frequency sharing between passive sensors and the Fixed and Mobile Services appears feasible above 20 GHz.

Frequency sharing with the Fixed and Mobile Services between 10 GHz and 20 GHz is only feasible provided that the maximum equivalent isotropically radiated power of a station in the Fixed or Mobile Service does not exceed 35 dBW at 10 GHz, increasing to 40 dBW at 20 GHz, and that the power delivered by a transmitter to the antenna of a station in the Fixed or Mobile Service does not exceed -3 dBW. However, there are fixed systems operating in the 10 GHz range 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. 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. There may be possibilities that around 15 GHz the, as yet undeveloped, requirements of fixed and mobile services may be sufficiently constrained to permit sharing. Analysis shows, however, that some fixed and mobile applications are compatible with the stated criteria. *

Frequency sharing with the Fixed and Mobile Services 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 power flux-density at the Earth's surface produced by emissions from a fixed or mobile-satellite space station does not exceed -109 dB(W/m^2) in a 200 MHz reference band for all angles of arrival.

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.

Sharing with the Broadcast-Satellite Service is not feasible, except that time sharing may be feasible on a limited basis if the broadcast-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.

REFERENCE

CCIR Document
[1974-78]: 2/202 (USA).

ANNEX I

ANALYSIS OF SHARING FEASIBILITY BETWEEN PASSIVE SENSORS AND THE FIXED AND MOBILE SERVICES NEAR 1.4 GHz, 15 GHz AND 21 GHz

1. Introduction

This Annex illustrates the techniques used to determine the feasibility of frequency sharing between passive microwave sensors and fixed and mobile services, by performing interference analyzes at 1.4 GHz, 15 GHz and 21 GHz. The results of the 1.4 GHz analysis are typical for bands below 10 GHz, the results of the 15 GHz analysis are typical for bands between 10 GHz and 20 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. For the Fixed and Mobile Services this takes place when the spacecraft is on the horizon as seen from the terrestrial station.

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)	-38 (10 log S; S in m^2)
Spreading loss	-139 dB/m^2
Atmospheric loss	0 dB
Maximum allowable e.i.r.p.	12 dBW

Fixed and mobile 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 or mobile station is determined, by the gain-range quotient 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).

* In Japan, however, considerable development in the Fixed and Mobile Services has already occurred at frequencies around 15 GHz, and this must be taken into account in any consideration of the sharing problem.

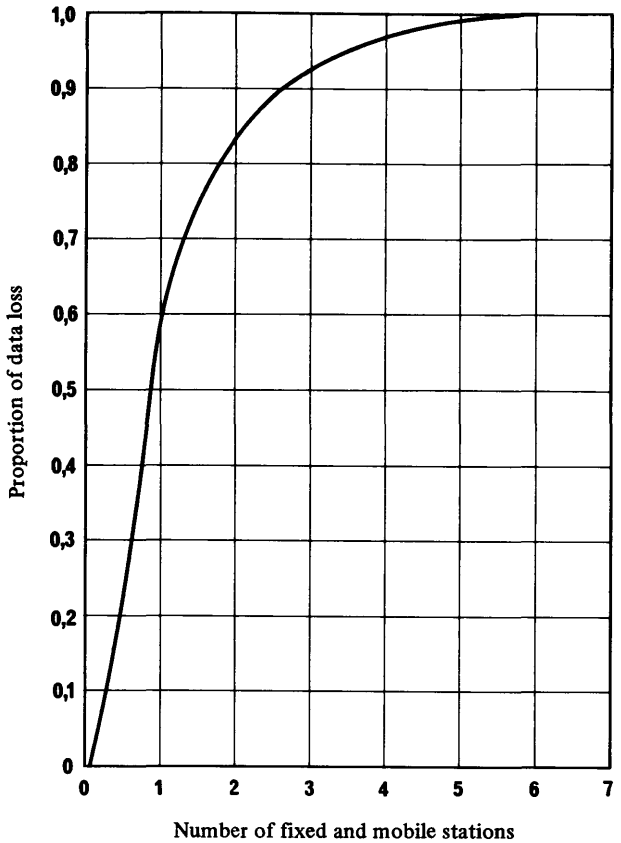

FIGURE 1 – *Data loss versus number of fixed and mobile stations*

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. Fig. 2 shows the areas of the world where total loss of data is expected, based on IFRB Master Register entries for transmitter locations operating near 1.4 GHz.

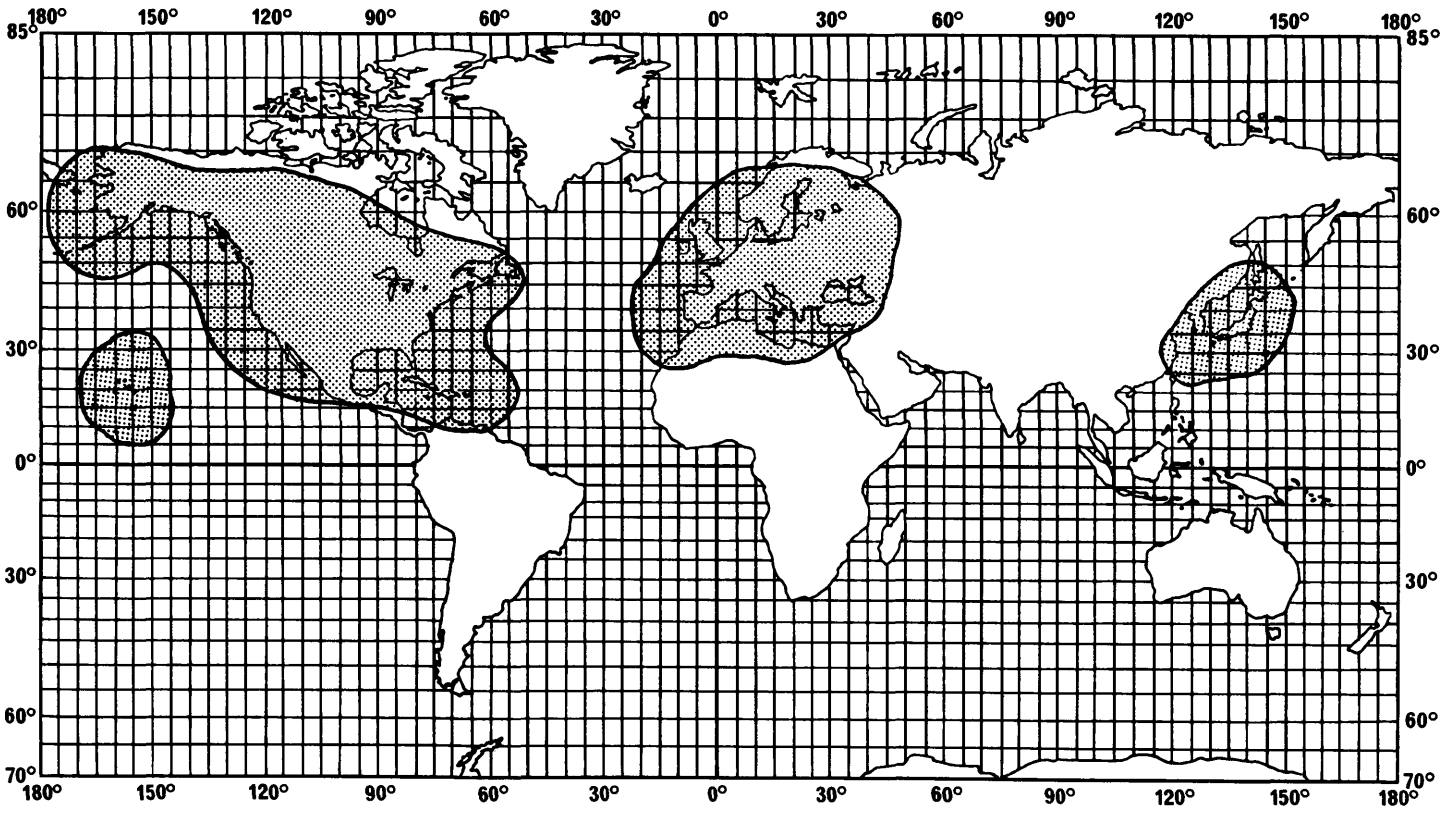

FIGURE 2 – *Loss of coverage area due to fixed and mobile services*

3. Sharing feasibility near 15 GHz

The interference threshold of a water vapour sensor operating near 15 GHz is −160 dBW in a bandwidth of 200 MHz.

There are three potential interference paths that must be analyzed:

- 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 by direct overflight of an interference source through the main beam of the radiometer.

Each interference path is analyzed 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 visibility sphere of the sensor.

3.1 *Interference contributions from main beam coupling of interferers*

Half the allowable interference level, or −163 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 interferers.

The permissible e.i.r.p. of the source of interference can then be calculated as follows:

Interference level	−163 dBW
Spreading loss	−139 dB/m^2
Atmospheric loss	− 5 dB
Radiometer antenna effective area (side lobe)	− 59 (10 log S; S in m^2)
Three sources of interference	+ 5 dB
	+ 35 dBW

The interference level of −163 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 popultion of 10 000 sources.

3.2 *Interference contributions from side lobe coupling*

Half the allowable interference level, or −163 dBW, will be assigned as the contribution from the additive effects of side lobe coupling of multiple sources into the radiometer side lobes.

The maximum acceptable power of the interfering transmitter can then be calculated as follows:

Interference level	−163 dBW
Transmitting antenna gain (side lobe)	− 10 dBi
Spreading loss (average)	−130 dB/m^2
Atmospheric loss (average)	− 0.2 dB
Radiometer antenna effective area (side lobe)	− 59 (10 log S; S in m^2)
10 000 sources	+ 40 dB
Maximum allowable transmitted power	− 3.8 dBW

3.3 *Interference contribution from main beam coupling of sensors*

Direct overflight 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	− 3 dBW
Transmitting antenna gain (side lobe)	− 10 dBi
Spreading loss	−125 dB/m^2
Radiometer antenna effective area	+ 13 (10 log S; S in m^2)
Interference level	−125 dBW

This interference level would exceed the interference threshold by 35 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	+17.8 (10 log A; A in km^2)
10 000 sources	+40 dB
Area of visibility sphere	+72.8 (10 log A; A in km^2)
Percentage total area loss to visibility sphere	3%

3.4 *Sharing potential*

Frequency sharing near 15 GHz between passive sensors and the Fixed and Mobile Services is feasible, provided the Fixed and Mobile Services are limited to a maximum isotropic radiated power not exceeding 35 dBW, and a maximum transmitter output power not exceeding −3 dBW.

The above constraints appear compatible with characteristics of fixed and mobile equipment using the low-power, wideband modulation techniques which the fixed and mobile services are expected to employ when frequency bands near 15 GHz are developed.

4. Sharing feasibility near 21 GHz

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 387-3, 609-1, and 610-1. 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 387-3 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)	− 61.4 (10 log S; S in m^2)
	−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 beams of 3000 fixed and mobile 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)	−130 dB/m^2
Atmospheric loss (average)	− 0.6 dB
Sensor antenna effective area (side lobe)	− 62.1 (10 log S; S in m^2)
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 and Mobile Services thus appears feasible near 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 and Mobile Services.

ANNEX II

ANALYSIS OF SHARING FEASIBILLITY BETWEEN PASSIVE SENSORS AND THE FIXED-SATELLITE AND MOBILE-SATELLITE SERVICES

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. The approach used in this Annex consists of analyzng two frequency bands for sharing potential with different types of fixed-satellite space-to-Earth links and one band for sharing potential with fixed and mobile-satellite Earth-to-space links. Frequencies selected for the above analyses are near 18 GHz and near 36 GHz.

2. Sharing feasibility with the Fixed-Satellite Service (space-to-Earth) near 18 GHz)

Rain rate, sea state, ocean ice and water vapour are the measurements which require a frequency near 18 GHz. Sensor interference threshold is -160 dBW for these measurements.

2.1 *Sharing analysis based on current power flux-density limits*

It is anticipated that the Fixed-Satellite Service down-link operating at 18 GHz will have characteristics similar to those of systems designed for the 11 GHz band. These satellites may make use of both spot beam and full-Earth coverage antennae. The down-link e.i.r.p., regardless of which antenna is used, should not exceed levels given in Report 387-3. The maximum allowable pfd in the 18 GHz band is -105 dB(W/(m^2 · MHz)).

Assuming a spot-beam antenna (0.5°), a fixed-satellite transmitter system having the following characteristics would produce the maximum allowable power flux-density level:

Transmitter power	22.4	dBW
Antenna gain	50	dBi
Transmitter e.i.r.p. (in a 35 MHz bandwidth)	72.4	dBW
Bandwidth conversion factor (1 MHz/35 MHz)	− 15.4	dB
Transmitter e.i.r.p. spectral density	57	dB(W/MHz)
Spreading loss	−162	dB/m^2
Spectral power flux-density	−105	(dB(W/m^2 · MHz))

The maximum interference level at the radiometer input would be produced when the spacecraft is in the main beam of the fixed-satellite down-link. Two interference paths are possible:

- Coupling of the down-link signal via the back lobe of the radiometer antenna.
- Coupling of the down-link signal into the main lobe of the radiometer antenna by backscattering from the Earth's surface.

The interference level for back lobe coupling from a single transponder is computed as follows *:

Fixed-satellite e.i.r.p.	72.4 dBW
Spreading loss	−162 dB/m^2
Power flux at radiometer	− 89.6 dB(W/m^2)
Effective area of radiometer antenna (back lobe)	− 63 (10 log S; S in m^2)
Received interference power	−152.6 dBW

Thus, back lobe coupling of the signal from a single fixed-satellite down-link would constitute a source of interference to the sensor, since the interference level would be 7.4 dB above the sensor threshold of −160 dBW.

The interference to the radiometer due to the isotropic backscattering of one fixed-satellite down-link signal from the Earth is computed as follows:

Fixed-satellite e.i.r.p.	72.4 dBW
Spreading loss	−162.0 dB/m^2
Power flux-density at Earth surface	− 89.6 dB(W/m^2)
Reflectivity factor (50% loss)	− 3.0 dB
Power reflected from Earth per square metre	− 92.6 dB(W/m^2)
Surface area within main lobe of radiometer	+ 63 (10 log A; A in m^2)
Reflected signal e.i.r.p.	− 29.6 dBW
Spreading loss	−125.0 dB/m^2
Power flux at radiometer antenna	−154.6 dB(W/m^2)
Radiometer antenna effective area	+ 10.5 (10 log S; S in m^2)
Received interference power	−144.1 dBW

Thus, backscattering of a single fixed-satellite down-link signal would result in reception by the radiometer of interference 15.9 dB in excess of its threshold of −160 dBW. This would effectively preclude use of the frequency band for radiometric purposes within about 1.9° of the fixed-satellite main beam.

No information is currently available concerning the operating schedule for the proposed Fixed-Satellite Service transmissions. It cannot be assumed, however, that these systems would be inoperative during the late night/early morning hours.

Consequently, time sharing with the Fixed-Satellite Service in this band is not feasible.

Due to anticipated large volume common carrier traffic served by fixed-satellite systems in this band, sharing on a simultaneous operational basis between spaceborne microwave sensors and the Fixed-Satellite Service is not feasible if the e.i.r.p. of the fixed-satellite is sufficiently great to produce the maximum power flux-density currently permitted by the Radio Regulations at the Earth's surface.

2.2 *Determination of sharing criteria*

The interference threshold of a water vapour sensor operating near 18 GHz is −160 dBW in a bandwidth of 200 MHz.

Half the allowable interference level, or −163 dBW, will be assigned as the contributions from the Fixed-Satellite Service in bands commonly shared with Fixed and Mobile Services.

The interference path due to backscattering of the fixed-satellite down-link signal from the Earth is a worse case than the interference due to back lobe coupling. The criterion which follow are therefore based on the back scattered signal.

The permissible power flux-density at the Earth's surface resulting from a fixed-satellite space station can then be calculated as follows:

Interference level	−163 dBW
Radiometer antenna effective area	− 10.5 (10 log S; S in m^2)
Spreading loss (Earth-to-space)	+125 dB/m^2
Surface area within radiometer beam	− 63 (10 log A; A in m^2)
Reflectivity factor	+ 3 dB
Maximum pfd at Earth's surface (200 MHz reference band)	−108.5 dB(W/m^2)

* It is assumed here that the transponder bandwidth is totally contained within the bandwidth of the radiometer.

2.3 *Conclusion*

Sharing is feasible provided that the power flux-density at the Earth's surface produced by emissions from a fixed-satellite space station does not exceed -109 dB(W/m^2) in a 200 MHz reference band for all angles of arrival.

The constraints of the Fixed-Satellite Service in order 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. Applications utilizing small earth stations might be limited by the imposition of decreased power flux-density limits.

3. 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 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 antennae. 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 is 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 (162 dB/m^2)

A_r: earth station receiver effective area (10 log $S = -3$; S in m^2)

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	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)	$-$ 67	(10 log S; S in m^2)
	-111.5	dBW

or 34.5 dB above the radiometer interference threshold of -146 dBW.

Fig. 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 quotient 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 orbit.

Fig. 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 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.

* Typical mobile earth stations.

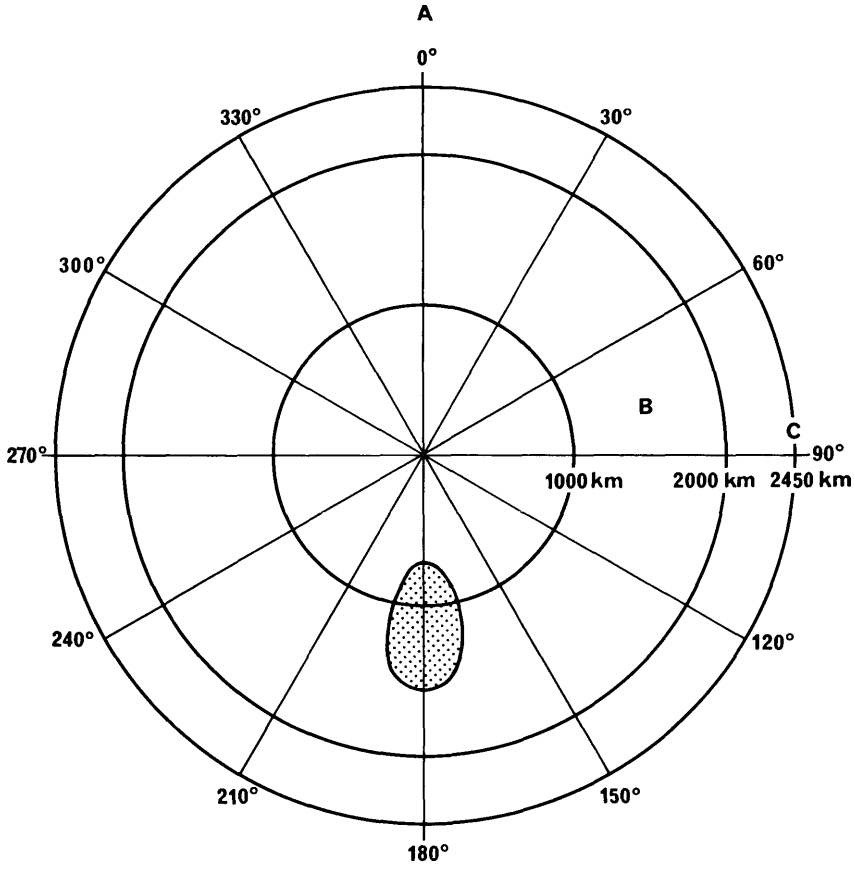

FIGURE 3 – *Map showing loss of coverage area (fixed and mobile-satellite services)*

A : Pointing azimuth

B : Great circle distance

C : Horizon

Note – Shaded areas indicate region where interference, and therefore loss of coverage, occurs. Earth station is located at the centre.

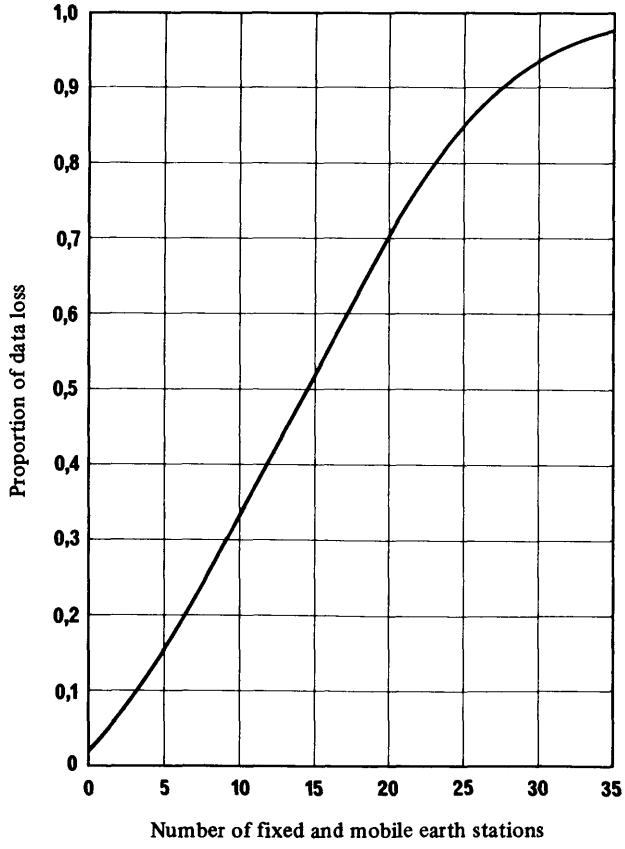

FIGURE 4 – *Data loss versus number of fixed and mobile earth stations*

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	−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	+ 57.7 (10 log A; A in m^2)
Effective area of radiometer antenna (main beam)	+ 12 (10 log S; S in m^2)
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)	− 70 (10 log S; S in m^2)
	−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 III

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 orbiting 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 analyzed 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 451-2.

Fig. 5 shows relative angular error due to station keeping uncertainties as given in Report 451-2.

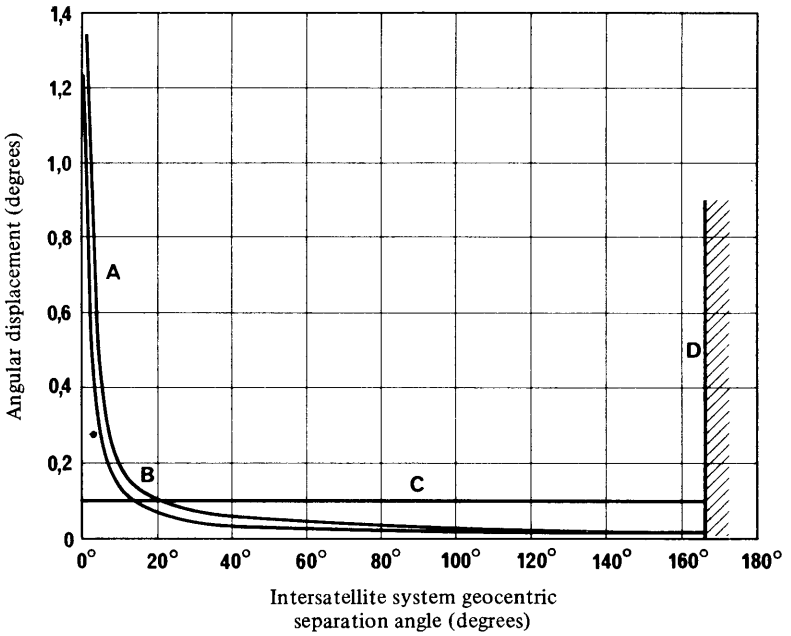

FIGURE 5 – *Relative angular error due to station keeping uncertainties*

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: receiver temperature = $9000\sqrt{f/55}$

P: power (W)

D: antenna diameter (m)

R: range (m) = $R_e\sqrt{2(1 - \cos\theta)}$

R_g: geostationary distance to center 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 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.

Fig. 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.

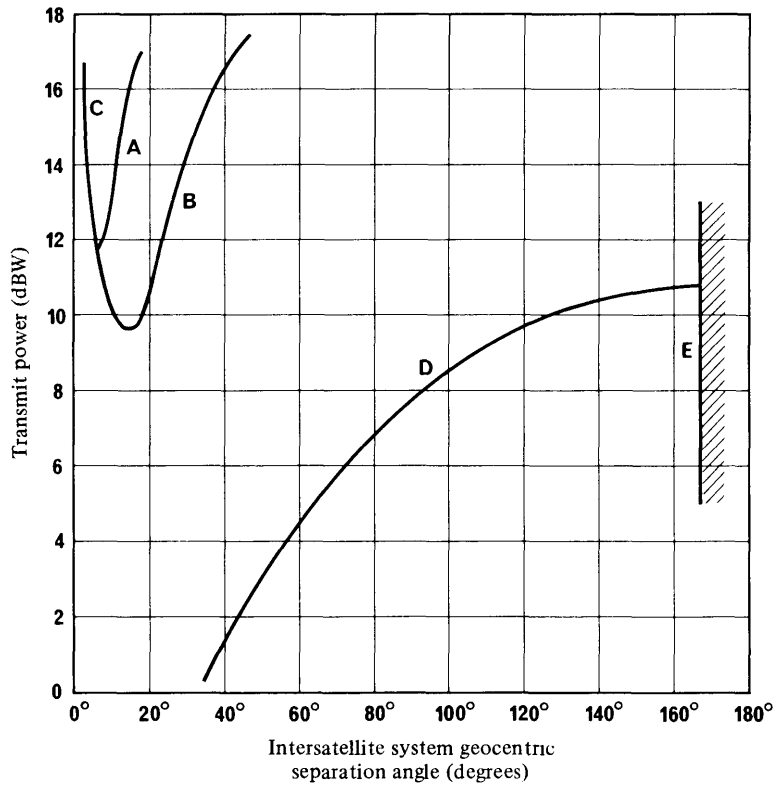

FIGURE 6 – *Intersatellite system required transmit power at 55 GHz*

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:

$$P_t = N + 10 \text{ dB} - G_t - A_r + L \quad (8)$$

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*

Fig. 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.

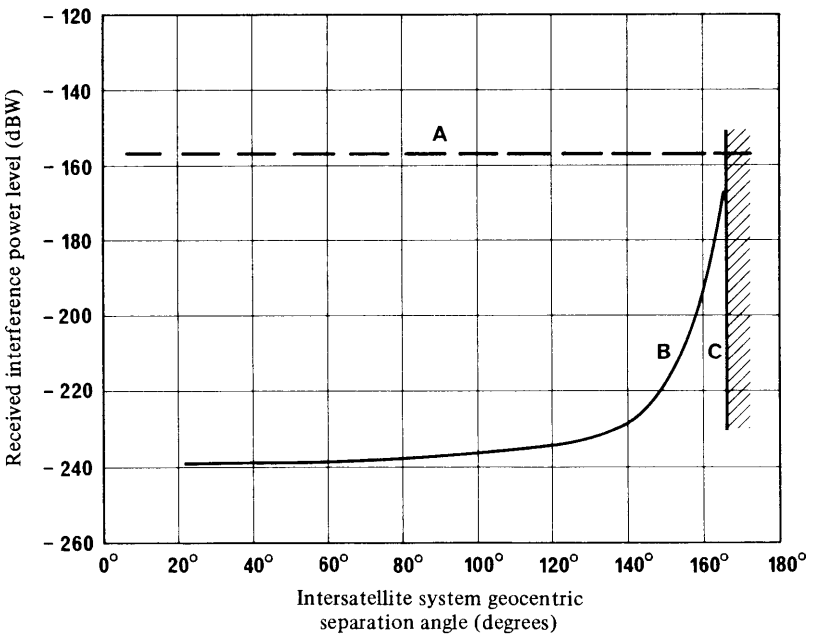

FIGURE 7 – *Worst case interference power received by nadir-looking radiometer at 55 GHz*

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	−163.0 dB/m^2
Radiometer antenna effective area (main beam)	+ 8.7 (10 log S; S in m^2)
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)	− 70.3 (10 log S; S in m^2)
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)	− 56.3 (10 log S; S in m^2)
Interference threshold	−(−157) dBW
Required spreading loss	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 IV

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 analyzed 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)	67dBW
Antenna gain	34.5 dBi
Pulse repetition rate	310 to 364 p/s
Pulse duration	2 us
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	−139 dB/m^2
Radiometer antenna effective area (side lobe)	− 38 (10 log S; S in m^2)
Received interference power	−107.3 dBW

or 57.7 dB above the sensor interference threshold.

The gain-range quotient analysis programme was utilized to simulate the couplings between the radiometer and transmitter antennae 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	− 134 dB/m^2
Effective area of radiometer antenna (side lobe)	− 48 (10 log S; S in m^2)
	− 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. *

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.

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. Fig. 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.

* 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.

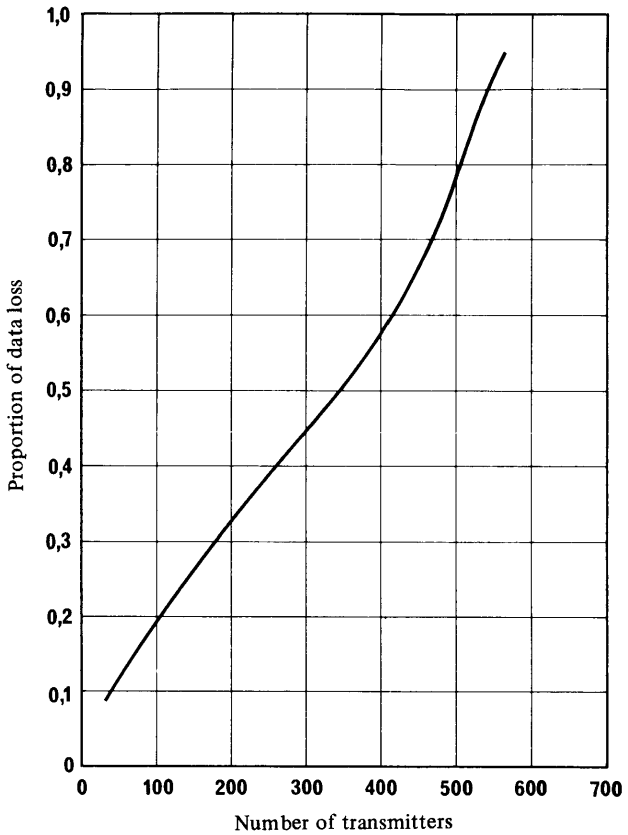

FIGURE 8 – *Data loss versus number of terrestrial transmitters of the aeronautical radionavigation service*

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.

RECOMMENDATION 515

PREFERRED FREQUENCIES FOR PASSIVE SENSING MEASUREMENTS

(Question 12-2/2)

(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 516 *

FREQUENCY BANDS FOR ACTIVE SENSORS USED ON EARTH EXPLORATION AND METEOROLOGICAL SATELLITES

(Question 12-2/2 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.

REPORT 695

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACEBORNE RADARS AND TERRESTRIAL RADARS IN THE RADIOLOCATION SERVICE

(Study Programme 12B/2)

(1978)

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. In particular, Nos. 401A and 412D of the Radio Regulations currently allow a weather radar to operate on meteorological satellites in certain portions of bands allocated to the radiolocation service. (See Bands 9800 to 10500 MHz and 34.2 to 35.2 GHz). However, no formal studies of sharing feasibility are known to have been documented.

2. Background

Although most of the active microwave sensor efforts to date have been concentrated in laboratory and aircraft experimentation, two 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.

Other active sensor experiments currently planned for launching prior to 1979 are the Altimeter, Microwave Scatterometer, and Synthetic Aperture Radar on SEASAT-A **. Additional active microwave sensors are being considered by the United States for flight missions in the 1980's. For example, active microwave sensor experiments are planned for SEASAT-B and the Severe Storm Observation Satellite (STORMSAT-B). It can also be expected that future Shuttle/Spacelab missions will have payloads containing active microwave sensors for Earth exploration.

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* This Recommendation is brought to the attention of Study Group 8.

** See Report 531-1.

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 share.

The spaceborne radar selected for the analysis was the synthetic aperture radar, since this type of radar is likely to be the most abundant and susceptible spaceborne radar. More specifically, the SEASAT-A Synthetic Aperture Radar (SAR) was chosen since its technical operating parameters are now known.

The terrestrial radar mode utilised 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 minute 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.

4. System characteristics

4.1 *Spaceborne radar*

The spaceborne radar, the SEASAT SAR, exhibits 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 beamwidth: 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 the terrestrial radar from a spaceborne transmitter is given by:

$$P_R = \left(\frac{P_t G_t G_R}{4\pi R^2}\right) \left(\frac{\lambda^2}{4\pi}\right) \left(\frac{BW_R}{BW_t}\right), \text{ for } BW_R \leqslant BW_t \quad (1)$$

where:

P_t: power of transmitter source (W)

G_t: gain of transmitting antenna

G_R: gain of receiving antenna

R: range (m)

λ: wavelength (m)

BW_R: bandwidth of receiver (Hz)

BW_t: bandwidth of transmitter (Hz)

rearranging,

$$\frac{P_R}{P_t}\frac{(4\pi)^2}{\lambda^2}\cdot\frac{BW_t}{BW_R} = \frac{G_t G_R}{R^2} \tag{2}$$

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. The term G_tG_R/R^2 is referred to as the gain-range quotient. A computer programme was developed to calculate the gain-range quotient. The resultant gain-range curve for the terrestrial radar and SAR antennae, and SEASAT orbital parameters, is presented in Fig. 1.

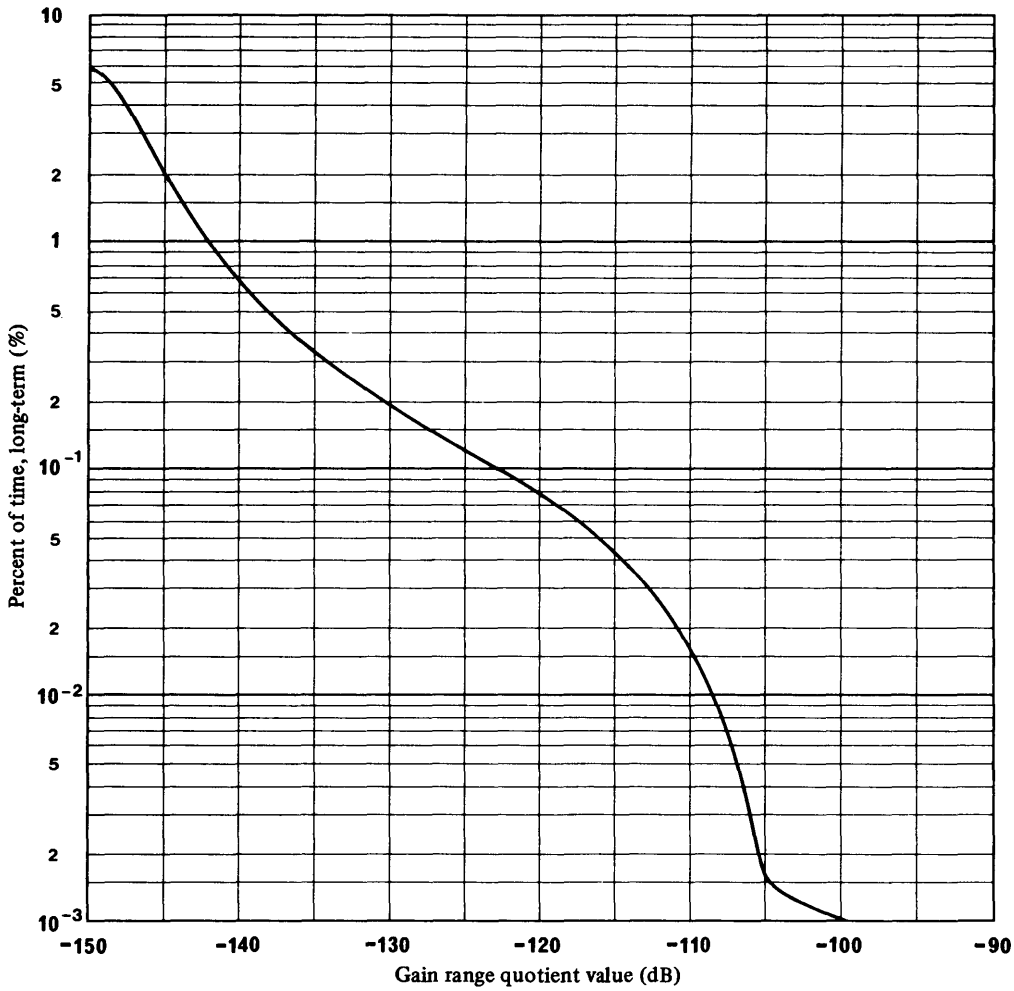

FIGURE 1 – *Gain-range quotient – long-term couplings between spaceborne side-looking fan beam, antenna and terrestrial radar scanning modified cosecant antenna, for the SEASAT orbital parameters*

The harmful gain-range quotient, utilising SAR and terrestrial radar system parameters, equals -122.6 dB in the normal mode and -120.6 dB in the MTI mode. From Fig. 1, these values correspond to long-term average interference times of 0.094 and 0.075% respectively.

Fig. 2 characterises 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.

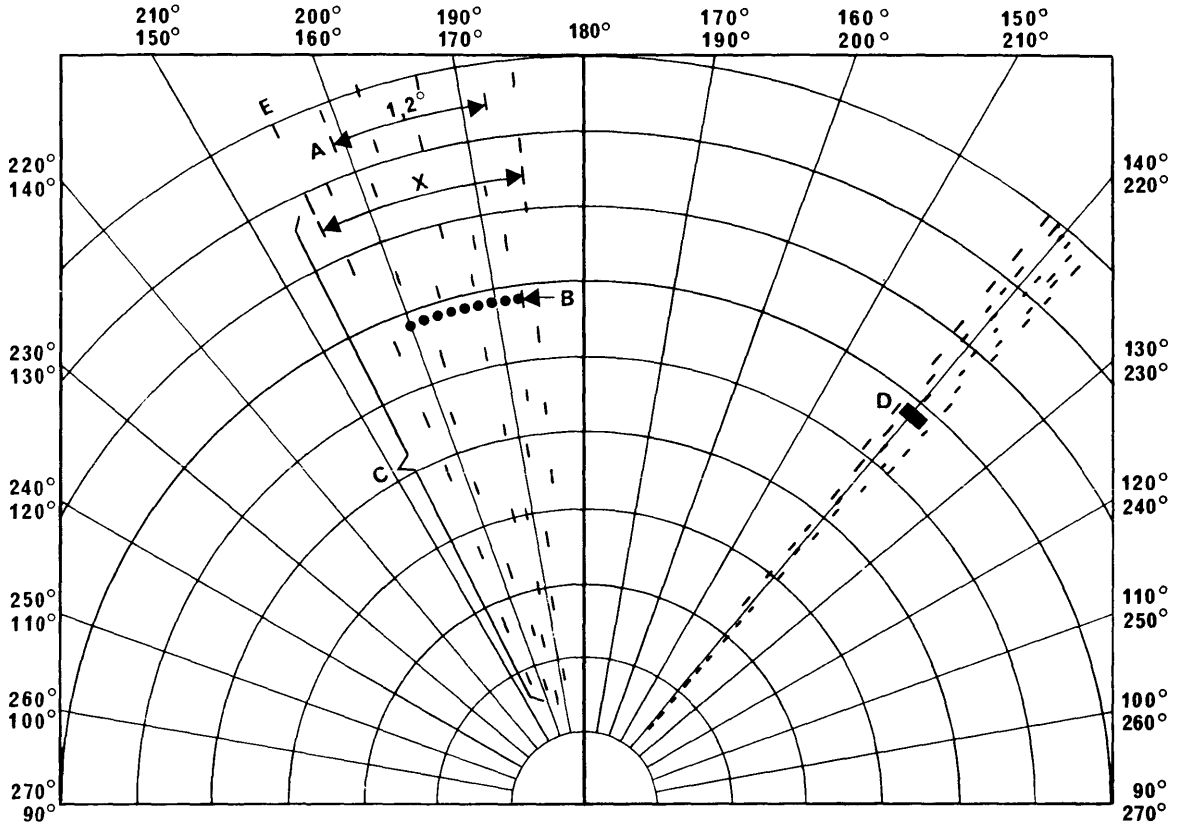

FIGURE 2 – *Normal video echo return with pulsed radar interference*

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 seconds 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 second 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 minute for a near horizon pass. For a pass occurring near 50° elevation from the terrestrial radar, the interference time reduces to 0.1 seconds per sweep (i.e. 1% of PPI display) for as long as the spaceborne radar is in line-of-sight, which is approximately 12 minutes. On a daily average basis, two passes will occur during the daytime 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.

5.2 *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 "synthesising" a long antenna by utilising coherent processing.

Consequently, the analysis requires development of the SAR system range and azimuth processing outputs for the desired 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:

$$\chi_{12}(\tau,\nu) = \frac{1}{2}\int_{-\infty}^{\infty} \mu_1(t)\,\mu_2^*(t-\tau)\,e^{j2\pi\nu t}\,dt \tag{3}$$

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.

$$Y(t) = C_0\,|\,\chi(t,\ \nu = \text{constant})\,| \tag{4}$$

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:

$$|\chi(\tau,\nu)| = \sqrt{BT}\left(1-\frac{|\tau|}{T}\right)\frac{\sin\left[\pi T(k\tau+\nu)\,(1-|\tau|/T)\right]}{\pi T(k\tau+\nu)\,(1-|\tau|/T)} \tag{5}$$

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 desired signals, an N-summation yields an output that is N times the originally received signal – for 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 a range corresponding to any 4 μs duration of succeeding range scans, are shown in Fig. 3. The bottom curve in Fig. 3 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. 3. 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.

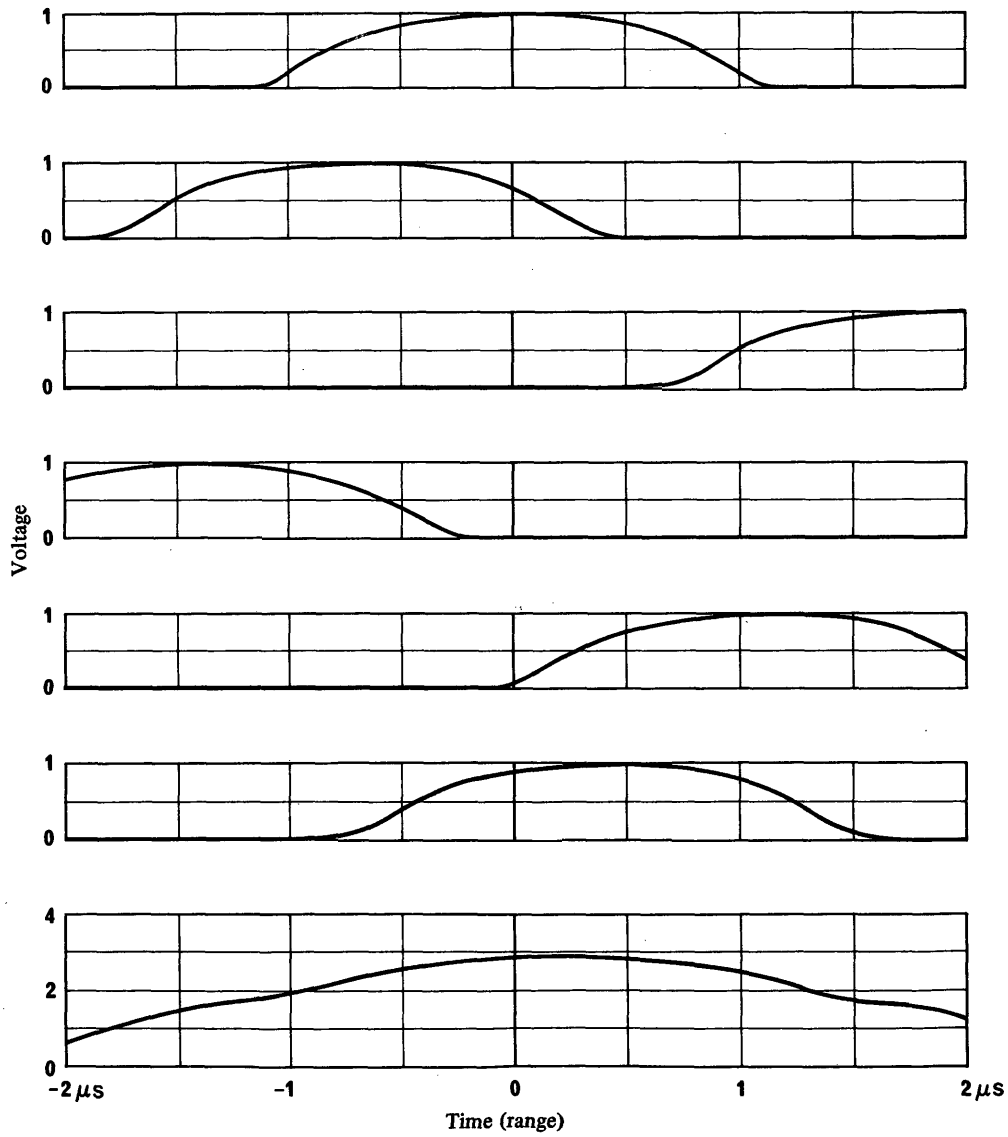

FIGURE 3 – *Interference output from SAR azimuth processor*

5.2.3 *Input/output system comparisons and summary*

Table I, presented below, summarises the input/output power relationships as determined by system processing gains.

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.

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 is amplified and frequency converted for transmission to an earth station – the range and azimuth processing takes place on the ground. The functional requirements for the SEASAT SAR receiver, call 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 is specified to be 77 dB, an interfering signal with −64 dBm of peak power would saturate 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 sweeps past the SAR. Locations of interference refer to the terrestrial radar site.

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

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. 3) could add during the azimuth processing of any 4 μs range group.

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 summarised as follows:

- The SAR is a state-of-the-art radar and is representative of a broad range of radars expected to be utilised 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 summarised as follows:

- The ARSR, on which the generic terrestrial radar model is based, is representative of a broad class of modern, high utilisation 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.
- 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 SAR.
- The analysis utilised a 800 km orbit for the spaceborne SAR, which is typical of the type forseeable for Earth exploration satellites. Also, the gain patterns of typical Earth exploration satellite active microwave sensor antennae 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 gain-range curve derived in the analysis is representative for this type of service. The analysis showed that even utilising 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 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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REPORT 395-3

RADIOCOMMUNICATIONS FOR METEOROLOGICAL SATELLITE SYSTEMS

(1963 - 1966 - 1970 - 1974 - 1978)

1. Introduction

The Radio Regulations define the Meteorological Satellite Services as an Earth exploration satellite service for meteorological purposes. In the past, the United States has launched near-Earth orbiting experimental and operational meteorological satellites, and more recently has expanded its meteorological satellite systems to include geostationary satellites.

Projects involving geostationary meteorological satellites are also in progress in Europe (under the auspices of the European Space Agency (ESA)), in Japan and in the U.S.S.R.

In addition to their specific purposes, these geostationary meteorological satellites will contribute to the World Meteorological Organization's (WMO) World Weather Watch (WWW) Programme, and in particular to the First GARP Global Experiment (FGGE) which should begin in 1977.

The chief use of meteorological satellite data is in weather forecasting. They are used in other ways also – in the study of climate, in hydrology and for many research purposes. Weather forecasts are predictions of the future state of the atmosphere and are based on a knowledge of its state shortly before a forecast is made. The errors in forecasts increase with the time interval between the known state and the forecast state and with the imperfections in knowledge of the initial state. Successful forecasts therefore, require observations of the atmosphere which are both detailed and up to date. The space and time scales depend on the range of the forecast; local forecasts for a few hours ahead require data on a scale of tens of kilometres for a distance of several hundred kilometres around the forecast area and with a delay of less than an hour; whereas forecasts for several days ahead require data on a scale of hundreds of kilometres covering the whole globe, but in this case a delay of several hours can be tolerated.

As a result of the experimental meteorological satellite programme, new operation sensing techniques have been developed and older methods have been refined. Technical characteristics of the present and planned US civilian meteorological satellites are given in *Radio Communications for Meteorological Satellite Systems*, GSFC X901-75-191. Characteristics of the ESA METEOSAT are given in ESA Meteorological Programme Office document MET. TN 63.75 DB-GP; and characteristics of the Japanese Geostationary Meteorological Satellite (GMS) are given in the *Proceedings of the 11th International Symposium on Space Technology and Science*, Tokyo, 1975.

2. Spectrum considerations

Satellites in the meteorological service utilize portions of the radio-frequency spectrum for passive sensors (e.g., atmospheric sounders), for telemetering data from the satellites to Earth, as well as from small data collection platforms to the satellites, and for the relaying of processed meteorological data.

2.1 *Meteorological satellite systems*

Table I summarizes US civilian meteorological and related satellite flights and functions provided and planned for the 1970-1979 period. The following sections describe these systems further.

2.1.1 *Present systems*

The improved TIROS Operational System (ITOS) and the present NIMBUS experimental spacecraft, generally make use of the lower frequency meteorological satellite service allocations. The ITOS satellites use the upper portion of band 8 (near 137 MHz) for command, tracking and narrowband telemetry functions, and band 9 (1 697 MHz) for the transmission of wideband telemetry. The NIMBUS spacecraft use these allocations for tracking and narrowband telemetry functions, but use the 149 MHz and 1700 MHz space research allocations for telecommand and wideband telemetry, respectively.

The NIMBUS system also operates with a data collection system, interrogating the data collection platforms at 466 MHz (NIMBUS 4) and receiving the platform information at 401 MHz.

The Geosynchronous Operational Environmental Satellite (GOES) operational system has been initiated recently with the launching of its prototype satellite, the Synchronous Meteorological Satellite (SMS) by the United States. These spacecraft use band 8 telemetry, tracking and command during the transfer orbit and band 9 (near 401 and 469 MHz for data collection platform receive and interrogation, near 2030 MHz for other up-links, and near 1690 MHz for other down-links) during normal operations.

2.1.2 *New systems*

Starting in 1977 and over the next few years, several new meteorological satellites will be launched. (More details are given in Annex I):

– *Geostationary meteorological satellites* will be placed in geostationary satellite orbit all around the equator, in order to achieve an almost complete Earth coverage. They will gather meteorological information from both on-board sensors (Earth imaging) and a large number of ground based Data Collection Platforms (DCP). In addition they will relay meteorological information to small earth user's stations (Dissemination mission).

- *The METEOSAT satellite* is a geostationary satellite under development by the European Space Agency for launching in autumn 1977. METEOSAT will be positioned over the equator at about 0° longitude, giving coverage of Europe, Africa and large portions of the Atlantic and Indian Oceans. The METEOSAT will use band 8 for telemetry tracking and command during the transfer orbit, and band 9 (near 402 and 469 MHz for data collection platform reports and interrogation, near 2100 MHz for other up-links and near 1685 MHz for other down-links) during normal operations.
- *A geostationary meteorological satellite (GMS)* by Japan will participate in the World Weather Watch (WWW) plan and provide coverage of East and South-East Asia, Oceania and the western half of the Pacific Ocean.
- *The U.S.S.R. geostationary meteorological satellite.*

  A description of the characteristics of the proposed system is given in § 5 of Annex I.
- *Low-orbit * meteorological satellites:* The TIROS-N Satellite, the prototype of a new series of near-Earth meteorological satellites will be launched in 1978. Because of the necessarily higher data rates involved with these meteorological systems, available frequency allocations in band 9 (near 1700 MHz) will be used for most communication functions, with the exception of the data collection system which will continue to operate in the vicinity of 400 MHz and the low-data-rate beacon system which will operate in band 8 (near 137 MHz).

2.1.3 *Advanced meteorological systems*

The advanced meteorological satellites include both operational systems (based upon the TIROS-N satellites) and experimental multidisciplinary spacecraft.

The multidisciplinary spacecraft are discussed in Report 535-1. Many of these systems will use communication systems with very high data rates and correspondingly large bandwidth requirements which are the order of 300 MHz per spacecraft. The spacecraft with very high data rate requirements will operate in band 10 for wideband telemetry transmission and the upper portion of band 9 will be used for some spacecraft with the lower data rate requirements for maintenance telemetry, command and tracking data transmission.

2.2 *Meteorological satellite sensors*

Weather data have very short-lived usefulness for operational purposes, and delivery via communication links from satellite to earth station and on to the user must be rapid. This can be achieved by multiple satellites, by frequent transmission of the essential information through the use of geostationary spacecraft, and by direct readout of data to the user.

Early meteorological systems used TV cameras to obtain images in the visible part of the spectrum which proved useful in the detection of fronts and large storm systems. Later, infra-red (IR) images were also obtained, primarily with scanning radiometers, to permit night viewing and to provide surface and cloud top temperatures. Further improvements were made in resolution to less than 1 km in both visible and IR images. These improvements increased communication bandwidth requirements. Now there are plans for 4-channel imagery on TIROS-N. Another increase in bandwidth requirements arises from continuous viewing through the use of geostationary spacecraft.

The ability to determine the vertical profile of temperature, humidity and atmospheric constituents has progressed in recent years to the point where operational spacecraft beginning with NOAA-2 now fly with an instrument (VTPR) for making measurements from which temperature and humidity profiles can be inferred. The "sounding" concepts were advanced by experiments flown on research and development spacecraft. Recently, development has focused on adding microwave channels which permit cloud penetration. Future advances in vertical and horizontal resolution, all-weather capability, and in constituent measurement are expected. In addition, sounding from geostationary orbit is expected in 1979 with the launching of GOES-D. In general, data rates from "sounders" are comparatively low, and direct readout to users has been provided beginning with the launching of ITOS-F (NOAA-3) in November 1973.

Radar is used extensively by aviation and weather forecasting services for the detection of three-dimensional precipitation patterns. The combination of precipitation information with cloud pictures is of inestimable value. Radar not only detects precipitation in itself, but also permits an estimate of intensity, volume, freezing level, and the extent of vertical convection etc.

Thunderstorms and their frequently associated ancillaries, such as hail, turbulence, precipitation, strong winds, etc., represent severe weather hazards to life and property and are especially important in aircraft operations. At the present time, radar and ground-based detection networks for atmospheric lightning discharges (sferics) provide meteorologists with the location and movement of thunderstorms over only a small fraction of the surface of the Earth. These observations have proved most valuable in weather analysis and forecasting.

* See Report 458-1 for the definition.

Potentially, satellites provide the means by which observations of thunderstorm activity can be obtained on a global basis. In addition, a sferic sensor aboard a meteorological satellite is probably the most economical method of extending the sferics network to a global basis. Supporting studies have been made to determine the feasibility of a satellite sferics sensor. Results from these studies are encouraging.

The collection of scientific, meteorological and other environmental data from fixed or mobile data sources by a satellite, provides important inputs into the weather prediction and other environmental prediction and warning processes. Several systems have been developed or are under development and are referred to in Report 692.

TABLE I – *US Civilian meteorological and related satellite flights and functions, 1970–1979*

Satellite	Purpose(1)	Launch date	Orbit	Instruments and functions(2)	Remarks
NIMBUS-4	R	8. 4.70	Sun Synch. 1100 km	IDCS, THIR, IRIS, SIRS, SCR, FWS, IRLS, BUV, MUSE	BUV, MUSE still operating
NOAA-2 (ITOS-D)	O	15.10.72	Sun Synch. 1450 km	2 SR, 2 VHRR, 2 VTPR, SPM	
NIMBUS-5	R	12.12.72	Sun Synch. 1100 km	THIR, ESMR, ITPR, SCR, NEMS, SCMR	SCMR not operable
NOAA-3 (ITOS-F)	O	6.11.73	Sun Synch. 1450 km	2 SR, 2 VHRR, 2 VTPR, SPM	Operational/ standby
SMS-1	R/O	17. 5.74	Geostationary 35 790 km	VISSR, DCDR, SEM	Located 75°W long.
ATS-6	R	30. 5.74	Geostationary 34 790 km	GVHRR, etc.	GVHRR failed 8.15.74
NOAA-4 (ITOS-G)	O	15.11.74	Sun Synch. 1450 km	2 SR, 2 VHRR, 2 VTPR, SPM	Operational
SMS-2	R/O	4. 2.75	Geostationary 35 790 km	VISSR, DCDR, SEM	Located 135°W long.
NIMBUS-6	R	12. 6.75	Sun Synch. 1100 km	THIR, ESMR, TWERLE, HIRS, SCAMS, LRIR, PMR, ERB, TDRE	
GOES-A (SMS-C)	O	16.10.75	Geostationary 35 790 km	VISSR, DCDR, SEM	Located 49°W long.
GOES-B (SMS-D)	O	.12.76	Geostationary 35 790 km	VISSR, DCDR, SEM	
GOES-C	O	. 5.77	Geostationary 35 790 km	VISSR, DCDR, SEM	
ITOS-H	O	29. 7.76	Sun Synch. 1450 km	2 SR, 2 VHRR, 2 VTPR, SPM	
TIROS-N	R/O	.78	Sun Synch.	AVHRR, SEM, SSU, MSU, BSU, DCS	
ITOS-I	O	.78	Sun Synch.	2 SR, 2 VHRR, 2 VTPR, SPM	
NIMBUS-G	R	.78	Sun Synch.	SMMR, SAMS, LIMS, SBUV/ TOMS, ERB, THIR, CZCS, SAM II	
SEASAT	R	.78		SAR, ALT, MWS, SR	
TIROS-N OPERATIONAL	O	.78	Sun Synch.	AVHRR, SEM, SSU, KSU, BSU, DCS	
FOLLOW-ON A AEM-B	R	4.79		SAGE	
GOES-D	O	.79	Geostationary 35 790 km	VAS, DCDR, SEM	
TIROS-N OPERATIONAL	O	.79	Sun Synch.	AVHRR, SEM, SSU, MSU, BSU, DCS	
FOLLOW ON B GOES-E	O	.80	Geostationary 35 790 km	VAS, DCDR, SEM	

(1) R: Research O: Operational R/O: Operational prototype

(2) See acronyms

2.2.1 *Passive microwave sensors*

The properties of the atmosphere in the microwave region have not yet been fully applied. Intensive research is being conducted to enable application of the microwave emissions and absorption lines to the measurement of atmospheric phenomena. However, it is necessary to know that no measurable interference exists at the absorption lines of interest so that the measurements are not distorted. Although several bands are allocated to space research (passive), namely, 52 to 54.25, 58.2 to 59, 64 to 65, 86 to 92, 101 to 102, 130 to 140, 182 to 185 and 230 to 240 GHz, experiments are being planned and conducted in other parts of the spectrum; such frequencies include: 4.99, 6.6, 10.69, 18, 19.35, 21.5, 22.2, 31.4, 37 GHz; many lines in the 50 to 70 GHz region, 118 GHz, and other lines above 100 GHz.

NIMBUS-5 was the first meteorological satellite to fly microwave sensors which demonstrated the utility of such instruments to sound the atmosphere through clouds, determine rain rates, etc. Numerous other passive microwave sensors are being built or planned. Sharing criteria for such sensors are given in Report 693.

2.2.2 *Active microwave sensors*

Although ground radar has been used extensively in meteorology, no active microwave instrument has yet been flown for this purpose. SKYLAB was the first spacecraft to fly an active microwave sensor; it used a frequency of 13.9 GHz. A meteorological radar in the 10 GHz region is being studied for use on a shuttle sortie mission.

It should be noted that at present the only allocations for active microwave sensors are at 34.4 to 34.5 GHz, and 9.975 to 10.025 GHz (RR401A); where weather radar on meteorological satellites is permitted. It is necessary to determine where active bands are needed and to resolve possible conflicts between active and passive sensors. Table I summarises active instrument efforts for meteorological and related spacecraft. Sharing criteria for such sensors are given in Report 693.

3. Conclusions

Much progress has been made in meeting the frequency allocation needs of meteorological satellite systems. As these systems continue to evolve, a continuing reassessment of the spectrum requirements for this important service must be made, especially for multidisciplinary and research efforts with operational potential and for microwave sensing requirements.

LIST OF ACRONYMS

AAFE	Advanced Applications Flight Experiments
AEM	Applications Explorer Mission
ALT	Radar Altimeter
APT	Automatic Picture Transmission
ATS	Applications Technology Satellite
AVCS	Advanced Vidicon Camera System
AVHRR	Advanced Very High Resolution Radiometer
BSU	Basic Sounding Unit
BUV	Backscatter Ultraviolet Spectrometer
CZCS	Coastal Zone Colour Scanner
DCDR	Data Collection and Data Relay
DCP	Data Collection Platform
DCS	Data Collection System
ERB	Earth Radiation Budget
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer
FGGE	First GARP Global Experiment
FPR	Flat Plate Radiometer
FWS	Filter Wedge Spectrometer
GARP	Global Atmospheric Research Programme
GMS	Geostationary Meterological Satellite
GOES	Geosynchronous Operational Environmental Satellite
GVHRR	Geosynchronous Very High Resolution Radiometer
HIRS	High Resolution Infrared Sounder

IDCS	Image Dissector Camera System
IR	Infra-red
IRIS	Infra-red Interferometer/Spectrometer
IRLS	Interrogation, Recording and Location System
ITOS	Improved TIROS Operational System
ITPR	Infra-red Temperature Profile Radiometer
LIMS	Limb Infra-red Measurements in the Stratosphere
LRIR	Limb Radiance Inversion Radiometer
MAPS	Measurement of Air Pollution from Satellites
MSU	Microwave Sounding Unit
MUSE	Monitor of Ultra Violet Solar Energy
MWS	Microwave Scatterometer
NEMS	Microwave Spectrometer
NOAA	National Oceanic Atmospheric Administration
PMR	Pressure Modulated Radiometer
SAGE	Stratospheric Aerosol and Gas Experiment
SAM II	Stratospheric Aerosol Measurement
SAMS	Stratospheric and Mesospheric Sounder
SAR	Synthetic Aperture Radar
SBUV/TOMS	Solar Backscatter Ultraviolet/Total O_3 Mapper System
SCAMS	Scanning Microwave Spectrometer
SCR	Selective Chopper Radiometer
SEM	Space Environment Monitor
SIRS	Satellite Infra-red Spectrometer
SMMR	Scanning Multichannel Microwave Radiometer
SMS	Synchronous Meteorological Satellite
SPM	Solar Proton Monitor
SR	Scanning Radiometer
SSU	Stratospheric Sounding Unit
TDRE	Tracking and Data Relay Experiment
THIR	Temperature / Humidity Infra-red Radiometer
TIROS	Television Infra-red Observational Satellite
TOS	TIROS Operational Satellite
TOVS	TIROS Operational Vertical Sounder
TWERLE	Tropical Wind, Energy Conversion, Reference Level Experiment
VAS	VISSR Atmospheric Sounder
VHRR	Very High Resolution Radiometer
VISSR	Visual Infra-red Spin-Scan Radiometer
VTPR	Vertical Temperature Profile Radiometer
WEFAX	Weather Facsimile
WMO	World Meteorological Organization
WWW	World Weather Watch

ANNEX I

METEOROLOGICAL SATELLITE SYSTEMS

1. Introduction

The purpose of this Annex is to provide brief descriptions of the operational and proposed meteorological satellite systems. The characteristics of such systems are more fully described in the main text of this Report.

2. Synchronous Meteorological Satellites (SMS)

The SMS is the first in a series of spacecraft which will comprise the eventual GOES system. Initially, SMS-1 was positioned in geostationary orbit over the eastern Atlantic to support the GARP Atlantic Tropical Experiment in the summer of 1974. It was later moved to its present position at 75° W longitude. This satellite,

together with SMS-2 positioned at 135° W longitude provides coverage of much of the western hemisphere. SMS has picture taking and communication functions on an operational basis that previously were available only experimentally. Growing out of concepts proven in the SYNCOM and ATS programmes, SMS yields new and improved data for weather prediction, environmental sensing and timely warning of hazardous environmental conditions.

SMS was conceived as a multifunction spacecraft with a high resolution radiometer responsive in both the visible and infra-red (IR) bands as its prime subsystem. In addition, it carries a high power transmitter for disseminating the radiometer video. A communications transponder is also on board which allows the relay of facsimile charts and the received visual and IR video data to weather stations in remote areas, and serves as a repeater for signals transmitted from a large number of inexpensive, low-power, known-location, environmental data collection platforms (DCP). Some of these platforms report data on a synoptic basis while others report only in the event of emergencies, such as flood stage or earthquake. As usual with multifunctional satellites, SMS was required to have band 8 telemetry and command equipment (separate from and in addition to the communications transponder). In addition to transmitting spacecraft maintenance telemetry, the telemetry system is used to transmit the output of the Space Environment Monitor (SEM), an instrument package to measure radiation and magnetic fields in space. Finally, a method for determining the subsatellite point in real time is necessary in order to overlay a highly accurate latitude and longitude grid on the cloud cover pictures. The SMS/GOES frequency utilization and salient transponder characteristics are shown in Table II and Table III respectively.

TABLE II – *SMS/GOES frequency assignments*

Up-link	Centre frequency	Transponder (3 dB bandwidth)
DCP Reports	401.900 MHz	400 kHz
Stretched VISSR / WEFAX	2030.100 MHz(1)	8.2 MHz
Ranging	2029.100 MHz	
DCP Interrogation	2034.925 MHz	200 kHz
S/C Command	2034.200 MHz	60 kHz
Down-link	**Centre frequency**	**Transponder (3 dB bandwidth)**
DCP Interrogation	468.850 MHz	200 kHz
VISSR Data	1681.600 MHz	23.2 MHz
Stretched VISSR / WEFAX	1688.100 MHz(1)	8.2 MHz
Ranging	1687.100 MHz	
DCP Reports	1694.500 MHz	400 kHz
Telemetry	1694.000 MHz	200 kHz

(1) Stretched VISSR, WEFAX and Ranging lie within the 8.2 MHz bandwidth.

2.1 *The TIROS-N Satellite*

The prototype of a new series of near-Earth meteorological satellites will be launched in 1978. Because of the necessarily higher data rates involved with these meteorological systems, available frequency allocations in band 9 (near 1700 MHz) will be used for most communication functions, with the exception of the data collection system which will continue to operate in the vicinity of 400 MHz and the low-data-rate beacon systems which will operate in band 8 (near 137 MHz).

In addition, some departures from present frequencies will be made in the NIMBUS-G and the GOES-D and following spacecraft due to the deletion of the band 8 ranging, telemetry and command functions, at the NASA ground stations. These functions will utilize the upper part of band 9.

TABLE III – *Salient characteristics of the SMS/GOES transponders*

	Upper band 9	Lower band 9
Transmitter power (W)	20	10/40
Transmit antenna gain (dB) (with losses, on beam centre)	15.7	7.4
Receive antenna gain (dB) (with losses, on beam centre)	9.2	4.4
Receiver noise temperature (K)	1630 (mixer)	385 (transistor)
Antenna design	Switched phased array	Switched dipoles
Antenna polarization	Linear	Right-hand circular
Receive frequency (MHz)	2030 ± 5	401.9 ± 0.2
Transmit frequency (MHz)	1681.6(1)	468.825 ± 0.75

(1) 14 Mbit/s sin X/X.

2.2 *Advanced meteorological systems*

The advanced meteorological satellites include both operational systems (based upon the TIROS-N satellites) and experimental multidisciplinary spacecraft.

The multidisciplinary spacecraft are discussed in Report 535-1. Many of these systems will use communication systems with very high data rates and correspondingly large bandwidth requirements (i.e., of the order of 300 MHz per spacecraft). The spacecraft with very high data rate requirements will operate in band 10 for wideband telemetry transmission. The upper portion of band 9 will be used for certain spacecraft with lower data rate requirements and for maintenance telemetry, command and tracking transmission.

3. METEOSAT

The METEOSAT system, under development by the European Space Agency (ESA), includes a geostationary meteorological satellite and all the associated ground facilities for communications between satellite and ground for operational control of the system and for data retrieval and processing. METEOSAT will be the European contribution to the WMO World Weather Watch programme, and in particular will participate in the Global Atmospheric Research Programme (GARP).

The main functions of METEOSAT are, Earth imaging in both the visible and the infra-red, dissemination of cloud pictures or other meteorological data to Data User Stations, and collection of environmental data from remote *in-situ* data collection platforms. METEOSAT will be a spin stabilized satellite rotating at 100 rpm. The launching of the first flight model is scheduled for autumn 1977.

The satellite will carry the following payload:

3.1 *The Earth Viewing Sub-system* which consists of a 3 channel radiometer for imaging at the Earth's surface and cloud systems both in the visible and infra-red regions, and equipment for image data handling and synchronization.

3.2 *The Data Transmission and Relay Sub-system for:*

- transmission of the image data to the Data Acquisition, Telecommand and Tracking Stations (DATTS) located in the Odenwald, Federal Republic of Germany;
- relay to Data User Stations of cloud cover pictures or other Meteorological data (Meteorological Data Dissemination);
- relay of local environmental data from remote Data Collection Platforms (DCPs);
- relay of interrogation commands to DCPs;
- reception of satellite housekeeping commands and transmission of housekeeping telemetry;
- relay of ranging signals for satellite orbit determination.

The main characteristics of the METEOSAT data transmission and relay subsystem are given in Table IV and Table V.

TABLE IV – *METEOSAT frequency assignments*

Up-links	Centre frequency (MHz)	Transponder 3 dB bandwidth (Signal Bandwidth) in parenthesis (kHz)
HK telecommand and ranging (Transfer orbit + back-up synch. orbit)	149.34	
DCP reports	402.1	250 (200)
DCP interrogation: international(1) or domestic(1)	2098	100 (30)
HK telecommand (synch. orbit)(1)	2098	100 (30)
Picture dissemination or ranging(2)	2101.5	1000 (660)
(Two interchangeable channels)	2105	1000 (660)
Down-links		
HK telemetry and ranging (Transfer orbit + back-up synch. orbit)	137.08	
DCP interrogation international(1) or domestic(1)	468.900	100
DCP reports	1675.281	250 (200)
HK telemetry (synch. orbit)	1675.929	50 (30)
Raw-picture data: (normal) stretched mode	1686.833	1000 (660)
real-time (back-up)	1686.833	6000 (5400)
Picture dissemination or ranging(2)	1691	1000 (660)
(Two interchangeable channels)	1694.5	1000 (660)

(1) The same channel is used in time sharing for the purpose of HK telecommand, or interrogation of the international or domestic DCP's.

(2) Two identical channels, both used in time sharing for the purposes of WEFAX dissemination, or high resolution picture dissemination, or ranging.

TABLE V – *Salient characteristics of the METEOSAT transponder*

	Band 9	
	Upper	Lower
Transmitter power (Watts)	10 × 2 (two channels)	20
Transmit antenna gain (dBi) (including losses, coverage's edge)	11	0
Receive antenna gain (dBi) (including losses, coverage's edge)	2.1	0
Receiver noise temperature (K)	750 (transistor)	660 (transistor)
Antenna design	*Transmision:* directional, electronically de-spun *Reception:* omnidirectional (toroïdal)	Omnidirectional (toroïdal)
Antenna polarization	Linear	Right-hand circular
Receive frequencies (MHz)	2098 2098 ± 0.025 2101.5 2105	402.1 ± 0.1
Transmit frequencies (MHz)	1675.281 1675.929 1686.833 1691 1694.5	468.875 468.925

4. Japanese Geostationary Meteorological Satellite (GMS)

4.1 *GMS programme*

The GMS was launched by Japan in July 1977 for participation in the World Weather Watch (WWW) plan, and in particular in the First GARP Global Experiment (FGGE) which will be conducted from 1977 to 1979. It is stationed at 140° E longitude, and covers East and Southeast Asia, Oceania and the western half of the Pacific Ocean.

The GMS will perform four missions: imaging of the Earth with a visible and infra-red, spin scan radiometer (VISSR) in both visible and infra-red spectra; dissemination of cloud pictures and other meteorological information, collecting of meteorological and oceanographic data from observation platforms (DCP) and monitoring of solar protons, alpha-particles and electrons.

4.2 *Meteorological sensors*

The characteristics of VISSR are summarized in Table VI.

TABLE VI – *Characteristics of VISSR*

Characteristics	Detector	
	Visible	Infrared
Wavelength (micrometers)	0.5 to 0.75	10.2 to 12.8
Instantaneous field of view (micro-radians X micro-radians)	35 X 31	140 X 140
Resolution (km)	1.25	5
Scan lines per frame	2500 X 4	2500

4.3 *Telecommunication system*

The characteristics of telecommunication system are listed in Table VII (up link) and Table VIII (down link).

5. Soviet Geostationary Operational Meteorological Satellite (GOMS)

5.1 *GOMS programme*

GOMS is being developed by the U.S.S.R. to assess the efficiency with which the information supplied by a satellite on a geostationary orbit is used in weather forecasting and also for activities connected with the Global Observing System of World Weather Watch.

It is proposed to launch the satellite on a geostationary orbit at a point located at 70° E. The satellite's service area will be the territory of the U.S.S.R., Central Asia, the Indian subcontinent and the Indian Ocean.

GOMS will be used for:

- obtaining Earth images in the visible and infra-red parts of the spectrum using a two-channel radiometer;
- relaying of cloud photographs and other meteorological information to autonomous data receiving points;
- relaying of meteorological and oceanographic data from automatic weather reporting equipment;
- measuring of charged particle streams in a wide energy range.

5.2 *Measuring equipment*

The main characteristics of the radiometer and the repeater are given in Tables IX and X respectively.

TABLE VII – *Telecommunication system of up-link*

Function	Centre Frequency (MHz)	RF Bandwidth (MHz)	Transmitter power (W)	Modulation
DCP report	402.2	0.4(1)	10	PCM-PSK
Facsimile				
High resolution	2029.1	1	1000	FM-FM
Low resolution	2033.0	0.026 or 0.26	100	AM-FM
Ranging	2026.0	2	1000	AM-PM
Ranging	2030.2	2	100	AM-PM
Ranging	2032.2	2	100	AM-PM
DCP interrogation	2034.9	0.2(2)	5	PCM-PSK
Command	2034.2	0.02	5	PCM-FSK-AM-PM
Command	149.7	0.02	4000	AM-PM

(1) 133 channels
(2) 33 channels

TABLE VIII – *Telecommunication system of down-link*

Function	Centre Frequency (MHz)	RF Bandwidth (MHz)	Transmitter power (W)	Modulation
DCP Interrogation	468.8	0.2(1)	6	PCM-PSK
VISSR data transmission	1681.6	20	20	PCM-4 Φ PSK
Facsimile				
High resolution	1687.1	1	5 or 20	FM-FM
Low resolution	1691.0	0.026 or 0.26	5 or 20	AM-FM
Ranging	1684.0	2	20	AM-PM
Ranging	1688.2	2	0.02	AM-PM
Ranging	1690.2	2	0.02	AM-PM
DCP Report	1694.5	0.4(2)	0.2	PCM-PSK
Telemetry	1694.0	0.2	0.6	PCM-PSK-FM-PM
Telemetry	136.89	0.085	8	PCM-PSK-FM-PM

(1) 33 channels
(2) 133 channels

TABLE IX – *Characteristics of radiometer*

Range designation	Visible	Infrared
Wave length (micrometer)	0.4-0.7	10.5-12.5
Instantaneous viewing field (microradians)	8 beam – 39 X 39	312 X 312
Resolution (km)	1-2	15
Scanning lines per frame	8100	1012

TABLE X – *Characteristics of satellite repeater*

Purpose of link	Frequency (MHz)	RF bandwidth	Transmitter power (W)	Modulation	Receiver sensitivity (dBW)
1. Interrogation of automatic weather recording equipment	468.825 MHz (National) 468.875 MHz (International)	6 kHz 6 kHz	5 5	PSK PSK	– –
2. Reception of data from weather recording equipment	402.0-402.1 (International) 401.7-402.0 (National)	3 kHz X 33 channels 9 kHz X 33 channels	– –	PSK PSK	–158 (in 3 kHz band)
3. Transmission of data collected from automatic weather recording equipment to data receiving points	1697.0-1697.1 (International) 1696.7-1697.0 (National)	3 kHz X 33 channels 9 kHz X 33 channels	1.5	PSK PSK	– –
4. Reception of facsimile information and interrogation of automatic weather recording equipment for relaying	2116.0 (International) 2117.0 (National) 2118.875 (International) 2118.825 (National)	30 kHz 30 kHz 6 kHz 6 kHz	– – – –	AM-FM AM-FM PSK PSK	 –128 (in 10 MHz band)
5. Transmission of facsimile information to data receiving points	1691.0 (International) 1692.0 (National)	30 kHz 30 kHz	10	AM-FM AM-FM	– –
6. Transmission of television information to data receiving points	1685.0	8 MHz	10	PSK	–

REPORT 541-1

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)

(1974 - 1978)

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 the Geostationary Operational Environmental Satellite (GOES) system under development by the United States and the METEOSAT system, under development by the European Space Agency. These systems will have communication links in the region of 400 MHz and in the upper part of band 9. Typical system transmitters, receivers and antenna characteristics that are relevant to an interference analysis for band 9 are shown in Tables I, II, III and IV.

The systems will also 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 V-A. 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 V-B.

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 co-ordinated and usually occur near 0000, 0600, 1200 and 1800 UT. 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 unstabilised 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 polarised. 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 radiosonde transmission. Table VI summarises 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 VII) somewhat different from those in Table VI 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 at the meteorological satellite receiver in the region of 400 MHz;
- radiosonde transmissions interfering with reception at the meteorological satellite in the region of 400 MHz;
- radiosonde transmissions interfering with reception at 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.

2.1 *Radiotheodolite transmission interfering with reception of 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 orbit is assumed). System parameters and hence the interfering power at the satellite are listed in Table VIII. This value of -154.4 dBW would be greater than the available signal level from either the DCP or the buoy, as shown in Table V. The typical signal levels from a DCP could be significantly less than the interfering theodolite signal.

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 co-ordination of frequency assignments may be necessary in operational systems within a shared band.

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 polarisation 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.

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 IX. 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 antennae such that the ratio of antenna diameter to the wavelength exceeds 100, the CCIR reference pattern ** 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.

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 X presents the computed maximum allowable interfering signal level for meteorological aids operation, using the minimum desired signal level approach to determining the maximum permissible level of interference. 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.

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* Although it is a gross assumption, the power is assumed to be equally distributed across the 1 MHz band.

** See Report 391-3.

2.6.2 *Probability of interference between the two systems*

The probability that the flux-density from a synchronous meteorological satellite would exceed the interference threshold has been analysed and summarised 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.

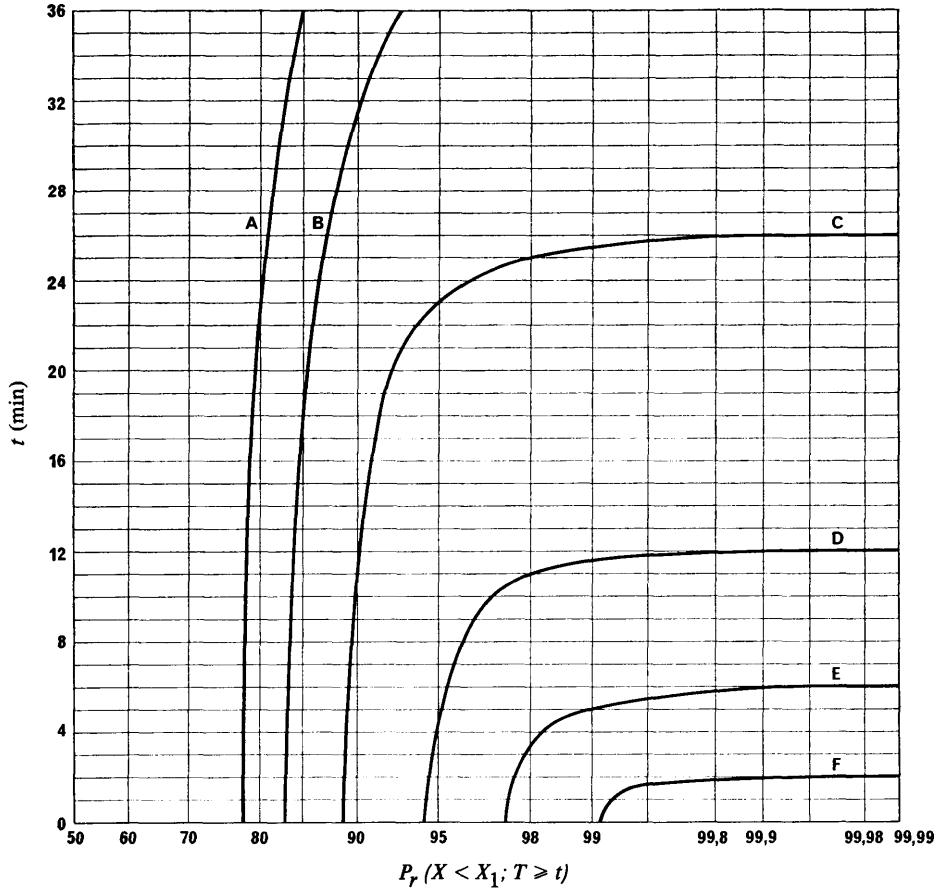

FIGURE 1 – *Probability that interference at the radiotheodolite receiver does not equal or exceed the maximum allowable interference for ⩾ t minutes*

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

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. Fig. 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.

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:

- co-ordination of frequency assignments;
- geographical separation.

It is noted that both systems would be operated by meteorological organisations 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/m^2) 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:

- co-ordination 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 co-ordination with radiosonde operations will depend upon the type of earth station and antenna discrimination available;
- co-ordination on the distance between radiosonde operations and satellite earth stations (the actual co-ordination distance will depend upon the type of earth station and antenna discrimination available).

REFERENCE

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TABLE I – *Characteristics of GOES satellite system which are pertinent to frequency sharing in the upper portion of band 9*

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/m^2))
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	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*

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	G_r (dB)	T_s (K)	Noise bandwidth
Meteorological satellite			
(Disseminated and ranging data)	3	750	1000 kHz
(HK telecommand)			200 kHz
(DCP interrogation)			200 kHz
DATTS			
(Picture data)	45	115	25 kHz
(DCP reports)			
(HK telemetry)			
(Ranging data)			
PDUS	35	250	1000 kHz
SDUS	30	560	50 kHz
LBT	30	250	1000 kHz

TABLE V – *Characteristics of meteorological satellite system in the region of 400 MHz*

TABLE V-A

Data collection platform (land-based) characteristics (for satellite elevation angles <45°)	GOES (Typical)	METEOSAT (Typical)
Transmitter power (dBW)	7	7
Feed loss (dB)	0·5	0·5
Antenna gain (dB)	10	10
Path loss (free space) (dB)	177	177
Polarization loss (dB)	0·2	1
Satellite antenna gain (dB)	7·3	0·5
Feed loss (dB)	2·9	1·4
Receiver power (dBW)	−156·3	−162·4

TABLE V-B

Satellite receiver characteristics	GOES	METEOSAT
Centre frequency (MHz)	401·9	402·1
Bandwidth (kHz)	400	200
Antenna gain (dB) (including feed losses)	4·4	0
Noise temperature (K)	385	600

TABLE VI – *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 VII – *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

TABLE VIII – *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

TABLE IX – *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

TABLE X – *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

ANNEX I

FREQUENCY SHARING OF THE UPPER BAND 9 BETWEEN RADIOSONDES AND THE METEOSAT DOWNLINK TRANSMISSIONS

1. Introduction

After more detailed studies, and in the light of the advanced systems definition of the METEOSAT meteorological satellite *, 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 will ensure 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 (0850E, 494ON). Besides its Earth-to-space transmission functions, which are not considered in the present Annex, DATTS will receive 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.

The nominal received signals, carrier frequencies and power flux-densities are summarised in Table XI.

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* The METEOSAT system is described in Report 395-3.

** DATTS: Data acquisition, telecommand and tracking station
PDUS : Primary data user station
SDUS : Secondary data user station

TABLE XI

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 XII.

TABLE XII

Type of sonde	Transmitter output power (W)	Antenna gain (dB)	Emission
Non-ranging	0.25 to 1	0	15F9
Ranging	0.25 to 1	0	400F9 to 1000F9

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 GMT.

3. Co-ordination requirements

The basic criteria for the interference study is a bit error rate 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.

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 1770 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.

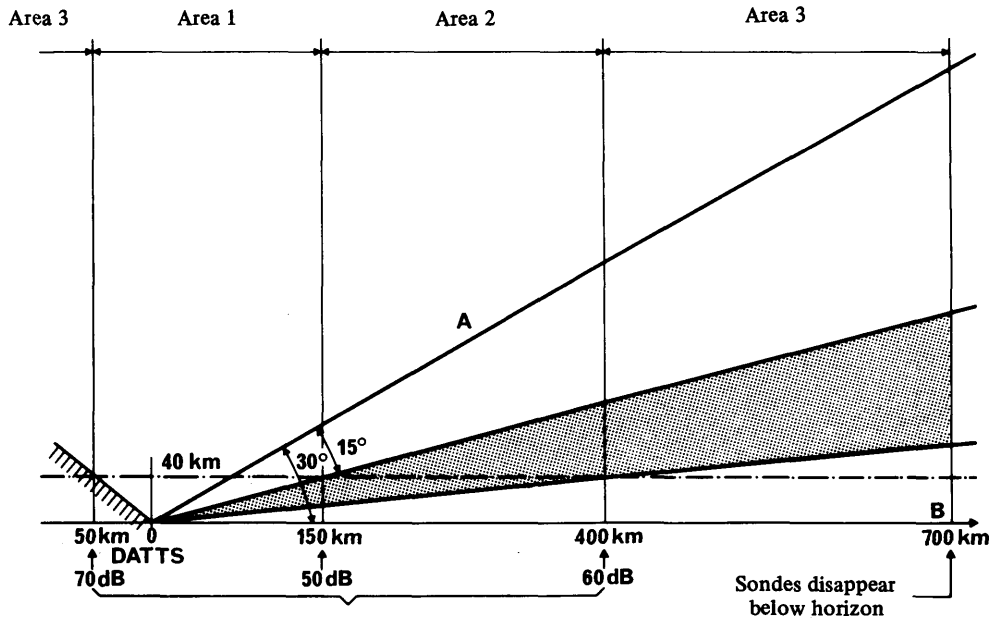

FIGURE 2 – *Co-ordination areas for METOSAT DATTS*

A : Elevation of antenna main beam

B : Satellite azimuth

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 co-ordination 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.

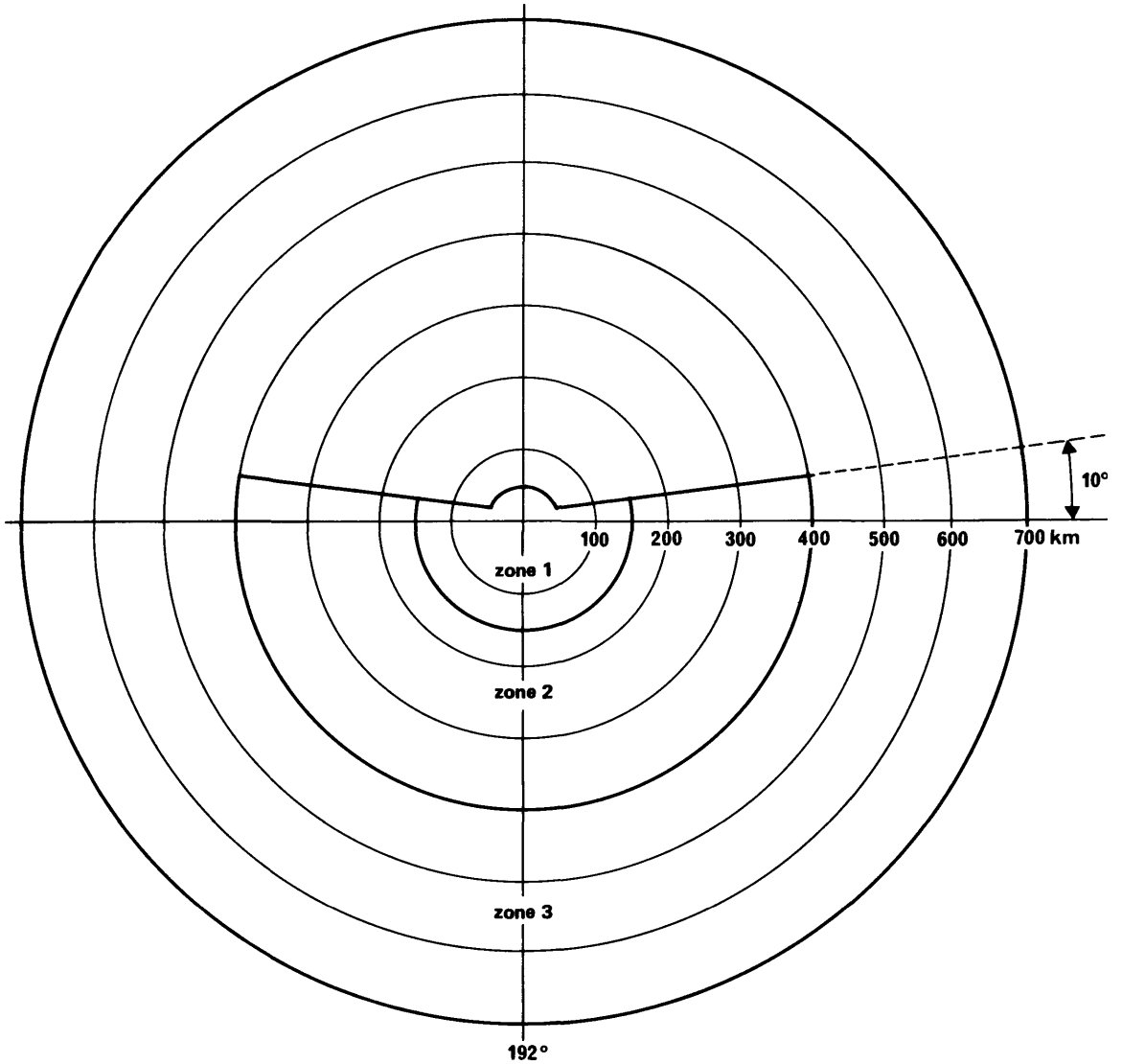

FIGURE 3 – *Co-ordination areas for METEOSAT DATTS*

4. Conclusion

The above interference study leads to the conclusion that sharing of the upper band 9 between the "meteorological aids service" and the "meteorological satellites service" is feasible provided that:

- close frequency co-ordination is effected between the two services;
- radiosonde e.i.r.p. is limited in co-ordination 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 co-ordination 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).

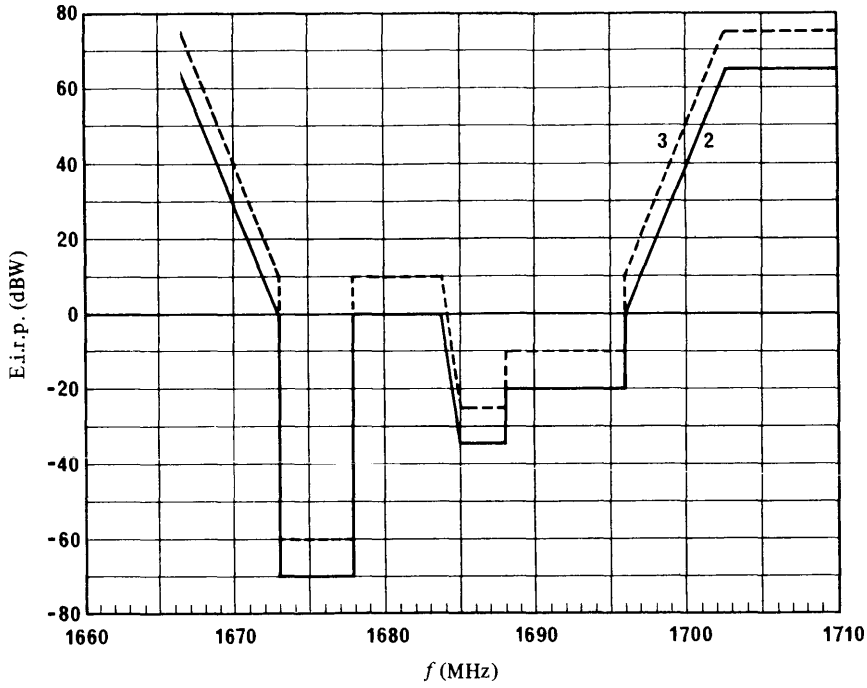

FIGURE 4 – *Maximum radiosonde e.i.r.p. towards DATTS*

——— Area 2

– – – – Area 3

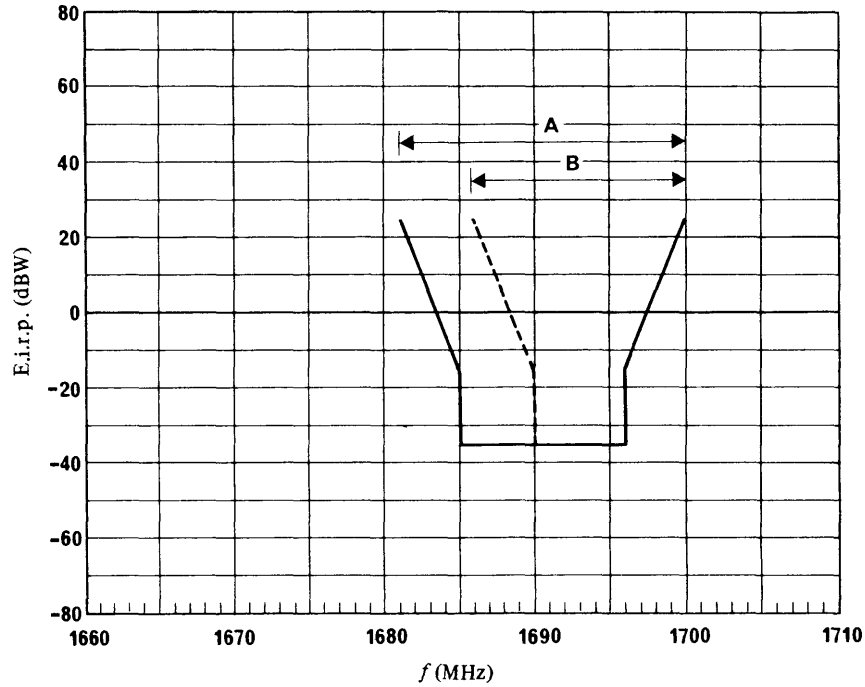

FIGURE 5 – *Maximum radiosonde e.i.r.p. towards data user stations*

Assumptions:
- CCIR standard antenna diagram following Recommendation 465-1
- Radiosonde outside main antenna beam
- Distance greater than 150 km

A: PDUS Protection

B : SDUS Protection

RECOMMENDATION 362-1

FREQUENCIES TECHNICALLY SUITABLE FOR METEOROLOGICAL SATELLITES

(Question 12-2/2 and Study Programme 12C/2)

(1963 - 1970)

The CCIR,

CONSIDERING

(a) that meteorological satellites have demonstrated their value to mankind;

(b) that some meteorological satellites are operating in a routine manner as indicated in Report 395-3;

(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 as meteorological satellites become more fully developed, and taking due account of reliability requirements and economical use of the frequency spectrum, frequencies within the bands used for meteorological satellites will be technically suitable for tracking, maintenance telemetry and telecommand;

3. 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 538-1

EARTH EXPLORATION SATELLITES

Satellites for location of earth stations and for data collection

(1974 - 1978)

1. Introduction

The development of space systems for data collection and location missions has shown that scientific, technical and industrial requirements can be satisfactorily met by systems using low-altitude satellites.

In 1971, an extensive survey of possible users in France indicated that the range of performances needed would require the coexistence of several systems with complementary characteristics. The implementation of two projects, one under development and the other in the feasibility study stage, and both using non-synchronous satellites with global coverage, could cover practically all the requirements brought to light by the survey. In both projects, the aim is to collect the results of measurements carried out at sites all over the world and to deliver them to central stations. Provision is also made for regional or local operation.

The characteristics of the two systems are determined by the missions they perform. The purpose of the first (ARGOS), whose space segment is carried on the United States satellite (TIROS), is to meet the need for comparatively large-scale data collection while locating with moderate precision (of the order of 5 km) the airborne, terrestrial or maritime platforms from which the data originate. The highly ambitious objectives of the second are to locate points on land or at sea with a precision of the order of 10 m on one satellite pass and, by processing the data accumulated over 24 hours, to locate points to within approximately 1 m. In the latter system, named "GEOLE", the collection of data is largely a question of acquiring service data to facilitate operation of the system and achievement of the desired precision.

Annex I analyses in some detail the principles of precise location systems. A brief description of the two projects is given in § 3 and in Annexes II (ARGOS) and III (GEOLE). In addition, an overview of the data collection and location system programmes being conducted by the United States is given in Annex IV.

2. Application of data collection and location satellites

2.1 *Need for a data-collection system with medium-precision location capacity*

The project to implement the first of the two systems mentioned in the previous section involves two tasks which must sometimes be carried out simultaneously:

- the location of the points measured to 5 km or better;
- the collection of data obtained locally by sensors installed at automatic measuring stations on land, at sea or in the air.

These two tasks correspond to the requirements identified during the survey carried out in 1971 (see § 1) which, although emanating from widely differing fields of activity, are sufficiently coherent to permit the identification of a set of characteristics for a group of users.

Table I shows the fields of application and the performance characteristics required by this group of users. So far as performance is concerned, the users listed in this table have moderate requirements so that it should be possible to meet them by means of a system combining a satellite with comparatively inexpensive, simple and robust platforms. These requirements have largely determined the selection of the technical characteristics of the system.

2.2 *Need for a high-precision location system*

The survey conducted in France in 1971 (see § 1) has identified those activities requiring precise location of points on the surface of the Earth with high precision.

Tables II and III describe these activities and give the performance required of them.

Another survey was carried out by France in all parts of the world in 1974 to estimate the volume of world requirements which might be met by the use of non-synchronous satellites by 1980-1990:

- for geodesic points on the Earth: 4000 to 8000 points per year
- for survey ships, oceanographic vessels and oil and mineral prospecting ships: 400 ships.

3. Principles of location and data-collection systems

3.1 *General*

The systems considered, aim at very different classes of performance, and this is not without a direct effect on the choice of principles to be applied in any particular case. Users will naturally expect that lower performance of a system by comparison with another will be reflected in a lower cost of acquiring the requisite equipment.

The needs for medium-precision location listed in Table I therefore have to be met by a satellite system associated with simple and sturdy low-cost earth stations. In view of the need for simplification, it is envisaged that the location system will be based on a one-way Doppler-shift measurement (station to satellite). The satellite receives, on a random access basis from the earth stations, modulated signals carrying data messages, while the Doppler measurement required for the location is made on the carrier.

On the other hand, in the high precision location system nothing is spared to ensure the highest possible precision. Here, the operating cost is likely to be high and must be carefully compared with the cost of alternative existing methods of achieving the objectives.

3.2 *Design of a data-collection system with medium-precision location capability (ARGOS)*

To fulfil all the prospective missions for the various users, the system must be designed to work with inexpensive – and therefore simple – platforms, which must however be reliable in view of the sometimes difficult environmental conditions in which they will be called upon to operate. The variety of applications calls for a platform design of great flexibility. From this point of view, the tasks which cannot be carried out by a geostationary satellite on account of its orbit, i.e. data collection in the polar zones and accuracy of location, present no particular difficulty.

3.2.1 *Principle of operation* (Fig. 1)

As already stated, in view of the need for simplification, it is envisaged that the location system will be based on a "one-way" Doppler-shift measurement (platform to satellite).

The chain operates as follows:

A platform continuously emits a signal of duration t, with a repetition period of T. The message consists of a pure carrier portion that is sufficiently stable for an accurate frequency measurement to be made on board the satellite and a modulated portion comprising the platform recognition signals and a number of measurement data. The platforms emit the various messages independently of the satellite, and hence, independently of each other, they arrive at the receiver in random order. In particular, several signals may be present together in the reception chain. The receiver therefore contains several processing channels (Fig. 2) to permit simultaneous processing of several platforms, and also a spectrum analysis apparatus for rapid analysis of the frequency and level of incoming signals and a control unit that not only programmes the frequency scanning of the spectrum analysis apparatus and processes its results, but also rejects signals or directs them to the processing channels.

TABLE I – *Fields of application and performance requirements for a group of users*

Activity	Performance required						Scale of French national activity or number of stations used (estimate for 1980)
	Data collection			Location			
	Volume of each message (bits)	Delays in availability of data	Time between two collections	Precision	Delays in availability of data	Time between two determinations	
Earth sciences							
— Vulcanology	28 to 35	6 to 24 h	12 to 24 h				10 stations
— Study of the marine environment (Meteo-oceanography)							
— Fixed buoys	150 to 400	3 to 6 h	6 to 12 h				35 buoys
— Drifting buoys	up to 800	3 to 6 h	6 h	1 to 5 km	3 to 6 h	6 h	15 buoys
Hydrology (1)							
— Level of underground water	10	15 days	Once a week				400 stations
Meteorology							
— Drifting buoys (research)	28	24 h	24 h	2 to 5 km	24 h	24 h	5 buoys
— Drifting balloons (research)	28	1 to 3 days	5 to 6 h	2 to 8 km track 10° speed 3 m/s	1 to 3 days	5 to 6 h	30 balloons
Oil and gas prospecting							
— Drifting buoys — Environmental studies	up to 800	24 h	24 h	2 to 5 km	24 h	24 h	6 stations

(1) There is little prospect of carrying out this mission in France by this means because of the prohibitive cost of a station.

TABLE II – *Requirements for the location of fixed earth stations, to a precision of 1 to 10 m*

Activity	Performance required		
	Precision (m)	Maximum time between 2 determinations (days)	Maximum delay in data availability (days)
Oil prospecting			
Land prospecting, determination of a basic topographic grid	1	1	2
Siting of radiolocation antennae . .	1	as required	3
Geodesy			
Establishment of a geodetic network for triangulation	1	3	2
Cartography			
Reference points for photogrammetry	10	1	2
Surveying			
Preliminary surveys for civil engineering projects	1	1	1
Glaciology			
Study of ice flow rates	1	as required	(1 year)

TABLE III – *Requirements for location of mobile earth stations, to a precision of 50 to 200 m*

Activity	Performance required		
	Precision (m)	Maximum time between 2 determinations (h)	Maximum delay in data availability (min)
Oil prospecting			
Locating vessels engaged in seismic observation	200	0	Information supplied immediately
	50 (1)	2	
Locating survey ships	200	0	15
	50 (1)	2	
Locating oceanographic vessels . .	200	0	15
	50 (1)	2	

(1) For resetting on-board local navigation systems.

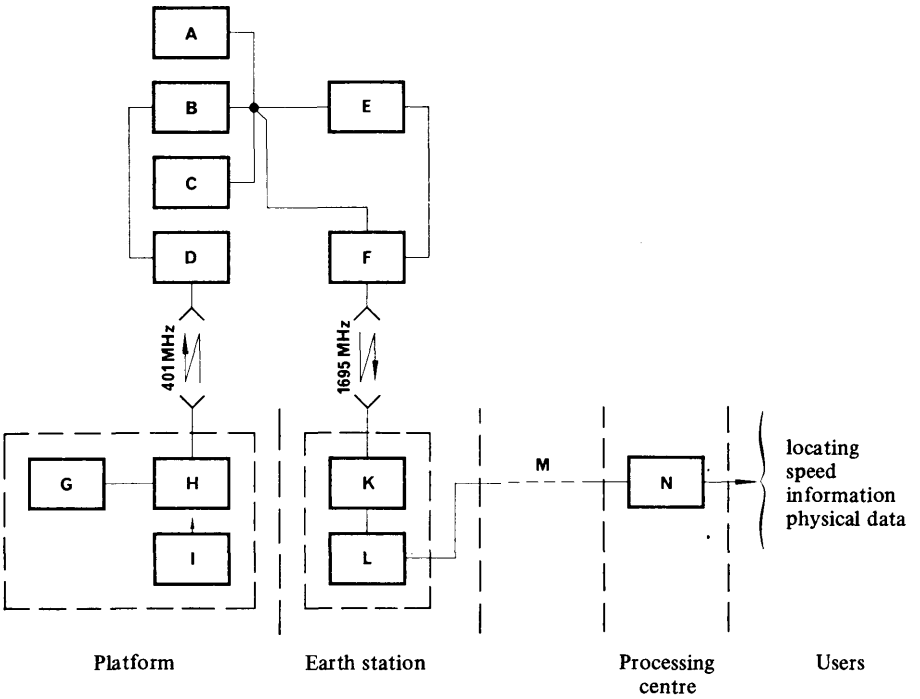

FIGURE 1 – *Block diagram of location and data-collection system (ARGOS)*

A: Doppler measurement
B: Information demodulation
C: Dating clock
D: Receiver
E: Memory information storage
F: Transmitter
G: Oscillators
H: Transmitters
I: Sensors
K: Receiver
L: Recorder
M: Data link
N: Data processing

In the case of a valid signal (free from interference by another platform message) for which a processing channel is available, the receiver will:

- acquire it,
- measure the frequency received,
- extract the information,
- add the date and time

and prepare a message containing:

- the identification of the platform,
- the frequency measured,
- the information,
- the date and time.

This message is then presented to the on-board processing system, which multiplexes it and stores it on magnetic tape.

All this information is later sent by telemetry to a receiving earth station in the network and then to a processing centre, where the location is carried out, using a sufficient number of measurements taken during two successive orbits and where the digital data are translated into physical quantities. The location may also be carried out with measurements taken during a single orbit but with a lower standard of accuracy.

The main characteristics and performance of the system are given in Annex II.

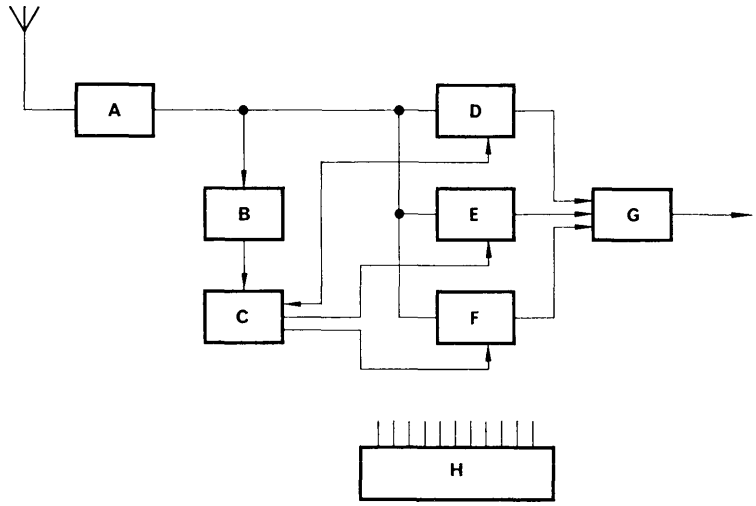

FIGURE 2 – *Block diagram of on-board equipment*

A: Receiver
B: Spectrum analysis
C: Processing control
D: Processing unit No. 1
E: Processing unit No. 2
F: Processing unit N
G: Telemetry interface
H: Support system

3.3 *The principle of a precise location system*

The principle used to locate an unknown point involves a combination of a satellite, a network of reference stations, one or more earth stations for telemetering and telecommand, and a data processing centre. The position of the unknown point is determined in relation to a series of positions of the satellite, which in turn are related to the positions of the stations in a reference network the relative positions of which are known with an accuracy of better than 2 m. Thus, it is finally with reference to this network that the position of the point is determined.

The problem to be resolved is therefore that of defining and establishing a frame of reference which will permit the calculation of the position of the satellite at each instant of measurement. The establishment of the system will be carried out in two phases.

Phase 1: During the first month of the satellite life a first-order geodetic network consisting of 10 to 40 reference points, the mutual accuracy of their siting being less than 1 m, will be established on the surface of the Earth.

Phase 2: Following phase 1, it becomes possible to use the system for the location of individual points. The positions of the stations situated at the points of the first-order network are now precisely known and can be used to determine the positions taken up by the satellite. To calculate the co-ordinates of an individual point, it is sufficient to install a station there and to await, according to the degree of precision required, one or more passes of the satellite. The distance and Doppler measurements made between the satellite and the station of which the position is to be determined, locate it by means of the intersection of spheres and cones of revolution.

The main factors in the choice of such a system are analyzed in further detail in Annex I and the characteristics selected for the GEOLE system are described in Annex III.

ANNEX I

FACTORS IN THE CHOICE OF A HIGH PRECISION LOCATION SYSTEM

1. Preferred characteristics of a precision location system

To meet the specifications set out in Tables II and III, it would seem that such a system should:

- be capable of locating a fixed station with an accuracy of 1 m on any day, and of providing the station itself and the user organization with the calculated position not later than 1 day after measurements have been completed (and, possibly, of providing a mobile station with its position to an accuracy of 50 m, every 2 h and not more than 15 min after the instant of measurement);
- provide world-wide coverage;
- ensure round-the-clock operation, regardless of weather conditions.

The last condition rules out systems based on optical sensors and renders the use of radio techniques obligatory.

2. Types of measurement

Since the positions and velocity vectors of the satellite or satellites are assumed to be fully known (see § 3 below and § 3.3 of the main Report), consideration can be given to the types of measurement which can be made from satellites to determine precise locations and their required accuracy for an accuracy of about 1 m on the ground. Two quite different classes of satellite must be envisaged, geostationary and non-geostationary.

2.1 *Geostationary satellites*

Although a geostationary satellite system cannot meet the world-wide coverage criterion, this disadvantage (limited to the polar regions) is not necessarily prohibitive for all applications. With these satellites which are fixed with reference to the point to be located, two different types of measurement may be necessary to provide the three co-ordinates of a point. Furthermore, random errors can be substantially reduced by taking the mean of measurements carried out over a sufficiently lengthy period although systematic errors (bias) cannot be eliminated.

Since the motion of the satellite with respect to the Earth is small, a Doppler measurement would not provide a useful relative velocity measurement.

Table IV shows the types, the minimum number of simultaneous measurements necessary, and the permissible systematic error in measurements relevant to systems with one, two and three simultaneously visible satellites, in the most favourable geometric measuring conditions, with the object of associating the measurements for each case.

TABLE IV – *Systematic errors equivalent to an uncertainety of 1 m in the location of an earth station by a geostationary satellite*

Number of simultaneously visible satellites	Types of measurement	Minimum number of simultaneous measurements	Permissible systematic error (approximate)
1	Distance	1	1 m
	Angles (interferometry)	2	10^{-8} radians
2	Distance	2 (one with each satellite)	0·5 m
	Angles	1	10^{-8} radians
3	Distances	3 (one with each satellite)	0·1 m

2.2 *Non-geostationary satellites (low orbit)*

With a non-geostationary satellite, only one type of measurement need be used to derive three co-ordinates, since the geometrical configuration varies. The measurements should present sufficient geometric diversity and hence be distributed evenly over the whole pass of the satellite while it is visible from the station.

The change in geometrical configuration reduces the effect of systematic errors, but not of random errors, which, if it is not possible to make better quality measurements, can only be reduced by application of the least squares method and this will be less effective than in the case of geostationary satellites.

To meet the requirements set out in Table II only one satellite is necessary, but three or four-phased satellites would have to be used to meet the requirements in Table III because of the time interval between two determinations of location.

Two types of measurements can be made on non-geostationary satellites:

- Doppler measurements, in which case the location of a point in relation to the satellite requires at least three measurements at different points;
- distance measurements, in which case calculation of the position of a point needs at least three measurements at different points;

If Doppler and distance measurements are carried out simultaneously, two pairs of measurements are sufficient to determine the position of point.

Table V below gives the permissible errors in obtaining locations with an accuracy of 1 m, by processing the measurements made over 24 h, or with an accuracy of 10 to 20 m, by processing the measurements carried out during one pass of the satellite while visible from the station.

2.3 *System selected*

A non-geostationary satellite was finally chosen for determining precise locations. The location is calculated by processing the measurements of distances and radial velocities between the satellite and the earth station. This is the only case dealt with in the rest of this Annex.

TABLE V – *Errors equivalent to an uncertainty of 1 m in the location of a fixed earth station using a non-geostationary satellite system*

Types of measurement	Permissible random error (1)	Permissible systematic error (1)
Distances	1 m	1 m
Doppler (or relative velocity)	0·2 mm/s	0·2 mm/s
Distances . . . . . and Doppler measurements (simultaneously)	2 m	2 m
	2 mm/s	10 mm/s

(1) These values were calculated for a circular orbit with an altitude of 3500 km and an inclination of 70° ; the measurements for a whole day were combined.
The measurements were carried out on satellite-station-satellite links.

3. The plotting of satellite positions

To achieve an accuracy of 1 m in the location of a point, the satellite tracking must be maintained with a similar degree of accuracy. Such accuracy cannot be achieved with conventional tracking techniques, such as interferometry, Doppler measurements or radar.

The problem may nevertheless be solved by means of a reference consisting of stations whose positions are exactly known and which are identical to those made available to the user organizations (see § 3.3 of this Report). Measurements made with this network can then be used to locate the satellite and the measurements made with the user stations will thus give the positions of these user stations.

When the reference network is set up, the positions of the earth stations and the successive positions of the space station are all unknown. There are two possible ways of dealing with the measurements.

3.1 *Geometrical approach*

If, at a given instant, four earth stations are visible simultaneously from the space station, a relation may be established between the co-ordinates of the four earth stations, the co-ordinates of the space station no longer being taken into account.

If this condition is fulfilled several times, with sufficient geometrical diversity, the relative positions of the four earth stations may be determined fully and gradually, applying a grouping method, the network of reference earth stations may be determined fully.

In fact, since the space station communicates with the earth stations in sequence, an interpolation is required. However, this is of brief duration and introduces a negligible additional error, without any need for a refined representation of the satellite movement.

The main drawback of this method is the requirement that four earth stations should be visible from the space station simultaneously. With a world-wide network of 40 earth stations, this means that the satellite must have an altitude of at least 3500 km.

3.2 *Dynamic approach*

The work performed in recent years on the modelling of the Earth's gravitation potential has led to a significant improvement in the models, a development which is likely to continue in the 1980s [Vincent and Marsh, 1975; Wagner *et al.*, 1976; Balmino *et al.*, 1976].

At the same time, the development of short arc methods, which consist in treating independently the observation relations obtained on sections of the satellite path, of a duration of the order of the revolution period of the satellite; has reduced the location error due to inadequate knowledge of the satellite movement.

It now appears possible, by using a short arc method, to determine the reference polyhedron with the required accuracy, with a network of only ten earth stations and a satellite altitude of 1500 km.

4. Types of possible system

Various combinations of the following factors lead to a variety of system concepts.

4.1 the locations and relative dispositions of:

- the place where the measurements are made,
- the place where the location is calculated and
- the place where the orbit is calculated;

4.2 the means used to transmit the measurements to the computing centre.

A number of possible systems is shown in Table VI and the advantages and disadvantages are shown in Table VII.

TABLE VI – *Possible types of system for precise location by satellite*

Point of measurement	Means used to transmit measurement data to the place where the location is calculated	Place where the location is calculated	Place where the orbit is calculated			
			Ground computer centre	In the satellite	Station to be located	Particular station in a set of stations to be located
Satellite	Delayed transmission after storage in the satellite	Ground computer centre	System 1			
	Transmission in real-time through a geostationary satellite	Ground computer centre	System 2			
	Distribution of data from the satellite to the station	Station to be located	System 3	System 4	System 5	
	.....	Satellite	System 6	System 7		
	Data distribution	Particular station in a set of stations to be located				System 8
Particular station in a set of stations to be located	.....	Particular station in a set of stations to be located				System 9

TABLE VII – *Advantages and disadvantages of the various types of system*

System	Advantages	Disadvantages	System operating with this type
1	– Centralization of calculations at a single point – Geometrical method	Data availability delay of several hours	EOLE IRLS(1)
2	– Centralization of calculations at a single point – Virtually no delay in data availability – Geometrical method	Requires two geostationary satellites for transmission	
3	– Virtually no delay in data availability	– Less accurate, unless the station to be located has a large capacity computer, which is incompatible with a transportable station – Extrapolated orbit prediction	
4	– Virtually no delay in data availability – Path calculation in real time	Less accurate, unless the station to be located has a high capacity computer	
5	– Virtually no delay in data availability – Geometrical method	Less accurate, unless the station to be located has a high capacity computer	
6	– Virtually no delay in data availability	Difficult to attain 1 m accuracy with a satellite-borne computer Extrapolated orbit predictions	
7	– Virtually no delay in data availability – Geometrical method	Difficult to attain 1 m accuracy with a satellite-borne computer	
8	– Small delay in data availability – Geometrical method	The station concerned must have a fairly large computer	
9	– Particularly short delay in data availability – Geometrical method	This particular station is a complex one with a computer and its measurement systems	SECOR(2)

(1) IRLS: Interrogation recording and location system.

(2) SECOR: Sequential collation of range.

5. Choice of frequencies

The choice of frequencies is governed mainly by problems of ionospheric propagation which introduces errors in the distance and radial velocity (Doppler) measurements.

Table VIII summarizes the errors calculated for an elevation angle of 20° when the total vertical electron content is 60×10^{16} electrons/m^2. (This value is exceeded for less than 5% of the time.) The satellite's altitude is 3500 km. The Doppler measurements are averaged out over a duration of 4 seconds.

In this Table, the ionospheric errors are random owing to scintillations caused by ionospheric discontinuities. The standard deviations were calculated with a correlation time $t_0 = 5$ s, and a correlation distance of $l_0 = 1$ km, i.e., with extreme values. The electron density at two points separated from one another by a distance l and a time t have a correlation of the form

$$e^{-\left(\frac{l}{l_0}+\frac{t}{t_0}\right)} \qquad (1)$$

TABLE VIII – *Errors caused by ionospheric effects*

Frequency (MHz)	150	400	1000	2000	5500
Mean Doppler error (cm/s)	320	45	7.2	1.8	0.24
Mean distance error (m)	2420	340	54.4	13.6	1.8
Standard deviations of Doppler error (cm/s)	41	5.8	0.93	0.23	0.03
Standard deviation of distance error (m)	1.2	0.170	0.027	0.007	0.0009

The effect of the total electron content along each path has been calculated by integration. It does not seem possible, therefore, to carry out measurements with an accuracy of 1 m or less with a single frequency below 5.5 GHz.

The use of an ionospheric model to introduce corrections must be ruled out at the present stage. To overcome this difficulty, a number of solutions may be suggested:

- measurement on two phase-coherent frequencies, i.e., frequencies derived from the same oscillator by frequency multiplication;
- measurement of the differential Faraday effect (that is, measurement of the rotation of the plane of polarization of the electromagnetic wave with respect to two frequencies);
- ionospheric topside sounding by satellite.

A priori, the first solution would seem the best; the frequency pair must be selected in such a way that the residual errors satisfy the accuracy required.

Let f_1 be the main frequency, f_2 the correction frequency, and $f_1/f_2 = \alpha$.

Let m be the exact value of the quantity to be measured, distance or speed. Measurements m_1 and m_2 include errors due to the ionosphere.

In the first order

$$m_1 - m = \frac{A}{f_1^2} \quad \text{and} \quad m_2 - m = \frac{A}{f_2^2} \tag{2}$$

By removing the coefficient A between these two equalities, we obtain:

$$m = \frac{\alpha^2 m_1 - m_2}{\alpha^2 - 1} \tag{3}$$

Hence in the first order the exact value of m may be obtained by means of the above combination formula.

In fact, this formula is merely approximate and there is a residual error due to three phenomena.

(1) The ionospheric refraction index does not depend exactly on the frequency in $1/f^2$. The first term neglected in the development of the index depends on the Earth's magnetic field and varies in $1/f^3$. The omission of this term produces after application of the combination formula, a systematic error:

$$\Delta m = \frac{B}{f_1 f_2 (f_1 + f_2)} \tag{4}$$

(2) The paths of the two electromagnetic rays at frequencies f_1 and f_2 are not identical owing to refraction. The omission of this difference produces after application of the combination formula, a systematic error:

$$\Delta' m \# \frac{C}{f_1^2 f_2^2} \tag{5}$$

(3) Owing to the path difference mentioned in (2), the heterogeneity of the ionosphere produces, after application of the combination formula, a random error:

$$\sigma m \# \frac{D}{f_1 f_2 \sqrt{f_1^2 - f_2^2}} \tag{6}$$

Table IX shows the residual errors after corrections resulting from the use of two frequencies, under the same conditions as those applied for Table VIII, for a satellite orbiting the Earth at an altitude of 3500 km and for an elevation angle of 20°.

TABLE IX – *Residual errors*

Frequency pair (MHz)	150/400	400/2000	1000/2000	1700/2100	2000/5000
Mean residual Doppler error (cm/s)	2.9	0.019	0.0037	0.0013	0.0002
Mean residual distance error (m)	14.5	0.12	0.028	0.011	0.002
Doppler standard deviation (cm/s)	8.6	0.14	0.065	0.05	0.005
Distance standard deviation (m).	0.25	0.0042	0.0019	0.0015	0.00014

However, this combination has a drawback; it increases the errors due to causes other than the ionospheric in the ratio $(\alpha^2 + 1)/(\alpha^2 - 1)$, where α is the ratio of the highest (main) frequency to the lower (correction) frequency. Therefore, α must be as large as possible; in practice, a value of 4 or 5 is adequate.

The correction measurements m_2 may be less accurate than the main measurements m_1 since they are reduced in the ratio $1/(\alpha^2 - 1)$.

It therefore appears that the use of no single frequency below 5.5 GHz allows the required measurement precision. However, satisfactory precision can then be obtained by using two coherent frequencies, the ratio (α) between the two being preferably at least 4 or 5. The lower frequency should be above 400 MHz, because of propagation anomalies through the ionosphere. Moreover, 2.5 GHz seems to be a reasonable upper frequency limit for small transportable and autonomous stations.

The optimum frequency pair seem to consist of one frequency about 400 MHz and the other about 2000 MHz. Both frequency links do not need to be two-way; the lower frequency link (which corrects for propagation through the ionosphere) may be one-way. If f is the interrogating frequency and f_1 and f_2 the response frequencies, it is established that the measurements combination formula is maintained by modifying the meaning of α:

$$\alpha^2 = \frac{\frac{1}{f^2} + \frac{1}{f_2^2}}{\frac{1}{f^2} + \frac{1}{f_1^2}} \tag{7}$$

6. Bandwidth

At the principal frequency, the emitted signals should provide:

- a distance measurement to an accuracy of 2 m,
- a Doppler or radial velocity measurement to within 2 mm/s,
- low-rate transmission (several hundred bit/s). The data may be, for example, the address of the station interrogated, the position calculated, or tropospheric propagation correction data.

The first condition involves the use of high-rate modulation signals; since phase measurements can now be made with a precision of 3.6° to 1.2°, a sine wave with a wavelength of 100 to 300 m (that is, a frequency of 1.5 MHz to 0.5 MHz) will be required. The second condition means that a part of the carrier power must be retained so as to maintain a phase-locked loop for the frequency measurement.

Therefore a low modulation index requiring a bandwidth of ± 1 to ± 3 MHz is necessary in this case, angle modulation being preferable. The correction frequency is divided by α or 2α; and taking $\alpha = 5$, in the latter case the bandwidth becomes approximately ± 100 kHz to ± 300 kHz.

7. Conclusions

The frequency requirements for each precise location satellite system in the 1980's are therefore likely to be:

- ± 1 to ± 3 MHz between 1.5 and 2.5 GHz for links from the satellite to the station (to be located),
- ± 1 to ± 3 MHz between 1.5 and 2.5 GHz for links from the station (to be located) to the satellite,
- ± 100 to ± 300 kHz at about 400 MHz for the ionospheric correction link from the station (to be located) to the satellite.

A single satellite system will probably suffice to meet world requirements for the scale of activities indicated in Tables II and III of the main body of this Report.

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ANNEX II

MAIN CHARACTERISTICS OF THE ARGOS SYSTEM

1. Principle

The CNES is developing a location and data collection system ARGOS which will be placed on board the United States satellite TIROS-N and whose operating principle is described in § 3.2 of this present Report.

2. Orbit of the satellites

The system comprises two satellites in orbit simultaneously. The anticipated 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

The signal emitted consists of repeated bursts with unmodulated and modulated parts.

Unmodulated part: duration of the order of 160 ms.

Modulated part: duration depends on the number of sensors per platform, ranging from 4 to 32 in multiples of 4 (4, 8, 12, 16, 20, 24, 28, 32), each datum being encoded in 8 bits; the duration thus 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 60 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 5 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: – 128 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. 16000 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 5 km for balloon-type mobile platforms the movements of which are subject to random fluctuations;
- about 3 km for drifting-buoy type mobile platforms with slow and regular drift;
- the ultimate precision of about 1 km is attained when the movement is known 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 III

THE GEOLE PROJECT

Over several years, the Centre National d'Etudes Spatiales (France) has been engaged on a project deriving from Eole (hence the title GEOLE, which is a contraction of Geodesy and Eole) and designed to meet the precise location requirements defined in § 2 of this Report.

1. Principle

The basic system selected at the beginning of the study corresponded to system 1 in Table VI (Annex I). The satellite operates by programmed interrogation of identical user stations and of the tracking network. It carries out distance and Doppler effect measurements, stores the measurement data on board, and then transmits them to a well-equipped computing centre via a telemetering network. After calculation, the station's position can be retransmitted directly to the station by data distribution.

This system is very well suited to the location requirement defined in Table II, but not to those in Table III. The study has made it possible to define and initiate the development of the distance and Doppler effect measurement system which was tested successfully on the ground in 1976. It will be possible, by changing some characteristics but without any modification of the measurement sub-system, to adapt the project to the requirements of Table III by means of one of the systems 2 to 7 in Table VI.

2. Orbit

The preferred orbit depends on the application. A circular orbit, of altitude 1500 km and inclination over the Equator of 75°, would seem suitable for most purposes.

3. Characteristics of the radio links

TABLE X

		Interrogating link	Response links	
Operation		Permanent	Intermittent Duration of sequence ≈ 5 s Repetition period ≈ 1 min	
Frequency band (MHz)		1525 – 1535	2096 – 2110	401 – 403
Bandwidth (MHz)		2.1	3.2	0.4
Space stations (1 to 4 satellites)	Spectral power density	–22 dB(W/Hz)		
	Gain	+ 3 dB	+ 3 dB	+ 3 dB
	Noise temperature		900 K	800 K
Earth stations (up to 300 beacons)	Spectral power density		–22 dB(W/Hz)	–22 dB(W/Hz)
	Gain type I	–1 dB	–1 dB	–1 dB
	Gain type II	–15 dB	+ 15 dB	+ 6 dB
	Noise temperature type I	900 K		
	Noise temperature type II	700 K		

Note 1. – The type I beacons, with fixed antennae, are intended for the user organizations. The type II beacons with variable antennae are designed for the reference network.

Note 2. – The antenna gains are given:

– vertically for the satellite and the type I beacons
– in the direction of maximum radiation for the type II beacons.

ANNEX IV

DATA COLLECTION AND POSITION LOCATION SYSTEMS IN THE UNITED STATES

An overview of the data collection and position location system programmes conducted by the United States is presented in the following paragraphs.

1. The Omega position location equipment experiment

In 1967, an experiment was begun using the Omega Navigational System in conjunction with synchronous satellites to establish a global location and data collection system. The experiment, designated OPLE (for Omega Position Location Equipment) consisted of an OPLE control centre, a synchronous satellite (ATS-3), Platform Electronic Packages and the Omega Navigational Network. For this experiment, the VHF communications transponder on the ATS-3 satellite was able to provide for up to 40 simultaneous, interrogated transmissions to the Platform Electronic Packages within its 100 kHz bandwidth. The communication links between the OPLE Control Centre via the ATS-3 satellite and the Platform Electronic Packages operates in the VHF bands using 135.6 MHz for the downlink and 149.2 MHz for the uplink. The Omega Navigational Network operates in the VLF band at 10.2 kHz, 11.33 kHz and 13.6 kHz.

Operational experiments provided sufficient data to allow a statistical performance analysis of the overall system operation. The largest source of position-errors was due to anomalies within the Omega Navigational Network. The resultant errors were of the order of 1.6 to 2.4 km during the daytime and 6.4 to 8.1 km at night. For the fixed platforms, position-error due to the OPLE equipment ran between 15 to 122 m in latitude and 91 to 152 m in longitude. The results of a test on a moving automobile going along a road showed that the vehicle could be located within 0.5 km after adjusting for the errors contributed by the Omega System. Also, by using a platform aboard an aircraft travelling at 160 knots, the position of the aircraft was determined within 8 km (16 km at night) of the estimated centre of its circular flight pattern.

These early experiments had demonstrated the feasibility of using the Omega Navigational System in conjunction with synchronous satellites to establish a global location and data collection system. Other early experiments were also performed and they are described in the following section.

2. Interrogation, recording and location system (IRLS)

The Interrogation, Recording and Location System (IRLS) [Cote, 1970] was a satellite system developed to demonstrate the feasibility of determining position location and the collection of scientific data from remote instrumented platforms deployed on a global scale on, or above, the surface of the Earth. The system utilized a range-range location technique which yields solutions as the intersection of ranging spheres. Up to 28 channels of sensory data were collected with each platform interrogation. In operation, discrete addresses of platforms expected in the satellites'field of view were programmed, on an orbit-by-orbit basis, from a Central Ground Acquisition and Command Station, for transmission at a discrete satellite position in the orbit. Upon receipt of the interrogation the platform transmits the scientific data to the satellite for storage. When the satellite passes within view of the Fairbanks, Alaska Data Acquisition Station, the stored data is readout and relayed to Goddard Space Flight Centre for processing. Over 3×10^6 bits of engineering and scientific data were collected from points around the globe, and the data quality has been excellent.

The inherent theoretical accuracy of the IRLS range-range location technique has been established as $\pm$ 1.5 km through mathematical computer modelling of system variables. The significant sources of error were identified as being:

- uncertainty in orbital prediction,
- the accuracy of range and time-of-range measurements, and
- the distance of the platform from the ground track.

The allowable limits on the preceding variables for the stated accuracy are < 0.5 km, $\pm$ 0.5 km, 0.1 second and > 278 km.

The evolution of the IRLS from a technological experiment to a significant scientific experiment was realized and achieved with IRLS 2 through improvements in the satellites memory capacity, an improved satellite receiver and platform improvements which decreases the weight from 45 kg to 4.5 kg.

Operation of IRLS 2 was the same as that used for IRLS 1. The same trends were observed, in that the location accuracies varied as a function of time from the orbital update (designated epoch). Significant scientific data for over 1500 interrogations was collected from this system.

3. LANDSAT-1 AND LANDSAT-2

The first random type of data collection system used was LANDSAT-1 (Painter and Seitner, 1973) launched in July 1972. The LANDSAT system can accommodate up to 2000 platforms within the continental United States (CONUS). Transmissions from the ground instrumentation (Data Collection Platform) occur in bursts (38 ms long), at random times (180 s between transmissions), and at random frequencies within a 100 kHz bandwidth. This provides a 95% probability of receiving a minimum of one noninterfered transmission every 12 hours. Each transmission burst contains 95 digital data bits of information. Convolutional encoding of the sensory data is used to improve the channel bit error rate.

Approximately 30 users are currently involved in the programme. Over 300 000 messages containing sensory data have been delivered to the various users. Operation has continued since the successful launch of LANDSAT-2 in January 1975. The system and operation is the same as was previously described for LANDSAT-1. Approximately the same number of users are being serviced by LANDSAT-2.

4. Random access measurement system (RAMS)

Another random type system being used is the Random Access Measurement System (RAMS) launched on the NIMBUS-6 satellite in June 1975. The RAMS will provide a means of locating/tracking and collecting data from a maximum of 1000 (200 in the satellite's field of view) mobile and/or fixed instrumentation packages.

In operation, each platform transmission will occur in one second bursts at random times every 60 seconds within a 30 kHz bandwidth. RAMS will perform satellite on-board processing of up to eight simultaneous platform transmissions. Each transmission burst contains a CW tone that is used for signal search and detection for 320 ms, and 64 data bits in the remaining 640 ms. Thirty-two bits of the 64 are used for housekeeping (synchronization, platform identification, etc.) and the remaining 32 bits are allocated for sensory data. Received platform data is preprocessed, formatted and stored into a 90 bit message for subsequent readout every 108 minutes as the satellite passes in view of the data acquisition station at Fairbanks, Alaska.

During the pass over the ground station in Alaska the stored data is read-out, and relayed to Goddard Space Flight Centre for processing. At this Centre, position and velocity parameters are derived from the relative motion between the satellite and platforms, as are determined from the frequency time measurement made by RAMS. These parameters are computed on the basis of doppler information in the signals received on any two of three successive orbital passes from each platform. In addition, the recovered sensory data is formatted for further processing by the users. The RAMS accuracy design goals are: $\pm$ 5 km for position location and $\pm$ 1 m/s for velocity determination.

5. SMS-1 and 2 data collection system

The SMS-1 and 2 Data Collection System on SMS-1 & 2 is operated by the National Environmental Satellite Service (NESS) of NOAA as an integral part of the National Operational Environmental Satellite Service. The two synchronous satellites will provide several services, one of which includes collecting and transmitting in-situ measurements from fixed and mobile platforms via the satellites to a Command and Data Acquisition (CDA) station at Wallops Island, Virginia, where the data is relayed to a common storage and user distribution facility in Suitland, Maryland.

The basic elements of the Data Collection System are the remotely located Data Collection Platforms (DCP), the SMS spacecraft, the Command and Data Acquisition (CDA) Station and data dissemination facility. This continuous data collection and relay capability has been designed to accommodate 10 000 or more platforms within each six hour period. These platforms will utilize the radio frequency band of 401.7 MHz to 402.1 MHz as the up-link to the satellite. Each platform will communicate to the spacecraft either in an interrogated (ordered) or self-timed (time division) mode of operation. The down-link to the platforms from the satellite will utilize the radio frequency band 468.750 MHz to 468.950 MHz.

The data received at the satellite will be transponded to 1694.5 MHz ± 200 kHz for transmission to the ground. At the CDA station the data is recorded and relayed to the distribution centre, where minimal processing necessary to determine the status of the platform and to evaluate the data link takes place. In near-real time applications the data is forwarded to the user via teletypewriter or computer link. In non-real time applications the raw data is forwarded to the user by mail or other means that are available and acceptable to the user.

Fifty self-timed platform channels, spaced 3.0 kHz, and 100 interrogated channels, spaced 1.5 kHz, are provided in each system. In addition, emergency channelling is provided. Interrogation of platforms is on a schedule or as needed basis.

6. TIROS-N data collection system

The Data Collection and Location System (DCS) for TIROS-N will be developed and manufactured by Centre National d'Etudes Spatiales of France (see Annex II). The TIROS satellite will be operated by the National Environmental Satellite Service (NESS) of NOAA as an integral part of an operational environmental satellite service.

Signals transmitted from ground or mobile instrumentation platforms will have a carrier frequency of 401.650 MHz and a transmission duration of about 360 to 920 ms depending upon the number of platform sensors. The first 160 ms of the transmission will be an unmodulated carrier followed by biphase PCM data which contains bit and frame synchronization, platform identification, and from one to eight groups of sensor words having four sensor words per group. Platforms to be located will have a chosen transmission repetition period between 40 and 60 s. For platforms to be used only for data collection, the repetition period will be chosen between 60 and 200 s.

Location of a platform is accomplished by using a Doppler technique. The satellite system measures the Doppler-shifted carrier frequency for each transmission and provides this data to the spacecraft Data System for storage. The platform location is then computed at the ground data processing facility. Up to four platform signals can be handled simultaneously by the spacecraft.

The system is designed to handle between 2000 and 16 000 platforms, depending upon the mixture requiring location and tracking capability.

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SECTION 2E: RADIOASTRONOMY AND RADAR ASTRONOMY

Recommendations and Reports

REPORT 223-4

LINE FREQUENCIES, ARISING FROM NATURAL PHENOMENA, OF INTEREST TO RADIOASTRONOMY AND RELATED SCIENCES

(Question 5-1/2)

(1963 - 1966 - 1970 - 1974 - 1978)

The amount of scientific information obtained from radioastronomical observations has greatly increased in recent years. Technology improvements in receivers and antennae have been partly responsible for this increase. Astronomical observations have now been made from ground based observatories using radio techniques, at wavelengths shorter than 1 mm (300 GHz), employing cooled bolometric detectors or various solid state devices. Thus from the point of view of availability of equipment, the entire radio spectrum can now be employed for astronomical measurements.

Another reason for the rapid growth of interest, particularly in that part of the spectrum from 100 MHz to 300 GHz, has been the discovery of line radiation from a number of extra-terrestrial substances of astrophysical importance.

First, 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 U.S.S.R. [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.

Second, there have 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. However, since then many more interstellar molecules have been identified, the majority by means of spectral lines at millimetre wavelengths. Table I lists, in order of increasing frequency, the lines of interstellar organic and inorganic molecules reported by radio astronomers. The first column in each table gives the frequency; the second column lists the molecular formula and name, and the third column indicates whether the spectral line has been observed in absorption (A) or emission (E). A double asterisk in this column indicates that the line is afforded at least footnote recognition by the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971. It is realized that only some of these lines can be afforded protection in the Radio Regulations by allocations, and the astrophysically most important lines are listed in Report 224-4 and Recommendation 314-4.

The formation mechanism for interstellar molecules is not well understood. For typical interstellar cloud densities ranging between one and one million molecules per cubic centimetre and temperatures between 10 K and 100 K, the time between molecular collisions ranges from one thousand years to one third of a day. Thus typical conditions in interstellar clouds do not enhance collisional formation of polyatomic molecules although it is possible to explain the presence of CH, CH^+ and CN by invoking radiative association. Also, recent laboratory determinations of lifetime against photo dissociation [Steif *et al.*, 1972], indicate that, given an ambient ultraviolet radiation field of 4×10^{-17} ergs cm^{-3} $Å^{-1}$ [Habing, 1968], it takes only ten years for unshielded interstellar carbonyl sulphide to be destroyed; thirty years for formaldehyde; forty years for ammonia; and one thousand years for carbon monoxide. Certainly, under these conditions an unshielded polyatomic molecule could not survive the harsh interstellar environment.

Even though molecular formation is not clearly understood, there are three reasons which appear to explain the remarkable observational results which radio astronomers are now obtaining. First, all the new molecules appear to be associated with regions of obscuration or interstellar dust. Experimentally, it has been found that molecular lifetime with respect to photo dissociation increases tremendously with each increment of visual extinction. Thus once formed, a molecule may exist many orders of magnitude longer inside a dust cloud than it can in unshielded space before ultra-violet photo dissociation occurs. Second, radio waves are not significantly attenuated by dust particles which are of sub-micron size; hence, radio signals can penetrate clouds which completely attenuate optical waves. Third, the excitation requirements are low for radio detection of molecules. For example, optical astronomers require a background source of excitation of at least 15 000 K in order to observe optical absorption lines; thus a very special geometry of a very hot star with an intervening

molecular cloud of low opacity places stringent conditions on optical astronomy. On the other hand, thirty times less excitation energy will produce a typical molecular rotational transition. Thus radio detection does not require a bright, hot star with an intervening molecular cloud; the background source might be an ionized hydrogen region, infra-red star, radio galaxy, or even the 3 K isotropic background radiation.

As a direct consequence of the interstellar molecular radio spectroscopy of the past few years, a number of phenomena have been discovered which indicate that radio astronomers are studying a new area of chemistry. The detection of as yet unidentified molecules, such as X-ogen, emphasizes the role of a typical interstellar cloud as a unique chemical laboratory – a sample cell which would be difficult if not impossible, to duplicate in its entirety in terrestrial laboratories. With mean free paths as long as 10^{15} cm, low temperatures, and catalytic dust grain surfaces present, it is not unreasonable to expect future detection of interstellar molecules which cannot be observed terrestrially because of rapid collisional destruction or rapid recombination mechanisms. This new chemistry should not be considered exotic or unusual, however, as it is the common chemistry of the galaxy and man stands to gain a greater understanding of his galactic environment from it.

Long, painstaking observations which often require many hours of integration are needed by radio astronomers in order to achieve initial detection of most of these lines. Many more orders of magnitude of time and effort are expended in detecting each line in other gas clouds and to obtain the signal-to-noise ratios necessary to draw conclusions of astrophysical interest from the observations. In general, bandwidths of 0.2 per cent or more of the rest line frequency are required in order to observe all components of the Doppler-shifted observed line frequency of these clouds moving along the line-of-sight within our galactic system. Wider bandwidths will of course be required for extragalactic observations.

The choice of wavelength for astronomical observations naturally depends on the lines to be observed, but it may also be strongly influenced by the transmission properties of the Earth's atmosphere, i.e., by the location of the so-called "windows" in the atmosphere. The regions of interest for ground-based observations known at present, are shown schematically in Fig. 1, based on Report 719 of Study Group 5. This Report contains the study of the attenuation in clouds at frequencies above 50 GHz. In general, the windows are defined by the resonances of molecular oxygen and water vapour. The abundance of other atmospheric constituents, for example, CO, NO, NO_2, etc., is sufficiently small that their presence in a window will not significantly alter the usefulness of this window for astronomical observations.

The curves in Fig. 1 show the total one-way absorption in the vertical direction for a dry atmosphere and for two representative atmospheres with water vapour concentrations of 0.5 and 7.5 g/m^3 at the Earth's surface. These curves are 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.

The Annexes summarize some of the types of spectral line observations that are being conducted at observatories throughout the world. The five Annexes deal with lines of atomic hydrogen and the four molecules OH, H_2O, H_2CO and CO. These are not the only lines important to radioastronomy, and for historical reasons the selection does not give full weight to the millimetre wave region of the spectrum. A more complete list is given in Recommendation 314-4. However, those included in the Annexes are a reasonably representative sample showing the kinds of observation made and the variety of results obtained. The Annexes also demonstrate how some of the significant conclusions concerning the nature of the Universe can be reached on the basis of spectral line observations.

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TABLE I – *Interstellar lines detected by radio astronomers and the corresponding rest frequencies (from ref. 10, Lovas et al., 1978, unless otherwise specified in column 3)**

(up to August 1977)

Frequency (GHz)	Molecule/Atom			Absorption (A) or emission (E)
(1)	(2)			(3)
0.834267	CH_3OH	–	methyl alcohol	E
1.065075	CH_3CHO	–	acetaldehyde	E
1.371709	CH_2CHCN	–	vinyl cyanide	E**
1.371794	CH_2CHCN	–	vinyl cyanide	E**
1.371947	CH_2CHCN	–	vinyl cyanide	E**
1.420406	H	–	hydrogen	A and E**
1.538135	NH_2CHO	–	formamide	E
1.538693	NH_2CHO	–	formamide	E
1.539295	NH_2CHO	–	formamide	E
1.539570	NH_2CHO	–	formamide	E
1.539851	NH_2CHO	–	formamide	E
1.541018	NH_2CHO	–	formamide	E
1.610249	$HCOOCH_3$	–	methyl formate	E
1.610906	$HCOOCH_3$	–	methyl formate	E
1.6122310	OH	–	hydroxyl	A and E**
1.62443	^{17}OH	–	hydroxyl	A^1
1.62617	^{17}OH	–	hydroxyl	A^1
1.637564	^{18}OH	–	hydroxyl	A
1.638805	HCOOH	–	formic acid	E
1.639503	^{18}OH	–	hydroxyl	A
1.6654018	OH	–	hydroxyl	A and E**
1.6673590	OH	–	hydroxyl	A and E**
1.7205300	OH	–	hydroxyl	A and E**
2.66161	HCCCCCN	–	cyanodiacetylene	E
2.66287	HCCCCCN	–	cyanodiacetylene	E
2.66476	HCCCCCN	–	cyanodiacetylene	E
3.139406	H_2CS	–	thioformaldehyde	A
3.195167	CH_3CHO	–	acetaldehyde	E
3.263794	CH	–	CH radical	E
3.335481	CH	–	CH radical	A and E
3.349193	CH	–	CH radical	A and E
4.3887786	$H_2C^{18}O$	–	formaldehyde	A
4.3887960	$H_2C^{18}O$	–	formaldehyde	A
4.3887963	$H_2C^{18}O$	–	formaldehyde	A
4.3888011	$H_2C^{18}O$	–	formaldehyde	A
4.3888035	$H_2C^{18}O$	–	formaldehyde	A
4.3888084	$H_2C^{18}O$	–	formaldehyde	A
4.5929563	$H_2{}^{13}CO$	–	formaldehyde	A
4.5929738	$H_2{}^{13}CO$	–	formaldehyde	A
4.5929759	$H_2{}^{13}CO$	–	formaldehyde	A
4.5929857	$H_2{}^{13}CO$	–	formaldehyde	A
4.5929934	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930494	$H_2{}^{13}CO$	–	formaldehyde	A

*/** See notes at the end of the Table.

TABLE I *(continued)*

(1)	(2)			(3)
4.5930690	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930800	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930812	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930864	$H_2{}^{13}CO$	–	formaldehyde	A
4.59308654	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930942	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930961	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930985	$H_2{}^{13}CO$	–	formaldehyde	A
4.5930994	$H_2{}^{13}CO$	–	formaldehyde	A
4.5931039	$H_2{}^{13}CO$	–	formaldehyde	A
4.5931741	$H_2{}^{13}CO$	–	formaldehyde	A
4.5931795	$H_2{}^{13}CO$	–	formaldehyde	A
4.5932003	$H_2{}^{13}CO$	–	formaldehyde	A
4.5932046	$H_2{}^{13}CO$	–	formaldehyde	A
4.5932099	$H_2{}^{13}CO$	–	formaldehyde	A
4.617126	NH_2CHO	–	formamide	E
4.618966	NH_2CHO	–	formamide	E
4.619988	NH_2CHO	–	formamide	E
4.660242	OH	–	hydroxyl	E
4.750656	OH	–	hydroxyl	E
4.765562	OH	–	hydroxyl	E
4.8296413	H_2CO	–	formaldehyde	A and E**
4.8296583	H_2CO	–	formaldehyde	A and E**
4.8296596	H_2CO	–	formaldehyde	A and E**
4.8296639	H_2CO	–	formaldehyde	A and E**
4.8296664	H_2CO	–	formaldehyde	A and E**
4.8296710	H_2CO	–	formaldehyde	A and E**
4.916312	HCOOH	–	formic acid	E
5.00532	CH_3OH	–	methyl alcohol	E
5.289011	H_2CNH	–	methanimine	E
5.289685	H_2CNH	–	methanimine	E
5.289814	H_2CNH	–	methanimine	E
5.290610	H_2CNH	–	methanimine	E
5.290880	H_2CNH	–	methanimine	E
5.291676	H_2CNH	–	methanimine	E
6.030747	OH	–	hydroxyl	A and E
6.035092	OH	–	hydroxyl	A and E
6.278631	H_2CS	–	thioformaldehyde	A
6.38949	CH_3CHO	–	acetaldehyde	E
8.135868	OH	–	hydroxyl	E
8.18883	–	–	not yet identified	E
8.77506	CH_3NH_2	–	methylamine	E
8.77738	CH_3NH_2	–	methylamine	E
8.77818	CH_3NH_2	–	methylamine	E
8.77947	CH_3NH_2	–	methylamine	E
9.058498	$HC^{13}CCN$	–	cyanoacetylene	E
9.059330	$HCC^{13}CN$	–	cyanoacetylene	E
9.059739	$HC^{13}CCN$	–	cyanoacetylene	E

TABLE I *(continued)*

(1)	(2)	(3)
9.060617	$HCC^{13}CN$ – cyanoacetylene	E
9.061700	$HC^{13}CCN$ – cyanoacetylene	E
9.062553	$HCC^{13}CN$ – cyanoacetylene	E
9.0970346	HCCCN – cyanoacetylene	E
9.0983321	HCCCN – cyanoacetylene	E
9.1002727	HCCCN – cyanoacetylene	E
9.118818	CH_3OCH_3 – dimethylether	E
9.119670	CH_3OCH_3 – dimethylether	E
9.120515	CH_3OCH_3 – dimethylether	E
10.152002	HCCCCCCCN – cyanohexatriyne	E^2
10.31003	CH_3NHD – deuterated methylamine	A and E
10.31070	CH_3NHD – deuterated methylamine	A and E
10.463970	H_2CS – thioformaldehyde	A
10.650643	HCCCCCN – cyanodiacetylene	E**
13.043832	SO – sulphur monoxide	E
13.434596	OH – hydroxyl	E
13.441365	OH – hydroxyl	E
13.778804	$H_2{}^{13}CO$ – formaldehyde	E
14.488458	H_2CO – formaldehyde	A and E**
14.488471	H_2CO – formaldehyde	A and E**
14.488479	H_2CO – formaldehyde	A and E**
14.488489	H_2CO – formaldehyde	A and E**
18.194936	HCCCN – cyanoacetylene	E
18.195190	HCCCN – cyanoacetylene	E
18.196279	HCCCN – cyanoacetylene	E
21.301247	HCCCCCN – cyanodiacetylene	E
21.98054533	HNCO – isocyanic acid	E
21.98147055	HNCO – isocyanic acid	E
21.98208535	HNCO – isocyanic acid	E
22.235044	H_2O – water	E**
22.235077	H_2O – water	E**
22.235120	H_2O – water	E**
22.235253	H_2O – water	E**
22.235298	H_2O – water	E**
22.65300	NH_3 – ammonia	E^3
22.68824	NH_3 – ammonia	E^3
22.834185	NH_3 – ammonia	E
23.098817	NH_3 – ammonia	E
23.694496	NH_3 – ammonia	E**
23.722633	NH_3 – ammonia	E**
23.870130	NH_3 – ammonia	E**
24.13941	NH_3 – ammonia	E
24.532986	NH_3 – ammonia	E
24.93347	CH_3OH – methyl alcohol	E
24.95908	CH_3CH – methyl alcohol	E
25.01814	CH_3OH – methyl alcohol	E
25.056025	NH_3 – ammonia	E
25.12488	CH_3OH – methyl alcohol	E

TABLE I *(continued)*

(1)	(2)			(3)
25.29441	CH_3OH	–	methyl alcohol	E
28.974781	H_2CO	–	formaldehyde	A
28.974804	H_2CO	–	formaldehyde	A
28.974814	H_2CO	–	formaldehyde	A
30.0015236	SO	–	sulphur monoxide	E
31.10526	CH_3OCH_3	–	dimethyl ether	E
31.10620	CH_3OCH_3	–	dimethyl ether	E
31.10712	CH_3OCH_3	–	dimethyl ether	E
36.16924	CH_3OH	–	methyl alcohol	E
36.309631	SiS	–	silicon sulphide	E
36.466	H	–	excited hydrogen	E
36.7952	CH_3CN	–	methyl cyanide	E^4
42.820539	SiO	–	silicon monoxide	E
43.122027	SiO	–	silicon monoxide	E
43.423798	SiO	–	silicon monoxide	E
43.96277	HNCO	–	isocyanic acid	E
45.490307	HCCCN	–	cyanoacetylene	E
46.247472	^{13}CS	–	carbon monosulphide	E
48.206948	$C^{34}S$	–	carbon monosulphide	E
48.284519	H_2CO	–	formaldehyde	E
48.37260	CH_3OH	–	methyl alcohol	E
48.37709	CH_3OH	–	methyl alcohol	E
48.583264	$C^{33}S$	–	carbon monosulphide	E
48.585906	$C^{33}S$	–	carbon monosulphide	E
48.589068	$C^{33}S$	–	carbon monosulphide	E
48.6516063	OCS	–	carbonyl sulphide	E
48.991000	CS	–	carbon monosulphide	E
68.972145	SO_2	–	sulphur dioxide	E
69.575918	SO_2	–	sulphur dioxide	E
72.039354	DCO^+	–	deuterated formyl ion	E
72.409097	H_2CO	–	formaldehyde	E
72.4134843	DCN	–	deuterium cyanide	E
72.4135143	DCN	–	deuterium cyanide	E
72.4135584	DCN	–	deuterium cyanide	E
72.4149054	DCN	–	deuterium cyanide	E
72.4149270	DCN	–	deuterium cyanide	E
72.4149732	DCN	–	deuterium cyanide	E
72.4170297	DCN	–	deuterium cyanide	E
72.758210	SO_2	–	sulphur dioxide	E
72.783822	HCCCN	–	cyanoacetylene	E
72.837974	H_2CO	–	formaldehyde	E
72.9767845	OCS	–	carbonyl sulphide	E
73.04401	CH_3NH_2	–	methylamine	E
73.04420	CH_3NH_2	–	methylamine	E
73.04515	CH_3NH_2	–	methylamine	E
76.305727	DNC	–	deuterium isocyanide	E
79.15	–	–	not yet identified	E
79.915101	NH_2CN	–	cyanamide	E
79.979596	NH_2CN	–	cyanamide	E

TABLE I *(continued)*

(1)	(2)			(3)
80.076611	H_2CCO	–	ketene	E
80.484	–	–	not yet identified	E[5]
80.50460	NH_2CN	–	cyanamide	E
80.536242	CH_2OCH_3	–	dimethyl ether	E
80.538541	CH_3OCH_3	–	dimethyl ether	E
80.540884	CH_3OCH_3	–	dimethyl ether	E
80.578283	HDO	–	deuterated water	E
80.832076	H_2CCO	–	ketene	E
81.44749	HNO	–	nitroxyl hydride	E
81.5427	–	–	not yet identified	E
81.586193	H_2CCO	–	ketene	E
81.881458	HCCCN	–	cyanoacetylene	E
82.65072	CH_3OCH_3	–	dimethyl ether	E
82.68849	CH_3OCH_3	–	dimethyl ether	E
83.58426	CH_3CHO	–	acetaldehyde	E
83.688071	SO_2	–	sulphur dioxide	E
84.50535	$(CH_2)_2O$	–	ethylene oxide	E
84.52121	CH_3OH	–	methyl alcohol	E
84.63440	CH_3OCH_3	–	dimethyl ether	E
84.74601	^{30}SiO	–	silicon monoxide	E
85.1391081	OCS	–	carbonyl sulphide	E
85.26542	CH_3CH_2CH	–	trans ethanol	E
85.435	–	–	not yet identified	E
85.442523	CH_3CCH	–	methylacetylene	E
85.450730	CH_3CCH	–	methylacetylene	E
85.455622	CH_3CCH	–	methylacetylene	E
85.457272	CH_3CCH	–	methylacetylene	E
85.5676	CH_3OH	–	methyl alcohol	E
85.758953	^{29}SiO	–	silicon monoxide	E
85.9	NH_2D	–	deuterated ammonia	E[6]
86.054961	$HC^{15}N$	–	hydrogen cyanide	E**
86.07420	CH_3NH_2	–	methylamine	E**
86.07444	CH_3NH_2	–	methylamine	E**
86.07543	CH_3NH_3	–	methylamine	E**
86.093969	SO	–	sulphur monoxide	E**
86.226728	CH_3OCH_3	–	dimethyl ether	E**
86.243350	SiO	–	silicon monoxide	E**
86.338767	$H^{13}CN$	–	hydrogen cyanide	E**
86.340184	$H^{13}CN$	–	hydrogen cyanide	E**
86.342274	$H^{13}CN$	–	hydrogen cyanide	E**
86.6154	CH_3OH	–	methyl alcohol	E**
86.639138	SO_2	–	sulphur dioxide	E**
86.67065	HCO	–	formyl radical	E**
86.70838	HCO	–	formyl radical	E[7]**
86.754330	$H^{13}CO^+$	–	formyl ion	E**
86.7568	–	–	not yet identified	E**
86.77752	HCO	–	formyl radical	E[7]**
86.80582	HCO	–	formyl radical	E[7]**

TABLE I *(continued)*

(1)	(2)			(3)
86.846891	SiO	–	silicon monoxide	E**
86.9035	CH_3OH	–	methyl alcohol	E**
87.090851	$HN^{13}C$	–	hydrogen isocyanide	E**
87.31705	HCC	–	ethynyl radical	E**
87.32870	HCC	–	ethynyl radical	E**
87.40210	HCC	–	ethynyl radical	E**
87.40723	HCC	–	ethynyl radical	E**
87.925238	HNCO	–	isocyanic acid	E**
88.239027	HNCO	–	isocyanic acid	E**
88.32372	CH_3CH_2CN	–	ethylcyanide	E**
88.6304157	HCN	–	hydrogen cyanide	E**
88.6318473	HCN	–	hydrogen cyanide	E**
88.6339360	HCN	–	hydrogen cyanide	E**
88.66806	CH_3NH_2	–	methylamine	E**
88.66862	CH_3NH_2	–	methylamine	E**
88.66961	CH_3NH_2	–	methylamine	E**
88.865692	$H^{15}NC$	–	hydrogen isocyanide	E**
89.0457	CCCN	–	C_3N radical	E**
89.0644	CCCN	–	C_3N radical	E**
89.188523	HCO^+	–	formyl ion	E**
89.5046	CH_3OH	–	methyl alcohol	E**
89.56224	CH_3CH_2CN	–	ethylcyanide	E**
89.56495	CH_3CH_2CN	–	ethylcyanide	E**
89.56803	CH_3CH_2CN	–	ethylcyanide	E**
89.57298	CH_3CH_2CN	–	ethylcyanide	E**
89.58998	CH_3CH_2CN	–	ethylcyanide	E**
89.59096	CH_3CH_2CN	–	ethylcyanide	E**
89.62841	CH_3CH_2CN	–	ethylcyanide	E**
89.68467	CH_3CH_2CN	–	ethylcyanide	E**
90.11761	CH_3CH_2OH	–	trans ethanol	E**
90.146	–	–	not yet identified	E**
90.663602	HNC	–	hydrogen isoyanide	E**
90.771546	SiS	–	silicon sulphide	E**
90.937539	CH_3OCH_3	–	dimethyl ether	E**
90.938099	CH_3OCH_3	–	dimethyl ether	E**
90.938674	CH_3OCH_3	–	dimethyl ether	E**
90.979023	HCCCN	–	cyanoacetylene	E**
91.20261	HCCCN	–	cyanoacetylene	E**
91.33332	HCCCN	–	cyanoacetylene	E**
91.54910	CH_3CH_2CN	–	ethylcyanide	E**
91.959206	CH_3CN	–	methyl cyanide	E**
91.971374	CH_3CN	–	methyl cyanide	E**
91.979998	CH_3CN	–	methyl cyanide	E**
91.985284	CH_3CN	–	methyl cyanide	E**
91.987054	CH_3CN	–	methyl cyanide	E**
92.3527	–	–	not yet identified	E
92.494084	^{13}CS	–	carbon monosulphide	E
93.17188	HNN^+	–	diazenylium	E

TABLE I *(continued)*

(1)	(2)			(3)
93.17370	HNN^+	–	diazenylium	E
93.17613	HNN^+	–	diazenylium	E
93.85711	CH_3OCH_3	–	dimethyl ether	E
93.87173	NH_2CHO	–	formamide	E
94.2766	CH_2CHCN	–	vinyl cyanide	E
94.40517	$^{13}CH_3OH$	–	methyl alcohol	E
94.40702	$^{13}CH_3OH$	–	methyl alcohol	E
94.5407	CH_3OH	–	methyl alcohol	E
95.16944	CH_3OH	–	methyl alcohol	E
95.44244	CH_3CH_2CN	–	ethyl cyanide	E
96.412953	$C^{34}S$	–	carbon monosulphide	E
96.73939	CH_3OH	–	methyl alcohol	E
96.74142	CH_3OH	–	methyl alcohol	E
96.75551	CH_3OH	–	methyl alcohol	E
96.84963	CH_3OCH_3	–	dimethyl ether	E
96.91971	CH_3CH_2CN	–	ethyl cyanide	E
97.171824	$C^{33}S$	–	carbon monosulphide	E
97.171843	$C^{33}S$	–	carbon monosulphide	E
97.3012130	OCS	–	carbonyl sulphide	E
97.702389	SO_2	–	sulphur dioxide	E
97.71539	^{34}SO	–	sulphur monoxide	E
97.981007	CS	–	carbon monosulphide	E
98.17755	CH_3CH_2CN	–	ethyl cyanide	E
98.52380	CH_3CH_2CN	–	ethyl cyanide	E
98.52458	CH_3CH_2CN	–	ethyl cyanide	E
98.53201	CH_3CH_2CN	–	ethyl cyanide	E
98.53391	CH_3CH_2CN	–	ethyl cyanide	E
98.56478	CH_3CH_2CN	–	ethyl cyanide	E
98.56674	CH_3CH_2CN	–	ethyl cyanide	E
98.61007	CH_3CH_2CN	–	ethyl cyanide	E
98.70107	CH_3CH_2CN	–	ethyl cyanide	E
98.9399	CCCN	–	C_3N radical	E
98.9586	CCCN	–	C_3N radical	E
99.299867	SO	–	sulphur monoxide	E
100.029644	SO	–	sulphur monoxide	E
100.076392	HCCCN	–	cyanoacetylene	E
100.09451	H_2CCO	–	ketene	E
100.1570	–	–	not yet identified	E
100.2004	–	–	not yet identified	E
100.61428	CH_3CH_2CN	–	ethyl cyanide	E
100.62950	NH_2CN	–	cyanamide	E
100.6404	CH_3CHO	–	acetaldehyde	E
100.878119	SO_2	–	sulphur dioxide	E
101.03671	H_2CCO	–	ketene	E
101.139	–	–	not yet identified	E
101.477752	H_2CS	–	thioformaldehyde	E
101.98139	H_2CCO	–	ketene	E
103.040399	H_2CS	–	thioformaldehyde	E

TABLE I *(continued)*

(1)	(2)			(3)
103.91527	$(CH_2)_2O$	–	ethylene oxide	E
104.029398	SO_2	–	sulphur dioxide	E
104.05124	CH_3CH_2CN	–	ethyl cyanide	E
104.06076	CH_3OH	–	methyl alcohol	E
104.239272	SO_2	–	sulphur dioxide	E
104.589	–	–	not yet identified	E
104.616977	H_2CO	–	thioformaldehyde	E
104.667	–	–	not yet identified	E
104.70266	CH_3OCH_3	–	dimethyl ether	E
104.711416	$^{13}C^{18}O$	–	carbon monoxide	E
104.80862	CH_3CH_2OH	–	trans ethanol	E
104.811	–	–	not yet identified	E
105.472	–	–	not yet identified	E
105.577	–	–	not yet identified	E
106.74292	^{34}SO	–	sulphur monoxide	E
108.924267	SiS	–	silicon sulphide	E
109.173634	HCCCN	–	cyanoacetylene	E
109.252226	SO	–	sulphur monoxide	E
109.463079	OCS	–	carbonyl sulphide	E
109.65029	CH_3CH_2CN	–	ethyl cyanide	E
109.782182	$C^{18}O$	–	carbon monoxide	E
109.905753	HNCO	–	isocyanic acid	E
110.2	NH_2D	–	deuterated ammonia	E[6]
110.201370	^{13}CO	–	carbon monoxide	E
110.330728	CH_3CN	–	methyl cyanide	E
110.349706	CH_3CN	–	methyl cyanide	E
110.364490	CH_3CN	–	methyl cyanide	E
110.374986	CH_3CN	–	methyl cyanide	E
110.381362	CH_3CN	–	methyl cyanide	E
110.383494	CH_3CN	–	methyl cyanide	E
110.70955	CH_3CN	–	methyl cyanide	E
110.71222	CH_3CN	–	methyl cyanide	E
112.24872	CH_3CHO	–	acetaldehyde	E
112.25448	CH_3CHO	–	acetaldehyde	E
112.35872	$C^{17}O$	–	carbon monoxide	E
112.358980	$C^{17}O$	–	carbon monoxide	E
112.360016	$C^{17}O$	–	carbon monoxide	E
113.144192	CN	–	cyanogen radical	E
113.170528	CN	–	cyanogen radical	E
113.191317	CN	–	cyanogen radical	E
113.488140	CN	–	cyanogen radical	E
113.490982	CN	–	cyanogen radical	E
113.499639	CN	–	cyanogen radical	E
113.508944	CN	–	cyanogen radical	E
113.97821	CH_3CH_2CN	–	ethyl cyanide	E
114.93990	CH_3CHO	–	acetaldehyde	E
114.95965	CH_3CHO	–	acetaldehyde	E
115.15392	NS	–	nitrogen sulphide	E

TABLE I *(continued)*

(1)	(2)			(3)
115.15697	NS	–	nitrogen sulphide	E
115.271204	CO	–	carbon monoxide	E**
115.55643	NS	–	nitrogen sulphide	E
115.57120	NS	–	nitrogen sulphide	E
115.89435	CH_3CH_2CN	–	ethyl cyanide	E
127.367666	HCCCN	–	cyanoacetylene	E
129.363262	SiO	–	silicon monoxide	E
130.268574	SiO	–	silicon monoxide	E**
135.69602	SO_2	–	sulphur dioxide	E**
138.178645	SO	–	sulphur dioxide	E**
138.73897	^{13}CS	–	carbon monosulphide	E**
140.839529	H_2CO	–	formaldehyde	E
144.617117	$C^{34}S$	–	carbon monosulphide	E
144.8265727	DCN	–	deuterium cyanide	E
144.8268097	DCN	–	deuterium cyanide	E
144.8268414	DCN	–	deuterium cyanide	E
144.8280003	DCN	–	deuterium cyanide	E
144.8281093	DCN	–	deuterium cyanide	E
144.8303358	DCN	–	deuterium cyanide	E
145.09375	CH_3OH	–	methyl alcohol	E
145.09747	CH_3OH	–	methyl alcohol	E
145.10323	CH_3OH	–	methyl alcohol	E
145.12441	CH_3OH	–	methyl alcohol	E
145.12637	CH_3OH	–	methyl alcohol	E
145.13188	CH_3OH	–	methyl alcohol	E
145.13346	CH_3OH	–	methyl alcohol	E
145.602971	H_2CO	–	formaldehyde	E
145.755619	$C^{33}S$	–	carbon monosulphide	E
145.755635	$C^{33}S$	–	carbon monosulphide	E
145.756374	$C^{33}S$	–	carbon monosulphide	E
145.756392	$C^{33}S$	–	carbon monosulphide	E
145.9468205	OCS	–	carbonyl sulphide	E
146.969039	CS	–	carbon monosulphide	E
150.498359	H_2CO	–	formaldehyde	E
168.76276237	H_2S	–	hydrogen sulphide	E
169.33534	CH_3CH	–	methyl alcohol	E
172.107956	$HC^{15}N$	–	hydrogen cyanide	E
172.676573	$H^{13}CN$	–	hydrogen cyanide	E
172.677959	$H^{13}CN$	–	hydrogen cyanide	E
172.680209	$H^{13}CN$	–	hydrogen cyanide	E
177.2596767	HCN	–	hydrogen cyanide	E
177.2599233	HCN	–	hydrogen cyanide	E
177.2611104	HCN	–	hydrogen cyanide	E
177.2611112	HCN	–	hydrogen cyanide	E
177.2612232	HCN	–	hydrogen cyanide	E
177.2634450	HCN	–	hydrogen cyanide	E
183	H_2O	–	water	E[8]
217.238531	DCN	–	deuterium cyanide	E

TABLE I *(continued)*

(1)	(2)			(3)
219.560369	$C^{18}O$	–	carbon monoxide	E
220.398714	^{13}CO	–	carbon monoxide	E
230.538001	CO	–	carbon monoxide	E**
345	CO	–	carbon monoxide	E^{9}

* A complete list of radio atomic and molecular lines is given in order to facilitate protection arrangements. There are also a large number of important recombination lines of hydrogen, helium, carbon etc. A full table of recombination line frequencies is available [Lilley and Palmer (1968)].

** Afforded some measure of protection by the Radio Regulations.

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ANNEX I

THE NEUTRAL HYDROGEN LINE AT 1420.406 MHz

Emission from atomic hydrogen occurs from a hyperfine spin-flip transition at the ground level of the atom. This emission was first observed in 1951 [Ewen and Purcell, 1951]. The study of the neutral hydrogen component of the interstellar medium is particularly suitable for a number of fundamental astronomical problems. Hydrogen, the most abundant element in the Universe, is also the main observed constituent of the interstellar medium. The motions and distribution of hydrogen are closely related to those of other galactic constituents, both stellar and interstellar. The interstellar medium is transparent enough to radio emission at 1420 MHz, so that, with the exception of a few directions along the galactic equator, it is possible to investigate the entire Milky Way galaxy and other distant galaxies. This transparency allows investigation of regions of the Milky Way which are too distant, or are too obscured by dust in the interstellar medium, to be studied optically. Interstellar neutral hydrogen is so abundant and is distributed in such a general fashion throughout the galaxy, that the emission line has been detected at every direction in the sky at which a suitably equipped radio telescope has been pointed. No time variation of this line has been found. Many 21-cm surveys of galactic hydrogen have been published. These are listed by [Kerr, 1969] and [Burton, 1974] and [Heiles and Wrixon, 1976].

What is detected is a line profile giving intensity, usually expressed as a brightness temperature, as a function of frequency. The frequency observed for the line may indicate a Doppler shift from the natural rest frequency of 1420.406 MHz. The Doppler-shift information inherent in observations of hydrogen within a galaxy is very important since it allows the kinematic distribution of the gas to be studied, in addition to the spatial distribution of intensities. In practice, the measured frequency shifts are converted to radial velocities. At 1420 MHz, a velocity of recession of 1 km/s corresponds to a reduction in frequency of 4.74 kHz. The natural width of the neutral hydrogen line is 5×10^{-16} Hz and is thus infinitesimally small compared to that which can be measured by radioastronomical methods. However, profiles observed near the Milky Way typically extend over 500 kHz. This broadening occurs throughout several mechanisms. The broadening corresponding to the thermal velocities of atoms within a single concentration of gas is typically 5 or 10 kHz. Turbulent motions within a concentration of hydrogen gas will also produce profile broadening of this order of magnitude. Large-scale streaming motions with Doppler-shift amplitudes of the order of 30 kHz have been observed in our galaxy and in others, and these motions influence the measured width of features in a profile. However, most of the total line broadening in galaxies comes from the differential rotation of the galaxy as a whole. For many galaxies this rotation broadens the profiles by 2500 kHz. Large-scale expansion motions in the still poorly understood central region of the Milky Way result in profiles broadened by a similar amount.

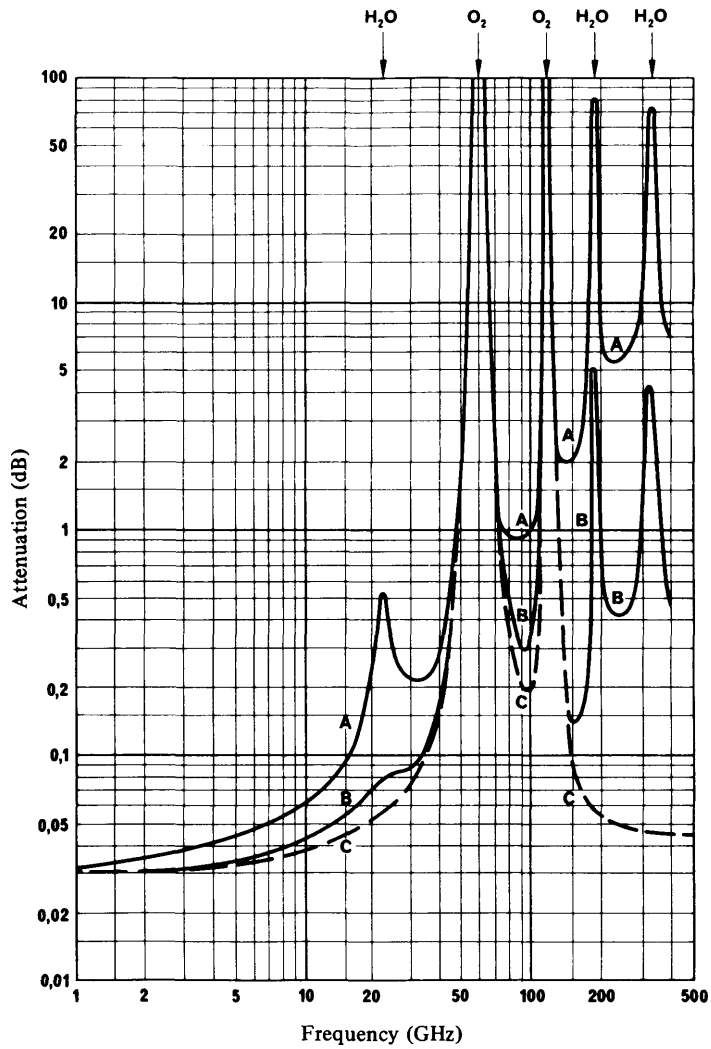

FIGURE 1 – *Total attenuation along vertical path through a clear atmosphere*

A: Average atmosphere with water vapour concentration of 7.5 g/m^3 (1.5 cm equivalent depth) at the Earth's surface

B: Average atmosphere with water vapour concentration of 0.5 g/m^3 (1 mm equivalent depth) at the Earth's surface

C: Dry atmosphere

The most intense emission features are measured near the plane of the Milky Way resulting in brightness temperatures of about 100 K. In other regions of our Galaxy, brightness temperatures from normal gas range down to about 1 K. Abnormal gas, with high velocities, provides temperatures which range down to arbitrarily small values, and sensitivity requirements are severe. Special studies of normal gas, including for example, the measurement of Zeeman splitting to derive the magnetic field in the Galaxy, also place severe requirements on sensitivity; with modern equipment, integration times of 50 hours are sometimes necessary [Verschuur, 1971].

The zero level of the intensity scale is usually found by interpolation between the wings of the profiles which are considered to contain no hydrogen emission. This method of zero-level determination requires an addition of about 100 kHz, or more, which must be observed beyond the wings of the line itself. To eliminate the contribution of the continuum background emission, frequency-switching techniques are generally employed. Frequency switching over 1.5 or 2 MHz is typical, but observations of high-velocity gas may require switching over 3 to 5 MHz, usually on both the high and low frequency sides of the line.

In addition to the emission arising from the hyperfine transition, absorption effects are also present and extensively studied. The frequency requirements for absorption studies are similar to those for emission studies. Absorption observations provide unique information on the spin temperature of hydrogen concentrations, and provide measures which are very sensitive to low temperature.

External galaxies exhibit the well-known "red shift", a decrease of the observed frequency dependent on the distance of the galaxy. Receivers used at present allow successful studies to be made at intensities below 0.01 jansky *. Most normal spiral galaxies at this flux density level have radial velocities of 4000 to 6000 km/s, and therefore are observed at frequencies down to 1390 MHz. The number of normal galaxies for which hydrogen-line data are available is approximately 500; this number is increasing rapidly, and is being augmented by investigations of nearby dwarf galaxies which were heretofore undetectable. These studies are important for determining the gross properties of galaxies such as distance, mass and hydrogen content. Data on a wide variety of objects will facilitate the development of theories of galactic formation and evolution. Concurrently, detailed synthetic aperture observations of the larger nearby galaxies are being made to confirm theories of spiral structure.

Some of the most exciting and important present day radio observations involve detection of the observed hydrogen line in distant continuum sources. These have been accomplished for the radio galaxy Perseus A [De Young *et al.*, 1973] and for the quasi-stellar objects 3C 286 [Brown and Roberts, 1973] and AO 0235 + 164 [Roberts *et al.*, 1976]. The detection of red-shifted 21 cm radiation from AO 0235 + 164 is of great cosmological significance. Since red-shifted optical lines (Mg^+) had been previously detected in this source it became possible to make a direct comparison between the radio and optical red-shifts over a large cosmological distance. The fact that the radio and optical red-shifts agreed to within the experimental uncertainties (1 part in 5000 for the optical measurement, and 1 part in 50 000 for the radio), allows one to place upper limits on the time variations of the physical constants which enter the atomic theory of spectroscopy.

Historically, the first line to be detected in the radio spectrum, the 21-cm hydrogen line, continues to grow in importance. The development of sensitive receivers has broadened the scope of extra-galactic studies to include objects with large Doppler shifts. Current observational programmes are directed towards obtaining spectra of large numbers of galaxies having emission frequencies at and below 1370 MHz at intensities of about 0.01 jansky. At the same time, detailed studies of our own and nearby galaxies are continuing between 1415 and 1427 MHz.

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ANNEX II

THE OH LINES IN RADIOASTRONOMY

1. Introduction

Radio-frequency spectral lines due to the hydroxyl molecule (OH) were first detected and measured in the laboratory in 1959 [Ehrenstein *et al.*, 1959], and in interstellar space in 1963 [Weinreb *et al.*, 1963]. Absorption of radio-frequency radiation from the radio source Cassiopeia A was observed at frequencies ** which correspond to those of the two principal ground state lines, at 1665.401 and 1667.358 MHz. Shortly afterwards, even stronger absorption lines were found from the region of the galactic centre [Bolton *et al.*, 1964a; Robinson *et al.*, 1964; Goldstein *et al.*, 1964], and two expected subsidiary ground-state lines, arising from alternative configurations of spins within the OH molecule, were detected and their rest frequencies determined at 1612.231 and 1720.527 MHz [Goss, 1968]. The very much lower intensity absorption line at 1639 MHz has been detected in the direction of the galactic centre [Rogers and Barrett, 1966]. This line is due to the $O^{18}H$ molecule where the oxygen is the mass-18 isotope of the normal O^{16}. Investigation of narrow-band emissions from regions of ionized hydrogen in the galaxy [Weaver *et al.*, 1965; Zuckerman *et al.*, 1965] identified them as arising from OH. This emission is unexpectedly intense, producing increases in antenna temperature of as much as 150 K, and it has, surprisingly, been found to have a circularly polarized component [Davies *et al.*, 1966]. A number of the sources of OH emission have now been studied with interferometers, to get more precise positions of the sources [Rogers *et al.*, 1967] and estimates of the angular sizes of the sources [Davies *et al.*, 1967]. The new technique of "very long base-line" or VLB interferometry, with base-lines of length comparable with the diameter of the Earth, have been used to study some OH sources [Moran *et al.*, 1967] and, also apparent angular sizes of less than 0.005 seconds of arc have been measured. This last technique, by an equipment improvement which is within the state of our present knowledge,

* One jansky (Jy) = 1 flux unit (f.u.) = 10^{-26} W/m^2 per Hz.

** The frequencies in this Report are the *rest frequencies* for the radiation concerned.

opens up possibilities of using radio sources of very small angular size as position references for the location of the observing points on the Earth. Possible uses in measuring earth tides, continental drift, and accurate terrestrial rates of rotation, have been predicted [Gold, 1967; MacDonald, 1967].

The discovery of lines due to OH is of great astrophysical significance. The extent by which the observed frequencies are displaced from their rest frequencies by Doppler effects provides direct information about the motions of the gas clouds in which the OH occurs. The anomalies in the line intensities, both in emission and absorption, throw new and unexpected light on the physical conditions in particular regions of our galaxy. The observations also give more information on the structure of our galaxy.

2. The distribution of OH in the galaxy

Early survey work [Goss, 1968] showed, and later more thorough work [Turner, 1970; Turner, 1972] confirmed, that OH is very widely distributed throughout the galactic disk in a region within a few hundred parsecs * of the galactic plane. It is somewhat more closely confined to the plane than atomic hydrogen, and appears to be an excellent tracer of spiral arms. It does not appear to be closely associated with continuum sources, but rather to delineate the presence of dense neutral clouds of gas in a manner which is not possible optically or by means of 21-cm line of atomic hydrogen. This latter aspect has been of immense importance in the burgeoning studies of many other newly discovered interstellar molecules, as these molecules have been found in just these same dense clouds. In a literal sense, OH has proved to be the tracer molecule in the new field of interstellar molecular chemistry. Apart from its location in dense neutral gas clouds, OH has been discovered in some types of infra-red stars. A variety of other types of astronomical objects, such as planetary nebulae, Wolf-Rayet and T-Tauri stars, young and highly reddened stellar associations and clusters, do not yield observable OH to very low limits. It is anticipated that studies of physical conditions in these objects will shed light on the questions of formation and destruction of interstellar molecules in general, and OH in particular. Detection of OH in both absorption and emission has been made in comets, and research in this area is having important implications as to the origin and history of the solar system.

3. The properties of the absorption lines

The anomalies in the intensities of the lines when observed in absorption, continue to pose important problems, as these relative intensities in the observed lines sometimes differ considerably from the expected values for a source in thermodynamic equilibrium. For example, the absorption spectrum of the supernova remnant, Cassiopeia A, was examined at the frequencies of the two satellite lines, 1612 and 1720 MHz. Whereas both the 1665 and 1667 MHz transitions show splitting into two lines, neither the 1612 nor the 1720 MHz transition shows any splitting. Furthermore, the absorption at 1612 MHz is approximately one half of that at 1665 MHz, instead of one fifth, as expected. Finally, the observations indicate a small amount of OH emission at 1720 MHz, but none is detectable at 1612 MHz. The unusual absorption features and the presence of weak emission have been independently confirmed. It is very difficult to see how any of these observations can be explained in terms of a medium in thermodynamic equilibrium, and these observations are among the many that require further explanation.

Other absorption anomalies have been found in the spectrum of the galactic centre [Robinson *et al.*, 1964; Goldstein *et al.*, 1964; Goss, 1968; Bolton *et al.*, 1964b]. For example, the observed ratios of line intensities among the four lines are quite different from the ratios that are expected on the basis of thermal equilibrium. It is tempting to try to explain the observed values in terms of a medium exhibiting large attenuation, for which all ratios would approach unity, but this attempt fails. For example, isolated regions near the galactic centre show stronger absorption at 1665 than at 1667 MHz, and many regions show unequal absorption at 1612 and at 1720 MHz. It seems clear that these observations require the assumption of non-thermal distribution of the OH molecules among the internal energy states from which the radio lines are derived.

The OH observations in the galactic centre pose problems other than anomalous line-intensity ratios. OH absorption is very strong and extends over a considerable frequency, or velocity range. If OH profiles for the galactic centre are interpreted in a manner similar to that described for Cassiopeia A, then one derives on OH/H abundance ratio of $\sim 10^{-4}$ some 10^3 times the ratio in the direction of Cassiopeia A. However, this value must be used with extreme caution, because any derived values, based upon observations, must await a full understanding of the mechanism by which OH is formed, how it is distributed with respect to its internal energy levels, and how it absorbs and emits radio energy. From the frequency at which OH absorption occurs, one can determine the velocity in the line-of-sight of the OH cloud relative to the Sun; and it is found that much of the OH is moving toward the galactic centre with a velocity of 40 km/s. This cloud also contains other molecules and neutral hydrogen. On the other hand, most of the other gases associated with the galactic centre appear to be streaming away from the centre. The motions in the central region are clearly very complex. This is a curious situation and may force a revision of our ideas about the physical conditions in the galactic nucleus. It should be emphasized, though, that the observations tell us nothing about the distances to the OH and H; the concept that they are associated with the galactic centre rests strictly on interpretations of the accumulated evidence.

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* 1 parsec = 3.26 light years.

4. The properties of the emission lines

The observations of the OH emission lines have similarly opened up a new and complex area of astronomical research. Early attempts to detect OH emission were confined to observations at 1667 MHz because it was thought this would be the strongest transition, but all attempts gave negative results. When OH was finally discovered in emission at 1665 MHz, not 1667 MHz, its properties were so unusual that two out of the first three groups of radio astronomers to observe it did not attribute the line to OH.

Australian observers first observed OH emission in June, 1964, when a narrow, intense emission line was detected to the side of an absorption line at 1665 MHz in the direction of the galactic centre [McGee *et al.*, 1965]. However, the effect was apparently thought to be an instrumental effect and was not reported at the time. Six months or more later, OH emission was observed by groups at Harvard and Berkeley, with properties so unexpected that the Berkeley radio astronomers thought they had detected an unidentified micro-wave spectral line; they nicknamed the line "mysterium" until identification could be established. Although "mysterium" was almost immediately identified as OH, the name can hardly be called a misnomer in view of the strange properties exhibited in interstellar OH.

The first OH emission sources found, were characterized by intense, narrow emission lines at 1665 MHz, with lines of lesser intensity at the other three OH frequencies. Departures by several orders of magnitude from the expected intensity ratios were the rule; furthermore, the spectrum obtained at one frequency was usually completely uncorrelated with that obtained at another. This early type of OH emission source is now recognized as only one of three distinctly different types of such sources. A second type radiates solely in the 1720 MHz line, while the third type has strongest emission at 1612 MHz but may be accompanied by weaker emission at both 1665 and 1667 MHz. While the peculiarities of these three types of emission source may appear random, in fact this is not so. Observationally, each type is rather well defined with respect to the relative intensities among the four lines, and each type also shows distinct polarization properties. Theoretically, models have been developed which, although probably not unique, do appear to explain the salient properties of each type of source.

The objects with which the various types of OH emission source are associated, are a major factor in the models proposed to explain them. Unlike the 21-cm emission of atomic hydrogen which is widely distributed throughout the Milky Way, each type of OH emission source is found only in special regions. The type associated with strong 1665 MHz emission is found only in isolated positions near ionized hydrogen regions, at positions where strong sources of infra-red are often found; while the type associated with strong 1612 MHz lines comes from the atmospheres of cool stars. The sources emitting in only the 1720 MHz line have a more obscure origin, although they are definitely not associated with stellar-like objects.

Between 1968 and 1971, a total of five different emission lines have been discovered which arise from transitions within excited rotational energy states of OH [Zuckerman *et al.*, 1968; Yen *et al.*, 1969; Turner *et al.*, 1970]. Many other lines from these states which theoretically ought to be present are not found. This situation offers evidence as strong as that provided by the peculiar properties of the 18-cm lines, that the excitation of OH is in general not consistent with a medium in thermodynamic equilibrium. Observations of excited-state lines have also proved very valuable in distinguishing between the various theoretical models for anomalous excitation of OH.

5. The $O^{18}H$ and $O^{17}H$ lines

The strong OH absorption found in the direction of the galactic centre has made another experiment feasible. All the results discussed above have referred to the abundant isotopic species $O^{16}H$, but the observation of strong absorption suggested the possibility that the isotopic species $O^{18}H$ and possibly also $O^{17}H$ could be detected. The frequencies of these isotopes are shifted relative to those of the $O^{16}H$ lines because of mass-dependent effects on the molecular energy levels.

Early searches for the $O^{18}H$ lines were successful [Rogers and Barrett, 1966; Wilson and Barrett, 1970]. Although weak as expected, both main lines (at 1637 and 1639 MHz) were detected in the galactic centre, and yielded an abundance ratio $O^{18}H/O^{16}H$ of 1/390, which is consistent with the terrestrial ratio for O^{18}/O^{16} of 1/490 within the uncertainties in the observations.

Laboratory measurements of the 18 cm lines in the ground states of $O^{18}H$ and $O^{17}H$ have been made [Ball *et al.*, 1970]. Because of the nuclear spin of the O^{17} nucleus, there are many more hyperfine transitions within the ground state of $O^{17}H$ than in the other two isotopes. However, the line strengths of only two of these $O^{17}H$ lines are strong enough to warrant astronomical searches with present equipment. These two lines, at 1624.4 and 1626.2 MHz have been found in the direction towards the galactic centre.

6. Positions and sizes of OH emission sources

The positions of a number of the OH sources have been determined to an accuracy of better than one second of arc [Rogers *et al.*, 1967]. The results have shown that an emission source can be a number of very small bright regions separated by angular distances of a few seconds of arc. The angular sizes of the regions themselves have been studied with interferometers of ever increasing base lines and angular resolutions. First results come with spacings between the antennae of 127 km, or 7×10^5 wavelengths [Davies *et al.*, 1967], and these showed that one emitting region was less than 0.05 seconds of arc in size.

The technique of very long base-line (VLB) interferometry began at about this time. In these experiments, two very distant radio telescopes observe the same source, and work as an interferometer because the local oscillator or phase reference at each telescope is derived from a highly stable rubidium maser. The resulting records for each telescope are subsequently carried to a computer and cross-correlated to develop the interference fringes. This technique was shown to work first for continuum observations [Broten *et al.*, 1967; Bare *et al.*, 1967]; but it is now extensively applied to OH line studies. As examples of base lines used, the radio telescopes at Hat Creek (University of California), Lincoln Laboratory (Massachusetts Institute of Technology, near Boston), National Radio Astronomy Observatory (Green Bank, West Virginia) and Onsala (near Gothenburg, Sweden) have all experimented on OH line work in pairs. The results show that OH emission sources can be as small as 0.005 seconds of arc in size. This limit may be still further reduced as experiments continue.

If the frequency and phase stability of the VLB experiments can be improved (by the use of hydrogen masers, for example), the technique may be usable for measuring the absolute positions of sources in the sky to better than 10^{-3} seconds of arc. This in turn corresponds to position measures on Earth of 3 cm and the possibility of using such measures for a variety of geodetic and geophysical measurements is very attractive [Gold, 1967; MacDonald, 1967].

7. The emission mechanism

The emission line intensities and the very small angular sizes of the sources raise difficult problems in the understanding of the mechanism by which the sources emit. Most attempts to explain the OH observational results have centred around some kind of population inversion of the energy levels, whereby the OH medium would be converted into a medium which amplifies rather than absorbs. For amplification to occur, the population of the higher energy levels (those defining the radio lines) must exceed those of the lower-energy levels, so that the net effect of the passage of a radio wave through the OH is to induce more transitions from high to low energy levels than from low to high levels. As transitions from high to low energy levels add energy to the radio wave, and those from low to high levels subtract energy, a medium with population inversion will add energy to the radio wave – that is, will amplify the radio wave.

The most obvious reason for attempting to invoke maser action to explain the OH observations is to meet the requirement for explaining the extremely intense lines. The intrinsic temperatures of the lines correspond to temperatures in the range 10^{12} to 10^{14} K, a circumstance which is highly suggestive of amplification processes, because such temperatures exceed, by several orders of magnitude, known physical temperatures. But the intensity of the lines is not the only reason for suspecting maser processes. Extremely narrow lines have been observed, and amplifying processes can lead to a line narrowing, line shapes as well as widths being altered by the amplification. Thus line widths of 600 Hz, corresponding to kinetic temperatures of 5 K, could exist in situations where the line intensities correspond to temperatures between 10^{12} K and 10^{14} K. Furthermore, if the maser mechanism were sensitive to polarization, then the observed radiation might exhibit a large degree of polarization, such as is observed.

Finally, another property of maser processes should not be overlooked. If an OH medium can be brought to a state of amplification, then sources of radiation lying behind it, as viewed from the Earth, or emission of the medium itself, may appear as sources of extremely small angular size. This may be true because of the coherent nature of the amplifying processes, which produces a high degree of directionality in the amplified radiation. If this is indeed happening, then the small angular sizes observed in the interferometric observations may actually be "apparent" sizes rather than true angular sizes. For this reason, the linear dimensions of the OH emitting regions may be considerably larger than those inferences obtained from observations.

8. Techniques

The continuation of this research, and particularly the investigation of the mechanism by which the OH molecule is formed in interstellar space; will involve further detailed observations using the greatest attainable sensitivity and freedom from harmful interference.

Receivers used to study the OH lines need to have narrower resolutions than those used in the observation of the 1420 MHz line of hydrogen. The OH lines are usually narrower than the hydrogen lines because the OH molecule exists only in regions which are both more quiescent and of higher density. Linewidths of 1 to 10 kHz are typical. The receivers need, however, to be tunable over an appropriate range, since the lines observed are broadened and displaced in frequency up to several megahertz, as a result of Doppler effects due to relative motions in the line-of-sight. Furthermore, accurate measurements of the shape of the spectral lines require comparison measurements at adjacent frequencies which are free from the effects of OH absorption or emission. The overall frequency band technically necessary for detailed study of the two principal lines at 1665.4 and 1667.4 MHz, taking into account the requirements for comparison observations and Doppler shifts, is at least 5 MHz, and preferably about 10 MHz. In the foregoing, the OH molecule referred to is the OH molecule within our galaxy; however, OH has also been detected in external galaxies [Welizchew, 1971]. The studies in this area require downward extensions in frequency since the Doppler shift of the lines is much larger for gas residing in external galaxies than in our own galaxy.

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ANNEX III

WATER VAPOUR LINE AT 22.235 GHz

1. Introduction

The 22.235 GHz spectral line of the water molecule is well known to radio engineers because of its contribution to atmospheric absorption of radio waves. The water vapour line in the atmosphere is pressure broadened causing significant propagation loss over a band of several GHz around the 22.235 GHz centre frequency.

The important possibility that water molecules in space could be detected through identification of this line was considered feasible [Snyder and Buhl, 1969], since the line width will be much narrower for molecules at very low pressure in space, and can easily be distinguished from the very broad atmospheric line. The line emission from H_2O molecules in space was discovered in 1968 [Cheung *et al.*, 1969] in three separate regions in the Galaxy, and at a suprisingly high intensity level. In fact, by orders of magnitude, the H_2O sources are the most intense celestial radio sources in this frequency range, with the exception of continuous emissions from the Sun and the Moon.

In rapid succession, a number of additional very intense celestial H_2O sources were discovered and it was found that the sources emit complex spectra of Doppler-shifted lines; that the radiation is in some cases linearly polarized; that the sources are smaller than the beams of large radio telescopes; and that the line intensities are highly variable, in some cases over periods of a week which suggests extremely small source sizes [Knowles *et al.*, 1969a,b; Meeks *et al.*, 1969; Buhl *et al.*, 1969; Turner *et al.*, 1970; Sullivan, 1971, 1973; Johnston *et al.*, 1971a, 1973; Turner *et al.*, 1971]. Investigations by the technique of very long base-line interferometry have shown angular sizes for the sources as small as 0.0003 arc seconds, comparable in angular diameter with the smallest known celestial radio continuum sources [Burke *et al.*, 1970, 1971; Johnston *et al.*, 1971b; Abliazov *et al.*, 1974]. Maser amplification by the water molecules is indicated by the very high line intensities and very small source

diameters giving apparent brightness temperatures greater than 10^{12} K; and by polarization of the radiation. The first celestial H_2O sources were found in, or near, galactic ionized hydrogen clouds and positions near OH emission sources and in some cases infra-red sources. Subsequently, the line emission of water molecules was found in a number of infra-red stars [Knowles *et al.*, 1969a; Turner *et al.*, 1970; Schwartz and Barrett, 1970; Schwartz, 1971; Dickinson *et al.*, 1973], and in external galaxies [Churchwell *et al.*, 1977].

The discovery of the intense non-thermal radio radiation from water molecules in space, is of great astrophysical significance and practical importance. It provides a new means for investigating the distribution of molecules in the Universe, the motions of the gas clouds, and the physical conditions in space which support the maser amplification process. These intense, very small radio sources in the sky give a new potential for applications as known radio beacons, and with the very long base-line interferometry a technique for accurate position determination on earth over great distances.

Thermal emission or absorption by water molecules in space has not yet been detected and it is important to extend the research to weaker signal levels to determine the distribution of water molecules in the Universe.

2. Spectral properties

Spectrometry with high resolution shows the H_2O source spectra to be complex composites of intense, narrow lines which are Doppler-shifted in frequency by different amounts depending on the velocities in the line-of-sight of the emitting gas clouds, with respect to the Earth. The broadest known spectrum, in the source W49, shows lines spread over a range of line-of-sight velocities of at least $\pm$ 240 km/s corresponding to a frequency spread of 37 MHz. Individual lines have total widths at the half intensity point as small as 40 kHz (corresponding to about 0.5 km/s in the line-of-sight velocity), the range of line widths extends up to three times this value, and lines at different Doppler shifts blend together to produce broad spectral features.

Individual line intensities range up to a flux density of approximately 10^{-21} W/m^2 · Hz and vary with time. In some cases, order of magnitude intensity variations are observed on a time scale of weeks, while some lines vary little over time periods of a year or more. An increase in line intensity is, in many cases, accompanied by maser narrowing of line width. Small variations of line frequency with time are observed, and are probably the result of intensity variations in unresolved line blends. The intensity variations of individual lines are largely unrelated, indicating separate emission regions, and neither order nor periodicity has been found in most sources. Exceptions are the H_2O sources associated with long period variable stars, where the H_2O emission varies periodically in phase with the stellar light variation.

3. Polarization properties

Linear polarization of a magnitude up to approximately 50% has been observed in some lines, but the linear polarization of the majority of the observed lines is less than 10%. The degree of polarization observed in the Orion Nebula varies with time in the same sense as the line intensity. Circular polarization has not been detected.

4. Sizes and positions of H_2O sources

The sizes and positions of the H_2O sources are currently being investigated by the technique of very long base-line interferometry. The intense source, W49, has been most intensively studied at increasingly longer base lines up to 7375 km (547 million wave lengths) where the fringe spacing is 0.00038 arc seconds. At this base line, the strongest emission source is partially resolved; this result is consistent with a uniformly bright source of diameter 0.0003 arc seconds. In comparison, the sizes of OH sources in the same vicinity are about 0.05 arc seconds. The H_2O sources in the Orion region, which is about 30 times nearer Earth than the W49 region, are in some cases partially resolved at a base line ten times shorter.

At shorter base lines, the relative positions of the sources, each of which corresponds to an individual line in the W49 spectrum, have been measured. They are found to scatter over an area of sky about 1.5 arc seconds in diameter. There is no obvious correlation between the positions and the line-of-sight velocities of the lines which would indicate systematic motions of the water molecule clouds. The absolute positions of the most intense lines were measured to 1″ × 10″ arc accuracy and there is agreement, within this range of uncertainty, with the position of the OH source. The dimensions of the space occupied by the Orion and W49 sources are roughly equal, despite a difference of over three orders of magnitude in their intrinsic intensities.

Accurate interferometer positions have been measured for several of the intense H_2O sources [Hills *et al.*, 1972] confirming the close association of H_2O and OH sources, and in some cases, close association in position with infra-red sources and compact ionized hydrogen regions.

These experiments demonstrate that H_2O sources can be used for interferometry over the maximum distances allowable on Earth for astrophysical, geodetic, and geophysical investigations.

5. Emission mechanism

The observed line intensities and the very small apparent source diameters observed by very long base-line interferometer techniques, give maximum source brightness temperatures of the order of 10^{15} K and hence require a non-thermal process. Maser amplification by water molecules is consistent with the intensity requirements and line narrowing from reasonable interstellar conditions, and provides possible mechanisms for extreme time variability through changes in population inversion of the molecular energy levels, changes in amplification path length, and changes in beaming of the radiation. The mechanism for overpopulating the higher energy level relative to the lower energy level to allow amplification may be radiative, collisional, or chemical. The occurrence and temporal behaviour of H_2O sources near cool stars, strongly suggests radiative inversion of the H_2O rotational levels via the 2 to 5 mμ near-infra-red vibration-rotation bands. This mechanism, however, appears to be inadequate to explain emission from the vicinity of ionized hydrogen regions. The apparent coincidence of the OH and H_2O masers in many objects suggests a common inversion mechanism, perhaps involving the creation and destruction of H_2O molecules by radiation or collision but, as yet, no quantitative description of such a process exists. Theoretical and experimental work is still proceeding to define a clear preference for one unique mechanism.

6. Technical requirements

Continuation of this research, and the important extension to the weak lines of normal water molecules, as well as research into the scientific applications of the very long base-line interferometer technique to make precise measurements of positions on the Earth, and earth motions for geodesy and geophysics, will require the highest possible measurement sensitivity and freedom from harmful interference.

The observed lines are narrow (40 kHz) but are spread over a band of at least 37 MHz by Doppler shifts. Extra-galactic water lines are Doppler-shifted by greater amounts. Detailed measurements require receivers with a frequency resolution of less than 40 kHz, but tunable over many megahertz. The overall frequency band required for detailed study of the 22.235 GHz H_2O line is at least 50 MHz.

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ANNEX IV

THE FORMALDEHYDE LINES

1. Introduction

Radio lines from clouds of formaldehyde (H_2CO) in our galaxy have been detected on at least eight different frequencies. Lines from the carbon-13 isotope at 4593 MHz and the oxygen-18 isotope at 4389 MHz have also been detected. The most important line is at 4830 MHz which generally appears in absorption against bright radio sources, ionized hydrogen regions, and even the microwave background in nearby dust clouds. The next lines of importance after this line, are those at 14.488 GHz and at 140.840 GHz, 145.603 GHz, and 150.498 GHz. The last three lines appear in the high density cores of rapidly condensing galactic clouds.

2. Formaldehyde absorption at 4830 MHz

The discovery in March, 1969, of the 4830 MHz absorption line of formaldehyde [Snyder *et al.*, 1969] had followed the detection of ammonia and water in late 1968, and so, clearly demonstrated the existence of organic polyatomic molecules in interstellar space. None of the molecular lines subsequently discovered in 1970 and 1971 (with the possible exception of the CO line at 115.267 GHz) are as important to the study of dust clouds and galactic structure as the 4830 MHz line of formaldehyde. A large number of radio sources have formaldehyde absorption lines in them [Zuckerman *et al.*, 1970; Whiteoak and Gardner, 1970] showing that formaldehyde, like hydrogen and hydroxyl, is a common constituent of galactic spiral arms. Hence, it can be used to study the structure of our Milky Way galaxy. High-resolution studies have been made of the formaldehyde lines in the galactic centre using lunar occultation techniques [Kerr and Sandqvist, 1970] and interferometry [Fomalont and Weliachew, 1973]. Absorption at 4830 MHz has been detected in external galaxies [Gardner and Whiteoak, 1974].

One of the most interesting aspects of formaldehyde absorption are the anomalous lines observed in a number of nearby dust clouds [Palmer *et al.*, 1969]. This aspect is quite anomalous, since only emission lines from other molecules are observed in the same cloud. The absorption must be produced against the 3 K background radiation, the microwave remnant of the primeval fireball. Accordingly many nearby dust clouds can be examined by means of the formaldehyde molecule without the need for a background radio source. This refrigerator mechanism is the inverse of a maser mechanism and it is only observed in dust clouds and possibly in the very dense cores of galactic sources [Townes and Cheung, 1969]. Hence the 4830 MHz transition is useful for studying the physical conditions inside dust clouds.

Formaldehyde is separated into ortho and para levels and transitions between the ortho and para states are forbidden by electric dipole transition. This can be thought of as two species of the molecule that differ in energy: ortho formaldehyde and para formaldehyde. The lowest energy state for ortho formaldehyde will normally have a high population. Not only is this the optimum configuration for producing an absorption line, but also 4830 MHz is a good frequency for large telescopes. At lower frequencies, the spatial resolution deteriorates and at higher radio frequencies, the continuum background necessary for absorption becomes weaker. A similar situation occurs in the OH molecule. The formaldehyde line is actually split into six components covering about 30 kHz [Tucker *et al.*, 1971]. In most cases the Doppler broadening of the line is much greater than this.

3. Other formaldehyde absorption lines

Absorption lines from two other pairs of levels of ortho formaldehyde have been found. The lines appear at 14.489 GHz, 28.975 GHz and 48.285 GHz, and have a large optical depth in the galactic centre [Evans *et al.*, 1970; Welch, 1970]. They are rarely seen outside this region, which indicates that the higher energy levels are not as well populated as those levels that give rise to the 4830 MHz transition. In addition, the continuum sources are considerably weaker at the above 14, 29 and 48 GHz lines. Increases in receiver sensitivity may make these lines useful in the future for studying the excitation of formaldehyde.

4. The 140 to 150 GHz emission lines

Three high frequency emission lines of formaldehyde have been found in the Orion Nebula. Lines of ortho formaldehyde have been detected in Orion A, the galactic centre source Sgr A (NH_3A) and at least two other galactic sources [Kutner, *et al.*, 1971; Thaddeus, *et al.*, 1971]. The emission lines are the most intense in Orion, whereas the 4830 MHz absorption line is very weak [Kutner and Thaddeus, 1971]. This happens because the molecular cloud is located in the dusty region behind the bright nebulae and radio source. The angular diameter of the emission region is about 3′ arc, and is generally centred on the OH maser [Thaddeus *et al.*, 1971], a region where emission lines from other molecules have been found. Another line at a frequency of 72.838 GHz has been detected, and is important because it is the lowest ground state transition of the formaldehyde molecule. We know from the 4830 MHz absorption measurements that the formaldehyde cloud extends southward for at least 30′ arc [Kutner and Thaddeus, 1971]. The conclusion is that the densities required to produce the 140 to 150 GHz emission lines are quite high, of the order of 10^5 hydrogen molecules/cm^3 [Thaddeus *et al.*, 1971]. Such densities are only achieved in the central part of the nebula. It is generally assumed that these dense regions are highly collapsed clouds in the process of forming stars. Hence we can see the importance of both the 140 to 150 GHz emission, and 4830 MHz absorption lines, in studying this region which is at an important stage in the evolution of interstellar clouds.

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ANNEX V

THE CARBON MONOXIDE LINES

1. Introduction

Carbon monoxide is a diatomic molecule with a simple rotation spectrum [Gilliam *et al.*, 1950]. This molecule was first detected in interstellar space in 1970 when line emission from $^{12}C^{16}O$ at 115.2712 GHz, $^{13}C^{16}O$ at 110.2014 GHz and $^{12}C^{18}O$ at 109.7822 GHz was discovered [Wilson *et al.*, 1970; Penzias *et al.*, 1971]. The most intense line, that of $^{12}C^{16}O$, has been found to be readily detectable over much of the area near the plane of our galaxy, as well as in the directions of ionized hydrogen regions, interstellar dust clouds, supernova remnants and an infra-red star. This emission typically covers a considerably larger area of the sky than the optical size of the object. The corresponding $^{13}C^{16}O$ lines are generally present with between one third to one tenth the intensity of the more common isotope. The weaker $^{12}C^{18}O$ line has been detected in the strongest sources and found to be about one fifth that of the $^{13}C^{16}O$ line.

2. General

Perhaps because it is, by a considerable margin, the most stable of the known interstellar molecules [Brewer *et al.*, 1948], it appears, after molecular hydrogen, to be the most abundant. Its wide distribution makes it an extremely useful tool in the study of a variety of astronomical problems pertaining to the chemical composition, mass motion, excitation and density distribution of interstellar space. It permits the study of galactic motion in direct analogy with the 1420 MHz line of neutral atomic hydrogen. The much shorter wavelength of the CO line affords a large increase in resolution: 1′ arc for the CO line on a 11 m diameter millimetre wave antenna compared with 10′ arc resolution for the hydrogen line on a 100 m antenna. Furthermore, by observing several CO isotope lines one can obtain opacity information in the dense regions near the centre of the galaxy. The observed CO column densities are so high that much of the interstellar carbon must be in the form of CO, enabling us to investigate the total mass of hydrogen from the C/H ratio.

3. Techniques

All the present work has been done with a receiver of almost two orders of magnitude less sensitive than those now used at the hydrogen-line frequency. With the advent of cryogenically cooled receivers for this work, a reduction in noise of at least a factor of ten seems likely. Such an improvement in sensitivity will undoubtedly reveal many fainter areas of CO. The most important of these will be external galaxies which may be expected to have Doppler shifts of several hundreds of MHz from the rest frequencies of the lines. The widest CO lines observed so far, those near the galactic centre, require a frequency band at least 100 MHz wide for their study.

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REPORT 224-4

CHARACTERISTICS OF THE RADIOASTRONOMY SERVICE, AND INTERFERENCE PROTECTION CRITERIA

(Question 5-1/2)

(1963 - 1966 - 1970 - 1974 - 1978)

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. 74, 75, and 75A 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 300 GHz.

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 service, and is covered in Question 6-1/2.

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 antennae 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 four distinct mechanisms:

- thermal emission from hot ionized gas and from solid bodies;
- non-thermal processes, mainly synchrotron emission from 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;
- primordial radiation fields.

These combine to produce:

2.1.1 *A continuum of radiation*, which extends relatively smoothly over the whole frequency range accessible to observation; upper and lower limits of observation are imposed by the Earth's atmosphere at roughly 300 GHz and 1.5 MHz respectively.

The continuum is composed of a background together with numerous small "bright" regions, the discrete radio sources. 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* (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 antennae 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 for Space Telecommunications, Geneva, 1971, represent a significant improvement over the international allocations made to the service in 1959 and 1963 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.

2.3 *Line radiation*

The first line radio radiation discovered in 1951 was that due to neutral atomic hydrogen at a rest frequency of 1420.4 MHz [Ewen and Purcell, 1951]. In 1963, the hydroxyl molecule OH was found [Weinreb *et al.*, 1963]; it has a group of 4 lines at about 1612, 1665, 1667 and 1721 MHz and other transitions including isotopes of the molecule, are known, which give frequencies near 4.6, 6.0 and 8.1 GHz. More complete descriptions of specific molecular lines in emission and absorption can be found in Report 223-4. Since that time, many other radio lines have been found. Hydrogen, helium and carbon in their excited states give rise to a whole series of lines throughout the spectrum. These have been observed at frequencies as low as 400 MHz and as high as 85.69 GHz [Lilley and Palmer, 1968].

Lines from more complex molecules and their isotopes have recently been discovered at a remarkable rate. 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 thirty-five different molecules have now been identified in interstellar space by means of radio observations of spectral lines. Isotopic forms of many of these molecules have also been identified. When it is considered that each of these molecules and their isotopic forms may have a number of spectral lines, each associated with different energy level transitions, then it is understandable that the radio spectrum is found to be heavily populated with line signals. More than two hundred and fifty radio spectral lines have already been detected in interstellar space and are listed in Report 223-4. Not all are of equal astronomical interest, and the most important are listed in Annex I of this present Report.

The value to astronomy of line observations is now very great. By using the neutral hydrogen line, the distribution and motion of hydrogen is mapped, both within our own galaxy and in many of our neighbouring galaxies. Studies of the Zeeman effect on radio waves absorbed in clouds of hydrogen allowed the very small magnetic fields in interstellar space to be measured [Verschuur, 1969]. The recombination lines allow measurements to be made of temperature as well as of the relative abundance of hydrogen and helium in the ionized nebulae in our galaxy. The OH lines, the water lines and the ammonia lines lead to complex theories of maser action in space to explain their behaviour. The formaldehyde line was the precursor to other, more complex, organic compound lines, with all the implications that their discovery might have on our knowledge of how life can be generated in our Universe.

The study of radio frequency lines is one of the most difficult fields in radioastronomy. The best antennae and receivers and the most highly developed electronic processing equipment is used. Integration times of many hours are common. For all these reasons, freedom from harmful interference is necessary. It is necessary over a band of frequencies for each line, a band wide enough to include broadening and shifting of the original emission due to Doppler effects, together with a band of comparable width for comparison or reference purposes, adjacent to that containing the line.

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, recently, 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. Frequency considerations of the radioastronomy service

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. Report 223-4 lists many details of spectral line observations already made by radio astronomers. Of the many spectral lines listed there, radio astronomers have identified a much smaller number which are of major importance and form part of the frequency requirements of the radioastronomy service. These are listed in Annex I. Bandwidths required for these spectral line observations are set by the changes in line frequency resulting from the Doppler frequency shifts. For many molecules, observable only within the Galaxy, the Doppler shifts are related directly to the velocity of galactic rotation. For the hydrogen line near 1420 MHz there is an additional requirement for a frequency band below 1400 MHz. In this case the Doppler shift in frequency is much greater because observations are being made of other galaxies which are retreating from us at very high velocities.

In the case of continuum observations the radio astronomer wishes to define the frequency variation of continuum emission, from sources of interest, over the entire spectrum available to them. It has been the experience of radio astronomers that observations at intervals of a factor of two in frequency are in general adequate for defining the overall spectrum, although closer spacings are needed for some specialized types of observation such as the measurement of polarization (see § 2.2). For ground based radioastronomy the lower limit of the frequency spectrum for which there is a requirement is about 1.5 MHz. At the present time the upper limit is set by the availability of suitable technology and is about 300 GHz. It may be expected to go to higher frequencies in the future. Within these broad limits there is a general requirement for a frequency band in each octave of the spectrum. Some adjustment may be necessary at frequencies above 30 GHz since it is of importance that radioastronomy have access to the atmospheric windows of low attenuation. The attenuation curve is shown in Fig. 1, Report 223-4.

The radioastronomy service has identified the need for bandwidths of the order of 1% to 2% for continuum measurements. As is pointed out later in this Report the sensitivity of radioastronomy receivers is improved when bandwidths are widened. For paraboloidal telescopes, wider bandwidths and consequent better sensitivities lead to improved efficiency in the use of these major astronomical installations. The same is true in the case of telescopes with unfilled apertures (such as the *T* or cross antenna). 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.

4. Classes of observations

4.1 Radioastronomy observations can be broadly divided into two classes:

4.1.1 *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.

4.1.2 *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.

4.2 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 § 7 this quantity is defined, and typical values for it are derived. It is convenient to measure the smallest detectable change (ΔT_c) in the equivalent temperature of the output terminals of the antenna connected to the radiometer.

5. Details of radioastronomy observatories

Appendix 1A (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 VIIIA). Collected information and the activities of radioastronomy and radar observatories can be obtained upon application to the Secretary-General of IUCAF, Appleton Laboratory, Slough, United Kingdom.

B. PROTECTION CRITERIA FOR THE RADIOASTRONOMY SERVICE

6. Introduction

The random radiation encountered in radioastronomy induces signals which have a Gaussian probability distribution in amplitude, and which qualitatively cannot be distinguished from the noise generated in the receivers or from thermal radiation from the Earth and its atmosphere. Furthermore, the intensity of cosmic radiation is usually much lower than that of noise, 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.

7. Sensitivity of radioastronomy systems

7.1 *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:

$$\Delta P \backsim \frac{P}{\sqrt{N}} \tag{1}$$

The standard deviation (ΔP) is often called root mean square or rms.

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)

$$\frac{\Delta P}{P} \backsim \frac{1}{\sqrt{\Delta f \cdot t}} \tag{3}$$

which is the basic sensitivity relation in radioastronomy.

The proportionality factor T_S 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:

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{\Delta f t}} \tag{4}$$

Now ΔP, the noise fluctuation in power density, in the sensitivity equation (4), is related to the total system sensitivity (noise fluctuations) expressed in temperature units throughout the Boltzmann constant, k, as shown in equation (5):

$$\Delta P = k\Delta T; \quad \text{also} \quad P = kT \tag{5}$$

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.

7.2 *Sensitivity estimates*

It is now possible to estimate the expected sensitivity by substituting reasonable numbers for Δf and t. This has been done in Table I by assuming Δf to be the bandwidth of an allocated radioastronomy band and the observing (or integration) time to be 2000 seconds. In Table II Δf is assumed to be the channel bandwidth of a typical spectral line observing system, and the observing (or integration) time is assumed also to be 2000 seconds.

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.:

$$\Delta P_H = 0{\cdot}1\ \Delta P \Delta f \tag{8}$$

Summarizing, 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 incident at the antenna, either in the total bandwidth or as a 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 propagation and f the frequency). Appropriate allowance must be made if the gain has a different value. Values of $S_H \Delta f$, in dB(W/m^2), are derived from ΔP_H by adding:

$$20 \log f - 38.6 \qquad \text{dB}$$

where f is in MHz. S_H is then derived by subtracting 10 log Δf to allow for the bandwidth.

Fig. 1 shows graphically the harmful interference levels for the radioastronomy service expressed in Tables I and II where S_H in dB(W/(m^2 . Hz)) is plotted as a function of frequency. The curves are not smooth because the different frequency bands have different bandwidths.

The calculated sensitivities and harmful interference levels presented in Tables I and II are based on assumed integration times of 2000 seconds. Integration times actually used in astronomical observations cover a wide range of values. Continuum observations made by telescopes operating singly (rather than in interferometric arrays) are reasonably well represented by the integration time of 2000 seconds. 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 seconds 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.

* In radioastronomy, S_H is generally denoted by the term "power flux-density". Because of the definition of power flux-density (W/m^2) used elsewhere in the CCIR, S_H is referred to in the following Tables as "power flux spectral density".

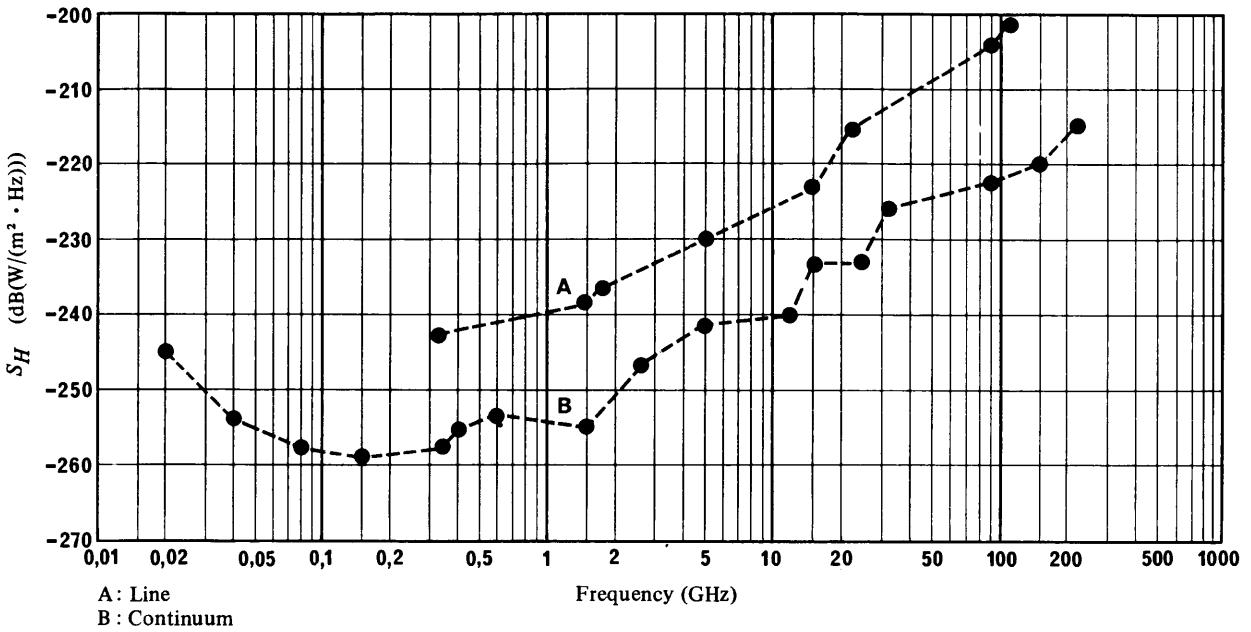

FIGURE 1 – *Harmful interference limits versus frequency as expressed in Tables I and II for t = 2000 s*

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 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 power flux-densities given in Table I. These sources however, are generally at known positions and of known constant flux 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 and spectrum, and can be highly time variable, so corrections cannot be made for its effects.

TABLE I – *Sensitivities and harmful interference levels for radioastronomy continuum observations with 2000 second integration time*

Nominal frequency f_n (MHz)	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 $S_H \Delta f_A$ (dB(W/m²))	Power flux spectral density S_H (dB(W/(m² · Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
20	21.860	0.020	30 000	100	3 365.00	−223	−190	−202	−245
40	38.000	0.500	6 000	100	136.00	−237	−190	−197	−254
80	73.800	1.600	1 000	100	13.75	−247	−195	−196	−258
150	152.000	3.000	200	100	2.74	−253	−199	−195	−259
327	325.300	6.600	40	100	0.86	−259	−201	−189	−258
408	408.050	3.900	25	100	1.00	−259	−203	−189	−255
610	611.000	6.000	15	100	0.74	−260	−202	−185	−253
1 420	1 413.500	27.000	10	20	0.09	−269	−205	−180	−255
2 700	2 695.000	10.000	10	20	0.15	−267	−207	−177	−247
5 000	4 995.000	10.000	10	20	0.15	−267	−207	−171	−241
10 650	10 690	100	12	20	0.05	−272	−202	−160	−240
15 350	15 375	50	15	30	0.10	−269	−202	−156	−233
23 800	23 800	400	15	50	0.05	−271	−195	−146	−233
31 400	31 400	200	18	100	0.13	−267	−194	−143	−226
90 000	89 000	6 000	30	150	0.04	−273	−185	−125	−223
135 000	135 000	10 000	40	150	0.03	−274	−184	−120	−220
235 000	235 000	10 000	35	200	0.04	−273	−183	−114	−214

(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 second integration*

Frequency	Assumed spectral line channel bandwidth	Minimum antenna noise temperature	Receiver noise temperature	System sensitivity (noise fluctuations)		Harmful interference levels		
				Temperature	Power spectral density	Input power	Power flux	Power flux spectral density
f (MHz)	Δf_c (kHz)	T_A (K)	T_R (K)	ΔT (mK)	ΔP (dB(W/Hz))	ΔP_H (dBW)	$S_H \Delta f_c$ (dB(W/m²))	S_H (dB(W/m² · Hz))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
327	10	40	100	22.10	–245	–215	–203	–243
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
14488	170	15	20	1.34	–257	–215	–170	–223
22235	250	40	50	2.85	–254	–210	–162	–216
88630	1000	30	150	2.85	–254	–204	–144	–204
115271	1300	50	150	2.77	–254	–203	–140	–201

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 TABLE I

Column

(1) The nominal frequency as it is customarily used to identify a radioastronomy band.

(2) The centre frequency of the allocated radioastronomy band.

(3) The assumed bandwidth.

(4) The minimum antenna noise temperature includes contributions from the ionosphere, the Earth's lower atmosphere and radiation from the Earth.

(5) The receiver noise temperature is representative of a good radiometer system intended for use in high sensitivity radioastronomy observations.

(6) The total system sensitivity in millikelvins as calculated from equation (4) using the combined antenna and receiver noise temperatures, the allocated bandwidth and an integration time of 2000 s.

(7) The same as (6) above, but expressed in noise power 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.

(8) The 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; $\Delta P_H = 0.1\ \Delta P \Delta f_A$. The numbers in the Table are the logarithmic expression of ΔP_H.

(9) The total power flux in the allocated band needed to produce a power level ΔP_H in the receiving system assuming an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of $S_H \Delta f_A$.

(10) The average power flux-density in the allocated band needed to produce a power level ΔP_H in the receiving system assuming an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of S_H.

COLUMN DESCRIPTIONS FOR TABLE II

Column

(1) The nominal frequency of the spectral line.

(2) The spectral line receiver channel bandwidth. The channel bandwidths used represent typical channel widths used for spectral line observations.

(3) The minimum antenna noise temperature includes contributions from the ionosphere, the Earth's atmosphere and radiation from the Earth.

(4) The receiver noise temperature is representative of a good radiometer system intended for use in high sensitivity radioastronomy observations.

(5) The total system sensitivity in millikelvins as calculated from equation (4) using the combined antenna and receiver noise temperatures, the assumed channel bandwidth and an integration time of 2000 s.

(6) The same as (5) above but expressed in noise power 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) The 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; $\Delta P_H = 0.1\ \Delta P \Delta f_c$. The numbers in the Table are the logarithmic expression of ΔP_H.

(8) The power flux in a spectral line channel needed to produce a power level of ΔP_H in the receiving system assuming an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of $S_H \Delta f_c$.

(9) The average power flux-density in a spectral line channel needed to produce a power level ΔP_H in the receiving system assuming an isotropic receiving antenna. The numbers in the Table are the logarithmic expression of S_H.

7.2.1 *Observed sensitivities*

The sensitivities in Tables I and II are extremely good, several orders of magnitude better 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.

The following Table gives examples of very sensitive continuum and line observations appearing in published literature.

TABLE III – *Comparison of observational results with harmful interference limits given in Tables I and II*

Frequency (MHz)	Line/ Continuum	Observed		Harmful limit		References
		ΔP (dB(W/Hz))	ΔT (mK)	ΔP (dB(W/Hz))	ΔT (mK)	
2700	Continuum	−269	0.0001	−267	0.00015	WADE, C.M. *et al.* (1971) *Astrophys. Journ.* **163**, L105.
8785	Continuum	−265	0.00024	≈−267	≈0.0001	FOMALONT, E.B. *et al.* (1975) *Astron. and Astrophys.* **36**, 273.
1420	Line	−254	0.003	−253	0.0035	BIGNELL, R.C. (1973) *Astrophys. Journ.* **186**, 889.
1690	Line	−256	0.002	−253	0.0035	GOTTESMAN, S. *et al.* (1971) *Astrophys. Journ.* **168**, 131.

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.

8. The radioastronomy antenna

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 fluxes indeed. For example at 1420 MHz, with a receiver sensitivity of 10^{-27} W/Hz (−270 dB(W/Hz)) and with an effective collecting area of the antenna of 4000 m^2 (61 dB gain), the detectable power flux density is:

$$S = \frac{10^{-27}}{4000} = 2.5 \times 10^{-31} \quad \text{W/(m}^2 \cdot \text{Hz)}$$

or:

$$-306 \text{ dB(W/(m}^2\text{. Hz))}.$$

Obviously a different antenna would yield a different sensitivity level.

To obtain a general feel for 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 and 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*

9. Interference

9.1 *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 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 power flux-density, assuming a bandwidth of 27 MHz (1400 to 1427 MHz) would be $3.7 \times 10^{-7} W/(m^2 . Hz)$ 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 fluxes above -110 $dB(W/m^2)$ belong in this category. With an assumed bandwidth of 27 MHz (the 1413.5 MHz band), the corresponding power flux-density is -184 $dB(W/(m^2 . Hz))$.

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.

9.2 *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.

9.2.1 *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 a reasonable IF filtering (see Report 696) 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 radio-astronomy 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.

9.2.2 *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 celestrial 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 in 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.

9.2.3 *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 also 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 if the characteristics of the wanted signal are known, this fact can be used to separate it from the interference and noise. However, for the general case of radioastronomy observations, there seems not to be any useful data processing technique that may be used to identify and reduce interference.

9.3 *Interference and long baseline interferometers*

High resolution observations require the use of interferometers or arrays of antennae with wide spacings between their elements. Each antenna may be subject to different interference conditions. In the extreme case of very long base-line interferometer (VLBI), the interference may affect only one antenna of the system. This may reduce the effect of interference by a small factor. On the other hand, it should be noted that VLBI experiments involve sophisticated data reduction and use of very distant antennae with consequent co-ordination 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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CCIR Document

[1971]: Report of the CCIR Special Joint Meeting, Geneva, 1971, Chapter 3, Table 3.3-IV.

ANNEX I

RADIO-FREQUENCY LINES OF THE GREATEST IMPORTANCE TO RADIOASTRONOMY

Substance	Rest frequency	Suggested bandwidth	Notes[1]
Deuterium	327.384 MHz	327.0 to 327.7 MHz	
Hydrogen	1420.406 MHz	1370 to 1427 MHz	(2) (3)
Hydroxyl	1612.231 MHz	1610.6 to 1613.8 MHz	(3)
Hydroxyl	1665.402 MHz	1660 to 1670 MHz	(3)
Hydroxyl	1667.359 MHz		
Hydroxyl	1720.530 MHz	1718.8 to 1722.2 MHz	(3)
CH Radical	3263.794 MHz	3260.0 to 3267.0 MHz	
CH Radical	3335.481 MHz	3332.0 to 3339.0 MHz	
CH Radical	3349.193 MHz	3345.8 to 3352.5 MHz	
Formaldehyde	4829.660 MHz	4780.0 to 4835.0 MHz	(3)
Formaldehyde	14.488 GHz	14.47 to 14.50 GHz	
Water vapour	22.235 GHz	22.01 to 22.28 GHz	(3)
Ammonia	23.694 GHz	23.6 to 24.0 GHz	
Ammonia	23.723 GHz		
Ammonia	23.870 GHz		
Excited hydrogen	36.466 GHz	36.43 to 36.50 GHz	
Silicon monoxide	42.821 GHz	42.77 to 42.86 GHz	
Silicon monoxide	43.122 GHz	43.07 to 43.17 GHz	
Carbon monosulphide	48.991 GHz	48.94 to 49.04 GHz	
Hydrogen cyanide	88.632 GHz	86.0 to 92.0 GHz	(3)
HCO^+ (Formyl ion)	89.189 GHz		
Carbon monosulphide	97.981 GHz	97.88 to 98.08 GHz	
Carbon monoxide $^{12}C^{18}O$	109.782 GHz	109.67 to 109.89 GHz	
Carbon monoxide $^{13}C^{16}O$	110.201 GHz	110.09 to 110.31 GHz	
Carbon monoxide $^{12}C^{16}O$	115.271 GHz	114.11 to 115.5 GHz	(3)
Formaldehyde	140.840 GHz	140.69 to 140.98 GHz	
Deuterated hydrogen cyanide	144.827 GHz	144.68 to 144.97 GHz	
Formaldehyde	145.603 GHz	145.45 to 145.75 GHz	
Carbon monosulphide	146.969 GHz	146.82 to 147.11 GHz	
Formaldehyde	150.498 GHz	150.34 to 150.65 GHz	
Carbon monoxide $^{12}C^{18}O$	219.560 GHz	219.34 to 219.78 GHz	
Carbon monoxide $^{13}C^{16}O$	220.399 GHz	220.17 to 220.62 GHz	
Carbon monoxide $^{12}C^{16}O$	230.538 GHz	230.30 to 230.77 GHz	

(1) The band limits for all lines in this table with the exception of those denoted by note(3) are the Doppler-shifted frequencies corresponding to radial velocities of ± 300 km/s.

(2) An extension of the present exclusive allocation of 1400 to 1427 MHz is required to allow for the large, cosmological Doppler shifts on radiation from very distant sources.

(3) These line frequencies are being observed in distant galaxies with large Doppler shifts, and therefore require bandwidths widened towards the lower frequencies.

REPORT 696

FEASIBILITY OF FREQUENCY SHARING BETWEEN RADIOASTRONOMY AND OTHER SERVICES

(1978)

1. Introduction

The objectives and techniques of radioastronomy are described in Report 223-4, in which it is demonstrated that the service requires a considerable measure of protection from interference. Levels of harmful interference are given in that Report for both continuous and line-frequency observations. Further information on the requirements for line-frequency measurements is given in Report 224-4.

The purpose of this Report is to provide guidelines under which the possibilities of frequency sharing should be considered, on the basis of the protection criteria given in Report 224-4. Possible interference from spurious radiations of transmitters in other bands, and problems of adjacent band interference are discussed in Report 697.

2. Sources of interference

Radioastronomy observatories are usually located at sites specially chosen to minimize interference from other services. Some possibilities of frequency sharing will then exist, but only with some services and under specified conditions. Sharing with some other services is not feasible. The more probable sources of interference and the problems which can arise when frequency sharing is adopted, are discussed in the following paragraphs.

2.1 Terrestrial transmitters closer than about 100 km are very likely to cause interference if operated in a band shared with radioastronomy, unless they are of low power and well-screened from the observatory by natural features. In meteorological conditions leading to anomalous tropospheric propagation, the distance from which interference can be caused by ground transmitters is likely to be increased to several hundred kilometres; but these conditions will occur only infrequently in most parts of the world. At VHF, interfering signals can be received occasionally by ionospheric propagation.

2.2 Transmitters carried in aircraft, spacecraft or balloons will cause interference if they are within line-of-sight from an observatory using the same frequencies.

2.3 At HF any interference received is almost invariably propagated via the ionosphere. 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 30 MHz are outlined in Report 699.

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.

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 Incoherent scattering of high-power transmissions by free electrons in the ionosphere is a further potential source of interference, but is at present less important than the sources already discussed.

3. Some examples of potential interference in shared bands

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 224-4 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 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.

Report 224-4 specifies the levels of power flux-density which should not be exceeded by a co-channel signal if radioastronomy observations of the highest sensitivity are not to suffer harmful interference. They are based on the assumption that the receiving antenna has zero gain relative to an isotropic antenna and are useful for planning purposes. In the study of particular situations, involving potential interference, the reception pattern of a single paraboloid antenna may be assumed to be that given in Recommendation 465-1.

Some experiments are performed with interferometers which may have high gain in a number of directions forming a coherent pattern over the whole sky. For example, in a direction in which each antenna of an assembly is effectively isotropic, the combined gain may be equal to the number of antennae. The examples which follow refer to a highly directive parabolic antenna; but it should be borne in mind that, because of this coherent high gain pattern, an interferometer may require a different degree of protection from that for a single, highly-directive antenna.

Interference studies are often made on the assumption that the unwanted signals are incident on side-lobes of the antenna with a gain of 0 dBi, independent of antenna diameter and main beam gain. For example, the data in Report 224-4 show that continuous observations at 2.7 GHz could be invalidated by interference with a power flux-density of -177 dB(W/m^2) incident on the 0 dB side-lobes. Since the gain of the inner side-lobes is typically in the range 10 to 40 dB, unwanted signals in these lobes would be harmful at correspondingly lower levels. It follows that interference from a single transmitter within line-of-sight, carried, for example, on a spacecraft, could be harmful at large distances. For instance, a 30 mW transmitter with an omnidirectional antenna on a geostationary satellite (36 000 km altitude) and sharing frequencies with a radioastronomy receiver, could interfere with reception through the side-lobes. Furthermore, it is likely that such a satellite, because of its high angle of elevation, may appear in the near side-lobe region of the antenna. In that case, an effective radiated power from the satellite of 3 μW or even less, could cause harmful interference.

A special case of the situation considered in the previous section is that of interference from a broadcasting satellite. As an example, the possible use of the band 2670 to 2690 MHz for radioastronomy (referred to in No. 364G of the Radio Regulations) may be considered in respect to potential interference from proposed broadcasting satellites in the band 2550 to 2690 MHz. With the maximum power flux-densities specified in the Radio Regulations (No. 470 NI) and a uniform spectrum, the flux density would be -103 dB(W/m^2) in a typical radioastronomy bandwidth of 10 MHz. This is 64 dB higher than the criterion recommended in Report 224-4. It seems certain therefore, that with line-of-sight conditions, a broadcasting satellite would interfere with radio-astronomy in a shared band, even with the observatory well outside the service area and even though the radio telescope was not pointed towards the satellite.

For frequencies greater than about 30 MHz the curvature of the Earth provides some protection against interference if the transmitter is on the Earth. However, energy will be propagated over large distances by tropospheric scatter and other mechanisms. For example, according to Report 541-1 a 2.7 GHz signal propagated along a 500 km path, over relatively smooth earth will be only 70 dB below free space intensity for about 1% of the time; in such conditions a 70 W transmitter with an omnidirectional antenna could cause harmful interference through 0 dBi side-lobes of the telescope. Other propagation mechanisms, though more sporadic than tropospheric scatter, may result in even more severe interference. These include reflections from sporadic-E ionization and from meteor trails at metre wavelengths and scattering of microwaves by heavy rain. Reflections from aircraft and artificial satellites may be effective over even greater distances, their importance increasing with the number of such objects.

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.

We 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.

4. Some conclusions on the possibilities of frequency sharing

4.1 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.

4.2 It is very difficult for the radioastronomy service to share frequencies with stations from which line-of-sight paths to the observatories are involved.

4.3 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.

4.4 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.

4.5 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.

4.6 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.

RECOMMENDATION 314-4 *

PROTECTION OF FREQUENCIES USED FOR RADIOASTRONOMICAL MEASUREMENTS

(Question 5-1/2)

(1953 - 1956 - 1959 - 1966 - 1970 - 1974 - 1978)

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;

(c) that, for the observation of known spectral lines, certain bands at specific frequencies are of particular importance;

(d) that account should be taken of the Doppler shifts of the lines, resulting from the motion of the sources, which are in general receding from the observer;

(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 radio-astronomical 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;

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* This Recommendation is brought to the attention of Study Group 1, with particular reference to Question 45/1.

(l) 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 for Space Telecommunications, Geneva, 1971, made improved allocations for radioastronomy, but that protection in many bands, particularly below 1 GHz, will need careful planning of other radio services;

(q) that Recommendation No. Spa 11 of the Extraordinary Administrative Radio Conference, Geneva, 1963, recommending that the next Administrative Radio Conference should give further consideration to the provision of improved frequency allocations for radioastronomy, has been maintained by the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971;

(r) that the technical criteria concerning harmful interference, referred to in Recommendation No. Spa2 – 12 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, should in respect of the Radioastronomy Service be those set out in Tables I and II of Report 224-4 for transmitters operating outside the main beam of the radioastronomy antenna,

UNANIMOUSLY RECOMMENDS

1. that radio astronomers 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, in addition to the protection afforded to the band 1400 to 1427 MHz, which is already allocated to radioastronomy on an exclusive world-wide basis, particular attention should be given to securing improved international protection to the following bands required for observations of natural line emissions:

Substance	Rest frequency	Suggested bandwidth	Notes(1)
Deuterium	327.384 MHz	327.0 – 327.7 MHz	
Hydrogen	1420.406 MHz	1370 – 1427 MHz	(2) (3)
Hydroxyl	1612.231 MHz	1610.6 – 1613.8 MHz	(3)
Hydroxyl	1665.402 MHz	1660 – 1670 MHz	(3)
Hydroxyl	1667.359 MHz		(3)
Hydroxyl	1720.530 MHz	1718.8 – 1722.2 MHz	
CH radical	3263.794 MHz	3260.0 – 3267.0 MHz	
CH radical	3335.481 MHz	3332.0 – 3339.0 MHz	
CH radical	3349.193 MHz	3345.8 – 3352.5 MHz	
Formaldehyde	4829.660 MHz	4780.0 – 4835.0 MHz	(3)
Formaldehyde	14.488 GHz	14.47 – 14.50 GHz	
Water vapor	22.235 GHz	22.01 – 22.28 GHz	(3)
Ammonia	23.694 GHz		
Ammonia	23.723 GHz	23.6 – 24.0 GHz	
Ammonia	23.870 GHz		
Excited hydrogen	36.466 GHz	36.43 – 36.50 GHz	
Silicon monoxide	42.821 GHz	42.77 – 42.86 GHz	
Silicon monoxide	43.122 GHz	43.07 – 43.17 GHz	
Carbon monosulphide	48.991 GHz	48.94 – 49.04 GHz	
Hydrogen cyanide	88.632 GHz	86.0 – 92.0 GHz	(3)
HCO^+ (Formyl ion)	89.189 GHz		
Carbon monosulphide	97.981 GHz	97.88 – 98.08 GHz	

TABLE *(continued)*

Substance	Rest frequency	Suggested bandwidth	Notes(1)
Carbon monoxide $^{12}C^{18}O$	109.782 GHz	109.67 – 109.89 GHz	
Carbon monoxide $^{13}C^{16}O$	110.201 GHz	110.09 – 110.31 GHz	
Carbon monoxide $^{12}C^{16}O$	115.271 GHz	114.11 – 115.5 GHz	(3)
Formaldehyde	140.840 GHz	140.69 – 140.98 GHz	
Deuterated hydrogen cyanide	144.827 GHz	144.68 – 144.97 GHz	
Formaldehyde	145.603 GHz	145.45 – 145.75 GHz	
Carbon monosulphide	146.969 GHz	146.82 – 147.11 GHz	
Formaldehyde	150.498 GHz	150.34 – 150.65 GHz	
Carbon monoxide $^{12}C^{18}O$	219.560 GHz	219.34 – 219.78 GHz	
Carbon monoxide $^{13}C^{16}O$	220.399 GHz	220.17 – 220.62 GHz	
Carbon monoxide $^{12}C^{16}O$	230.538 GHz	230.30 – 230.77 GHz	

(1) The band limits for all lines in this table with the exception of those denoted by Note (3) are the Doppler-shifted frequencies corresponding to radial velocities of ± 300 km/s.

(2) An extension of the Exclusive Allocation of 1400 – 1427 MHz is required to allow for the large, cosmological Doppler Shifts on radiation from very distant sources.

(3) These line frequencies are being observed in distant galaxies with large Doppler Shifts and therefore require wide bandwidths skewed to lower frequencies.

4. that Administrations give consideration to the technical needs that still exist for world-wide protection for a radioastronomy frequency band between 10 MHz and 15 MHz and that accordingly Administrations bear in mind Recommendation No. Spa2 – 7 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971.

5. that Administrations should bear in mind the technical desirability of affording protection to radio astronomy at frequencies below 10 MHz while taking CONSIDERINGS (e) and (g) into account;

6. that consideration be given to securing improvement in the international protection of the series of frequency bands above 20 MHz, now available to the Radioastronomy Service, in accordance with the Radio Regulations as amended by the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971;

7. 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;

8. 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.

REPORT 697

INTERFERENCE TO THE RADIOASTRONOMY SERVICE FROM TRANSMITTERS IN OTHER BANDS

(1978)

1. Introduction

The sensitivity limit of most radioastronomy observations is at a flux-density level much below that used for reception of radio communication signals. Values of these sensitivity limits for different frequencies are shown in Tables I and II of Report 224-4. That report deals with the factors affecting frequency sharing between Radioastronomy and other Services. However, as a consequence of the sensitivity of radioastronomy observations, interference can occur from transmitters which do not share the same band. Such interference may be divided into two general classes. One class, which will be called "harmonic and intermodulation" interference, results from harmonic radiation from transmitters in other bands or from the intermodulation of two or more signals from such transmitters. The second class will be referred to as "band-edge" interference. In this case the interference results from signals radiated by a transmitter located in a band adjacent to a band occupied by a radioastronomy receiver. There are three ways in which a transmitter operating in an adjacent band may be detected by a radioastronomy receiver:

- The frequency response of the receiver may have insufficient attenuation at the frequencies in the adjacent band to reduce the interference to the required level.
- 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.
- The transmitter may radiate sidebands which extend into the radioastronomy band.

In this report examples are given of the two classes of out-of-band interference. In addition consideration is given to the design of a radioastronomy receiver to minimise the interference problem.

2. Interference from terrestrial television transmissions

Interference to a radioastronomy receiver may result from a transmitter operating in any service in another band. However, services using high-power transmitters are naturally more likely to result in interference to radioastronomy receivers. Such a service is Television Broadcasting which occupies a large fraction of the UHF band. A radioastronomy allocation lies within the band allocated to UHF television and hence band-edge interference is a possiblility. In addition, because of the wide frequency range covered by the Television Broadcasting allocation, second and third harmonics and various intermodulation products of television transmitters in different channels can fall within the extremely important 1400 to 1427 MHz radioastronomy band.

A detailed consideration of possible interference from terrestrial UHF television transmissions is contained in Annex I. It appears that a guard band of about 2 MHz is necessary to allow for the finite slope of the attenuation characteristic of a high-power filter in the transmitter and to facilitate rejection of the main television signal by the radioastronomy receivers. Beyond this guard band it is possible, although it may be difficult and expensive, to reduce interfering signals to -100 dB relative to peak (sync.) power. With this level of signal at the transmitter, interference levels, in excess of those listed as limits in Report 224-4 may be received at a radioastronomy receiver 50 km distant. Indeed, because large radioastronomy antennae extend to much greater heights than 10 m, the limits may be very considerably exceeded.

Harmonic radiation or intermodulation radiation may also be responsible for unacceptably high interference levels. However, extra filtering is more easily achieved at frequencies well removed from the frequency of the television carrier.

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. In addition, the most sensitive use of higher antennae appears to rely on greater geographical separation or some protection from high ground.

3. Interference from satellite transmissions

In the previous section interference to a radioastronomy receiver from a high-power terrestrial transmitter was considered. In that case interfering signals are received in the far side lobes of the radioastronomy antenna. In addition the effect of the interference can be reduced by siting the observatory in a remote area and by taking advantage of intervening high ground. On the other hand, when the interfering transmitter is on board a satellite the radioastronomy receiver is exposed to interfering signals entering the antenna by the main beam or near side lobes and, furthermore, no protection can be obtained from a remote location or from terrain shielding. The serious nature of interference from out-of-band satellite transmissions is dealt with in some detail in Annex II.

In Annex II the radioastronomy band 2690 to 2700 MHz and the Broadcasting Satellite band 2550 to 2690 MHz is presented as an example of a problem of band-edge interference. If it is assumed that the satellite transmitter radiates the full permitted power flux-density right up to the band-edge and zero energy beyond that frequency, then the radioastronomy receiver band-edge would have to be withdrawn by 4 MHz in order to reduce the interference to an acceptable level. Careful control of the radiated spectrum, improvement of radioastronomy receiver characteristics, control of the satellite beam shape to minimise offbeam radiation and some separation between nominal band-edges will be necessary to avoid interference.

Harmonic radiation from satellites, particularly broadcasting satellites, is another possible mode of interference to radioastronomy. A number of cases are examined in Annex II. It is clear from this analysis that consideration needs to be given to the suppression of harmonic radiation from satellites and that in some cases special precautions might be necessary to achieve the desired degree of suppression.

Annex III 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 adjacent radioastronomy band 1660 to 1670 MHz.

4. Sensitivity of radioastronomy receivers to signals in adjacent bands

As mentioned in Section 1 of this Report, part of the band-edge interference problem is in the radioastronomy receiver itself. The frequency response of the receiver may be such that even in the total absence of any interfering signals in the radioastronomy band, an unacceptable level of interference may result from the response of the receiver to signals in an adjacent band. A detailed examination of the filter requirements is presented in Annex IV.

It is shown in Annex IV that, in most cases, signals in adjacent bands can be adequately rejected by the use of modern filter designs in the IF system of the receiver at the expense of a loss of between 25% and 50% in the usable bandwidth. A second problem arises where two or more strong signals, or spectral components of one signal, are close to the edge of the radioastronomy band. In this case a filter may be required at the receiver input to prevent the generation of intermodulation components. The design of this filter presents a difficult problem since the in-band attenuation must be kept very low in order not to degrade the performance of the low noise receivers used by radio astronomers.

5. Conclusion

An examination of the problem of interference to the radioastronomy service from transmitters in other bands has yielded a number of conclusions.

- 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.
- 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.

ANNEX I

FACTORS RELATING TO POSSIBLE INTERFERENCE FROM TERRESTRIAL UHF TELEVISION TRANSMISSIONS

1. Introduction

Because radioastronomy measurements need to be made at reasonably close intervals in frequency, and because large portions of the radio-frequency spectrum are allocated to broadcasting, and are being, or will be, used for television, it will occasionally be found necessary to operate the two services at frequencies in close proximity. Interference to radioastronomy may then occur, and several mechanisms need to be considered. 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. The dangers of interference are increased when two or more transmitters are operated with the same antenna system, since there may then be intermodulation components.

The radioastronomy receiver will, furthermore, be capable of picking up signals radiated within the television band, if inadequate receiver filters are used. Filters may be needed at the receiving antenna to reduce the voltages received from the television transmissions to a level which ensures that the preamplifiers in the receiver do not overload and generate spurious frequency components; additional intermediate-frequency filters are then needed to reduce the residual unwanted received energy to a level which will not degrade the accuracy of the radioastronomical measurements.

These forms of interference have been referred to as "band-edge" interference, the common problem being 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.

Another form of interference can be caused by harmonic radiation or by the intermodulation of two or more television signals to produce frequency components in radioastronomy bands in other parts of the spectrum. This form has been called "harmonic and intermodulation" interference, although it should be noted that some intermodulation products may be involved in the "band-edge" problem. The problems are generally less severe than those of band-edge interference because the filter requirements are less demanding and because the antennae are likely to be considerably less efficient radiators at frequencies remote from those for which they are designed.

The technical factors leading to these forms of interference are discussed below, together with possible measures for interference suppression.

Examples are quoted for the UHF band since, for radioastronomy, particular interest is attached to the use of frequencies in the range 602 to 614 MHz (in accordance with Nos. 329A, 330A, 330B and 332 of the Radio Regulations) which are allocated to the broadcasting service.

2. Band-edge interference

Band-edge interference presents a severe problem to transmissions on European Channel 39 (or on USA 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. Although the lower sideband can, if necessary, be well suppressed at low-power levels in the transmitter, it is partly regenerated from the vision carrier and upper sideband by non-linearity in the output stage of the transmitter. Only filters operating at the high-power level, that is, following the transmitter, can increase the overall suppression in this case.

One consequence of the interfering frequencies being close to the vision carrier-frequency is that they will be radiated efficiently from the transmitting antenna. Unless the radioastronomy station is remotely situated from the transmitter there must clearly be a "guard band"; for example at the upper end of the 606 to 614 MHz band. This is 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 guard band is also necessary to facilitate rejection of the main television signal by the radioastronomy receivers which might need to be designed to be relatively insensitive to frequencies outside the limits 608 to 612 MHz.

Two problems may arise in connection with the high-power filters installed at transmitters to suppress band-edge interference. Firstly, the pass-band attenuation in the region of the vision carrier may be significant (e.g. 1 to 3 dB for high stop-band attenuation and 2 MHz guard band) and this may call for a transmitter 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 further increase in the power rating of the transmitter if distortion is to be avoided. There is therefore a preference for phase-corrected filters.

A further problem of band-edge interference is associated with the difficulty in predicting its strength. The interference is caused by sideband components of the picture transmission as well as by discrete components derived from the colour sub-carrier and sound signals. The level of interference therefore 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 1 MHz receiver bandwidth and certain "quasi-worst" pictures, i.e. pictures which occur fairly frequently and which are most likely to cause interference.

As an example of band-edge interference, take the United Kingdom 625-line standard (CCIR Standard I) on Channel 39, and assume 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 quasi-worst picture conditions. An intermodulation product at 609.25 MHz produced as a 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, but otherwise the signals over most of the lower half of Channel 38 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.

To reduce the levels of out-of-band interference, high-power filters with group-delay correction will be necessary in the outgoing feeders handling the Channel 39 transmissions. Because of the sharp rate of cut-off of these filters, one or two decibels of loss may be unavoidable in Channel 39. In that case, higher-power transmitters 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.

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 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 will be 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.

3. Harmonic and intermodulation interference

This type of interference could occur in any band, and in particular could jeopardise measurements in the band 1400 to 1427 MHz which is exclusively allocated to radioastronomy. The interference will be generated mainly in the output stages of the transmitters. The usual type of output valve for a high-power transmitter is the klystron. Fig. 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.

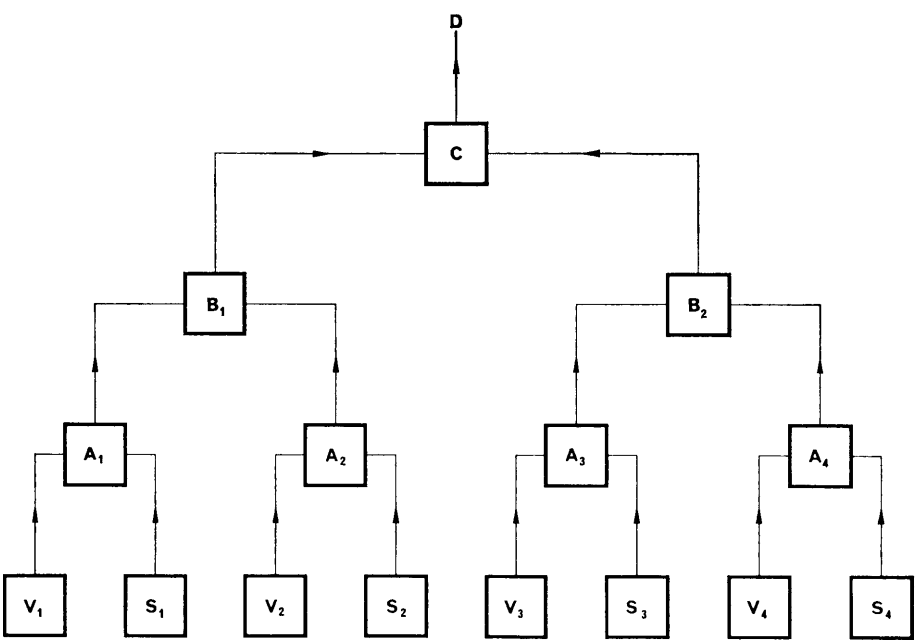

FIGURE 1 – *Typical arrangement of combining filters for feeding four programmes to a common antenna*

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: } combining filters
B_1, B_2: }
C: }

D: output to antenna array

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 antennae rather than a single four-channel antenna but coupling will still occur between transmitters because of the mutual coupling between the antennae. 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 antennae. 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.

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 antennae. 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.

4. 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 −10 dB, relative to an isotropic antenna, the interference level would be up to 10 dB above the values shown in Table I of Report 224-4 for continuum measurements for a small percentage of the time. It should be noted, moreover, that the mean heights of some large radioastronomy antennae 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 antennae of −92 dBW if the gain is −10 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 50 dB would be required to achieve the limits of Report 224-4

with a −10 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.

In view of the large number of ways in which interference can be caused, 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 organising checks of the degree of suppression will need consideration.

5. Conclusions

Band-edge radiation and non-linearity in the equipment at UHF television stations can generate interference in the UHF radioastronomy bands. It is technically feasible, although in some cases expensive, to suppress such interference when it is due to the output stages of the transmitters but an overall limit of −100 dB relative to peak (sync.) power may be set by the occurrence of intermodulation in the feeders and antenna systems. It may not be possible to achieve further improvement unless, by chance or by design, the transmitting antenna gain at the interference frequencies is appreciably less than that at the operating frequency. This means, for example, that interference fields exceeding a level of 20 dB below 1 μV/m at 10 m above ground in the UHF radioastronomy bands may be unavoidable for 1% of the time at a radioastronomy site situated only 50 km away from a typical high-power UHF television transmitting station. Parts of a large radioastronomy antenna, extending to much greater heights than 10 m, may be in a field nearly equal to that in free space.

In general, band-edge interference introduces more serious technical problems than does harmonic and intermodulation interference in radioastronomy bands well separated from the television frequencies. Special filtering may be needed but in the latter case the design problems will be less difficult. If the out-of-band television signals can be reduced to a relative level of −100 dB, the radioastronomy receivers can be designed to reduce the reception of the main television signals to a similar level.

The examples quoted show that adequate suppression of interference from a transmitter at a distance of 50 km is likely to extend techniques to their limit, if the receiving antenna height is about 10 m. The most sensitive use of higher antennae appears to rely on greater geographical separation or some protection by high ground. On the other hand, some types of observation can be carried out in the presence of interference somewhat greater than the CCIR limits. It may then be feasible to use even a high radioastronomy antenna at a distance of 50 km from a television transmitter radiating in an adjacent frequency band.

ANNEX II

TECHNICAL FACTORS RELATING TO THE PROTECTION OF RADIOASTRONOMY OBSERVATIONS FROM INTERFERENCE BY SATELLITE TRANSMISSIONS

1. Interference considerations relating to the use of adjacent bands

Transmission from satellites, and particularly the broadcasting of television and sound signals, for example, from geostationary satellites, may cause severe interference to radioastronomy. 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 26 dB higher than in the far side lobe region (see Report 391-3).

By the nature of a satellite broadcasting system, large areas of the Earth will be illuminated by the satellite transmitter. Within, and well beyond the service area, line-of-sight conditions will exist. It will not be possible for radio astronomers to avoid interference by appropriate siting of the observatories.

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. 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. 470NI of the Radio Regulations.)

With the high powers expected to be radiated by broadcasting satellites, and with the line-of-sight conditions which will exist, it is necessary also to consider the possibility of interference by harmonic or other spurious transmissions. A particularly difficult situation will arise when broadcasting satellites and radio astronomers use adjacent bands. Interference may be caused through the response of radioastronomy receivers to signals in the broadcasting band or to the radiation by the satellite of signals in the radioastronomy band itself. The response characteristics of radioastronomy receivers are discussed in Annex III.

At the same time the spectral density of the broadcasting satellite transmission is expected to decrease towards the band-edge and into the radioastronomy band. Insufficient data exist at present for an accurate assessment of interference through a convolution of the broadcast spectrum with the receiver characteristic. 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, with a typical receiver cut-off characteristic, 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 radio-astronomy 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 extent. 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 radio-astronomy band.

The paragraph above takes into account the band-pass characteristics of the radioastronomy receiver but has to assume a square wave cut-off of the transmitter spectrum since reliable figures on the spectrum are not available. Tests are planned to determine the spectrum shape for a television broadcast transmitter intended for use in a satellite. When this information is available the Broadcasting Service can determine how close to the band edge they can operate without causing harmful interference as indicated in Recommendation 314-4 in the radioastronomy band. It appears that avoidance of interference will necessitate careful control of the radiated spectrum, improvement of radioastronomy receiver characteristics to the maximum extent possible without significantly degrading sensitivity, control of the satellite beam shape to minimise off-beam radiation, and some separation between the nominal band edges.

2. Harmonic radiation from satellite transmissions

Another possible mode of interference to radioastronomy is second-harmonic radiation from broadcasting satellites in the band 11.7 to 12.5 GHz. The harmonic range 23.4 to 25.0 GHz includes the exclusive radio-astronomy band 23.6 to 24.0 GHz. For community reception a minimum power flux-density in the 11.7 to 12.5 GHz band, of -111 dB(W/m^2) is required and the density in the centre of the service area may well be -106 dB(W/m^2). According to Table I of Report 224-4, radioastronomy would be affected by interfering signals greater than -146 dB(W/m^2) at 24 GHz. The radio-telescope antenna may, for example, have a gain of about 70 dB and satellite signals of -216 dB(W/m^2) would therefore cause interference if the antenna were directed towards the satellite. The required harmonic suppression would therefore be 110 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 and possibly in the side lobes. Broadcasting transmissions for individual reception would need even greater harmonic suppression, by perhaps an additional 8 dB.

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 Broadcast Satellite Service, and the interference problems will be correspondingly less.

Proposals have been made for meteorological satellites which collect data from platforms on or near the surface of the Earth and relay the information to data collection centres. The plans 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 395-3 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 exclusive radioastronomy 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 224-4 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.

Although the presence of an interfering signal from a geostationary satellite would inhibit observations from only a small area of the sky at any one time, the need for long integration times, and the likely existence of several satellites spaced around the geostationary satellite orbit might result in a significant interference problem. This problem can be fully assessed only when further technical details of the nature of the transmissions are available.

ANNEX III

SUPPRESSION OF INTERFERENCE TO THE RADIOASTRONOMY SERVICE FROM OUT-OF-BAND RADIATION FROM A JAPANESE METEOROLOGICAL SATELLITE

A band-rejection filter has been inserted in the output of the band 9 (1681.6 MHz) transmitter of the geostationary meteorological satellite (GMS) * of Japan which was launched in July 1977. Fig. 2 shows the level of the signals in the radioastronomy band from the Visible and Infra-red Spin Scan Radiometer (VISSR), prior to and after the insertion of the filter. The values in Fig. 2 are calculated 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 rate of the VISSR signal 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.

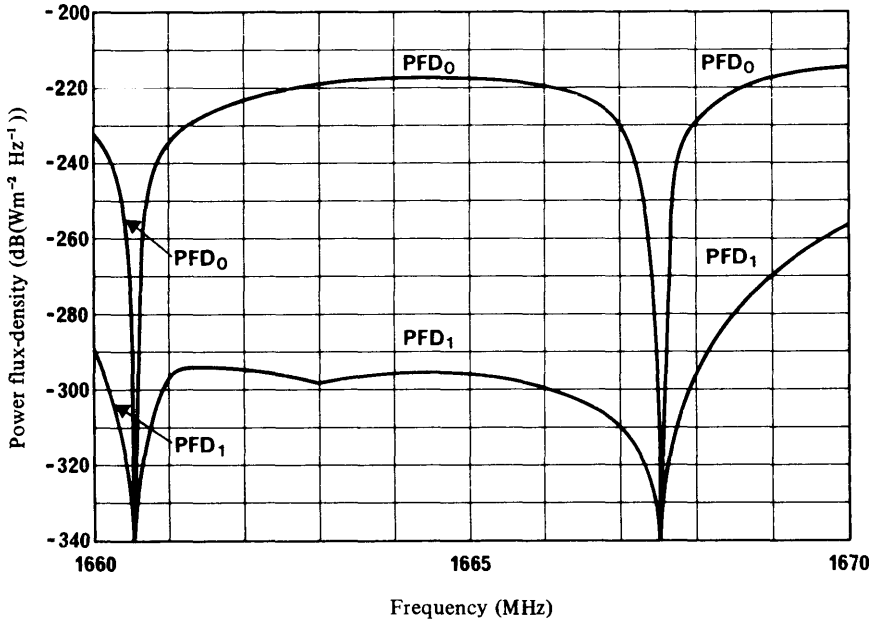

FIGURE 2 – *Estimated level at the surface of the Earth of power flux-density in the radioastronomy band emitted by GMS of Japan*

PFD_0 : Power flux-density before insertion of band-rejection filter

PFD_1 : Power flux-density after insertion of band-rejection filter

Report 224-4 lists the harmful interference level in the band 1660 to 1670 MHz as -237 dB(Wm^{-2} Hz^{-1}). 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. 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 this value. Observations at any observatory should be unaffected except within a few beamwidths of the satellite. Preliminary measurements made on 13 and 14 September 1977 at the radioastronomical observatory at Parkes, Australia, are in general agreement with the calculations discussed above.

ANNEX IV

SENSITIVITY OF RADIOASTRONOMY RECEIVERS TO SIGNALS IN ADJACENT BANDS

1. Introduction

Radioastronomical observations fall into two main categories: broadband observations, in which the total power within a specified passband is measured (continuum measurements), and spectral-line observations, in which intrinsically narrow-band measurements are made over a range of centre frequencies. In continuum measurements the achievement of maximum sensitivity requires the use of the largest possible bandwidth

* The GMS system is described in Report 395-3.

consistent with rejection of out-of-band signals; for line measurements the band of interest is determined by the characteristics of the source being observed and the effect of any Doppler velocities which may be present. This Report considers the restrictions imposed on the observations by the need to reject adequately those signals likely to be present in adjacent bands. The discussion and conclusions apply mainly to be continuum measurements with single antennae; spectral-line and interferometer observations are however included where the considerations are different.

2. Modes of interference

The three ways by which a transmitter operating in an adjacent band may be detected by a radio-astronomy receiver have been listed in Section 1 of the main body of this Report.

In each case, the result will be an increase in the power detected by the radioastronomy receiver. Interference arising in the third way, however, pertains to features of transmitter design and will not be discussed further in this Annex. Levels of harmful interference in the radioastronomy bands have been specified in Report 224-4 and these effective levels must not be exceeded if radioastronomical measurements are to be made without harmful interference.

3. Typical signal levels in adjacent bands

Signal levels encountered in adjacent bands vary widely with the nature of the service. Designations of services are of a very general nature and each one covers many different types of transmitting systems. It should also be noted that 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. Transmitters on satellites and aircraft present a particular problem since line-of-sight signal paths to observatories cannot usually be avoided.

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 10^{-10} W/m^2 and may exceed 10^{-5} W/m^2.

A proposed microwave aircraft landing system discussed by Parlow [1972] provides an example of another type of radiolocation service, this one in the 5.0 to 5.2 GHz frequency range immediately above a radioastronomy band. Just above the band edge air-to-ground signals may be transmitted by aircraft approaching airport runways, the peak power spectral densities at the aircraft being specified as 23.9 dB(mW/kHz) which is equivalent to 2.45×10^{-4} W/Hz. At a distance of 10 km from such an aircraft the power flux-density would be 2×10^{-13} Wm^{-2} Hz^{-1}. This figure is based on the assumption of isotropic transmission from the aircraft.

Services designated as fixed and mobile also include varied transmission techniques. The figure of 2×10^{-13} Wm^{-2} Hz^{-1} can again be taken as typical of the stronger power flux-density values likely to be encountered at an observatory. It corresponds, for example, to a transmitter with an e.i.r.p. of 100 W over a bandwidth of 10 kHz at a distance of 60 km.

Transmitters in satellites are of particular importance because in addition to reception in the far side-lobes of a radio telescope (the condition that prevails in most interference problems of terrestrial origin), there is also the possibility of reception in the main beam or near side-lobes. Satellite-transmitter power flux-density levels are limited by the Radio Regulations to 2×10^{-14} Wm^{-2} (4 kHz)$^{-1}$ or 5×10^{-18} Wm^{-2} Hz^{-1} for angles of arrival between 25° and 90°. As an example, the ATS-6 satellite complies with these limits.

The above examples of signal levels are collected in columns 1 and 2 of Table I, and will be used in the following discussion which mainly concerns the 1 to 20 GHz range where usage of the radio spectrum is rapidly growing. A general indication of adjacent band problems can thereby be obtained, but it should be understood that individual situations will depend strongly on the frequency band and observatory location concerned.

4. Design requirements for the radioastronomy receiver

Referring to § 2 above, two modes of interference must be considered. The first concerns the overall linear response of the receiver to signals at frequencies outside the radioastronomy band and will, in all practical cases, be determined by the intermediate-frequency response of the receiver. The second concerns the effect of any non-linearity or overloading in the initial signal frequency stages of the receiver and, for a given type of amplifier, can therefore be modified only by the addition of signal frequency filters which must generally be situated at the receiver input. The two effects will be considered separately.

4.1 *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 power flux-density S (Wm^{-2} Hz^{-1}) is encountered

(Fig. 3). 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 *. Then we have

$$P = AS \int_{f_0}^{\infty} 10^{-\{a_0 + k\,(f - f_0)\}/10}\, df = 4.45 \times 10^{-a_0/10}\, AS/k \qquad (1)$$

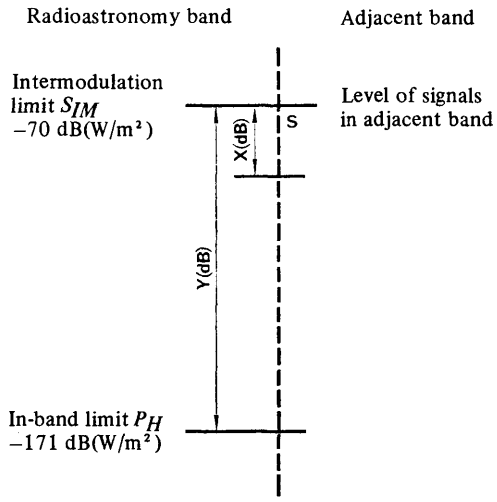

FIGURE 3 – *Signal levels in the vicinity of the band edge (Numerical values refer to the 5 GHz radioastronomy band)*

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 224-4 are in the range 10^{-17} to 10^{-21} W for typical bandwidths at frequencies greater than 1 GHz. For a continuous signal with $S = 2 \times 10^{-13}$ Wm^{-2} Hz^{-1}, 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 summarised in Table I 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.

4.2 *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 [McKay, 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. Transistor amplifiers are unlikely to be used at frequencies above 5 GHz in the near future and the performance of tunnel-diode amplifiers is likely to be similar to that of parametric amplifiers.

* 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 utilised over a few megahertz.

An effective interfering signal of ΔP_H (dBW) could result from intermodulation of out-of-band signals of equal amplitude. S_{IM}, given by:

$$S_{IM} = \frac{1}{3}(2\,IP + \Delta P_H) \qquad \text{dBW} \tag{2}$$

where IP dBW is the input level to which the intercept point corresponds. Adopting the values of ΔP_H given in Report 224-4 and assuming an isotropic antenna, the corresponding power flux-density limits can be derived. Values appropriate to the exclusive radioastronomy bands are given in Table II, 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 summarised in Fig. 3; the values apply to a parametric amplifier operating in the 5.0 GHz band and assume an isotropic aerial response. Taken in conjunction with the data of Table I, it appears that the response of a radiometer should be -100 to -110 dB down at the band-edge for frequencies in the gigahertz 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, attenuation at signal frequency would also be necessary.

TABLE I – *Examples of the required response characteristics of radioastronomy receivers*

Service	Assumed distance of transmitter (km)	Typical mean power flux-density at observatory	Required band-edge response of receiver (dB)
(1)	(2)	(3)	(4)
Broadcast satellite (maximum allowable flux)	36 000	5×10^{-18} Wm^{-2} Hz^{-1}	−56 to −63
Aircraft transmitter in proposed microwave landing system	10	2×10^{-13} Wm^{-2} Hz^{-1}	−102 to −109
Typical radio-relay transmitter	60	2×10^{-13} Wm^{-2} Hz^{-1}	−102 to −109
Aiborne radar (10 W mean power)	10 300	10^{-8} Wm^{-2} 10^{-11} Wm^{-2}	−100 −70

TABLE II – *Typical values of power flux-density of equal signals which might cause interference by intermodulation*

Radioastronomy band	Mean power flux-density (dB(W/m^2))	
	Parametric amplifier	Transistor amplifier
21.85 – 21.87 MHz	−112	−102
1400 – 1427 MHz	−80	−70
2690 – 2700 MHz	−76	−66
4990 – 5000 MHz	−70	−60
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	–
130 – 140 GHz	−32	–
230 – 240 GHz	−25	–

5. 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 application. 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.

5.1 *Intermediate-frequency filtering*

For the reasons indicated in § 1, 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 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. 4. For interferometers, however, use of three eight section filters is likely to be prohibited by the phase requirements of the system.

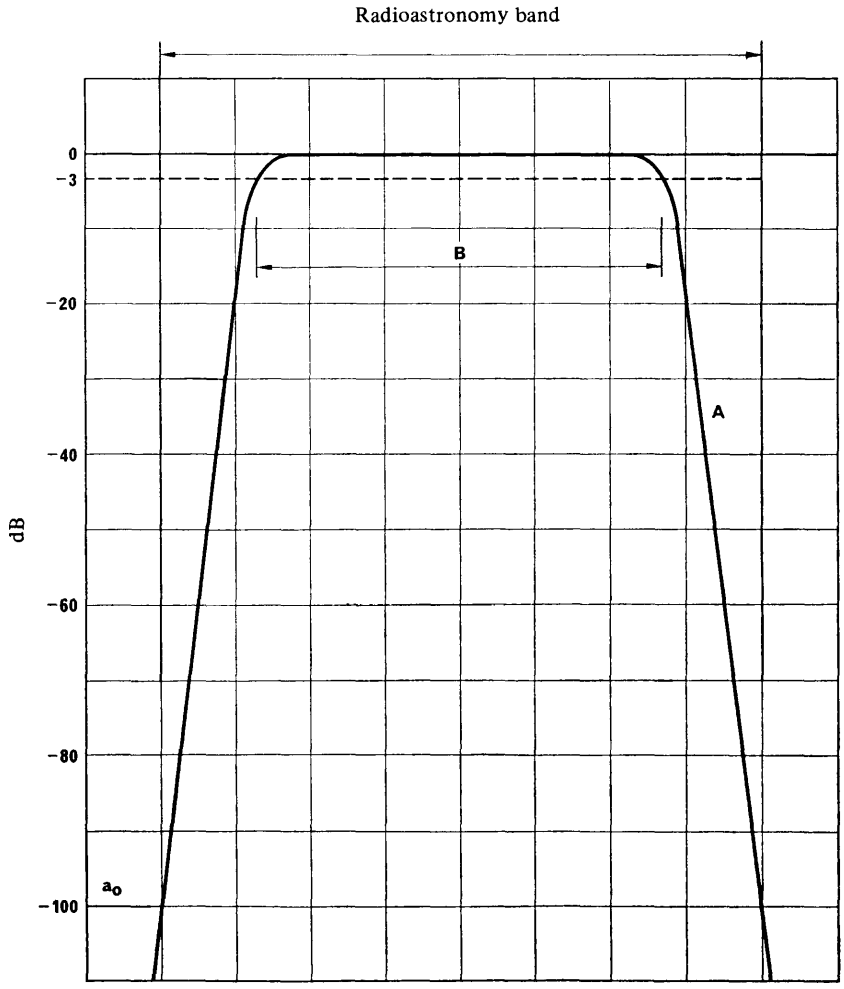

FIGURE 4 – *Relationship between a radioastronomy band and the required receiver characteristic*

A: Slope $-k$ dB/MHz

B: Half-power bandwidth

5.2 *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 recent development [Atia and Williams, 1971] of wave-guide cavity filters may also have application to radioastronomy receivers, but at the moment it would appear that signals having levels near the upper limit of those listed in Table I could, if situated within about 5 MHz of the band edge, present severe problems of receiver design.

6. Conclusions

It would appear, on the basis of the estimated signal powers given in Table I and the preceding discussion, that in most cases signals in adjacent bands can be adequately rejected by the use of modern filter designs in the intermediate-frequency system of the receiver at the expense of a loss of between 25% and 50% in the usable bandwidth. Difficulties in filter design might nevertheless arise where the use of interferometer techniques precludes the adoption of the most effective designs.

A problem could also occur where two or more strong signals (peak power greater than approximately 10^{-7} W) or spectral components of one signal are close to the edge of the radioastronomy band.

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McKAY [1967] *Electronic Design*, 3, 70.

PARLOW, R. D. [1972] *Spectrum sharing and compatibility of telecommunications systems in the 5.0-5.25 GHz band. System description for the universal microwave landing system.* Report prepared by the Frequency Measurement and Support Division, Office of Telecommunications, U.S. Department of Commerce.

REPORT 698

EMISSION MEASUREMENTS OF THE ATS-6 SATELLITE IN THE 2690-2700 MHz RADIOASTRONOMY BAND

(1978)

1. Introduction

At the World Administrative Radio Conference for Space Telecommunications (WARC-ST), Geneva 1971, the band 2500 to 2690 MHz was 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 exclusively allocated to the radioastronomy service. These two services have widely different requirements on receiving system sensitivity. A radioastronomy observatory typically uses a very large aperture antenna and low noise receiver to achieve the high sensitivity necessary to detect power flux spectral densities of the order of -230 to -240 dB(W/(m^2 · Hz)) in the 10 MHz bandwidth. Broadcasting satellite receiving systems generally use a small parabolic antenna and higher noise temperature receiver. Consequently, broadcasting satellites must transmit e.i.r.p.'s which will range from 48 to 60 dBW, in order to produce the required power flux-density at the surface of the Earth of the order of -114 to -102 dB(W/m^2) which, if uniformly dispersed over a 30 MHz bandwidth, yields a power flux spectral density of -189 to -177 dB(W/(m^2 · Hz)). Article 7 of the Radio Regulations (470 NI) permits a power flux spectral density of -173 dB(W/(m^2 · Hz)) for the Broadcasting Satellite Service when uniform dispersal over 4 kHz is adopted. It is this large difference between the power flux spectral density produced by a broadcasting satellite and the sensitivity of a radioastronomy observatory which causes the concern about the feasibility of avoiding harmful interference to observations in the radioastronomy band adjacent to the broadcasting-satellite band.

The first opportunity to make measurements of this potential interference situation was by using a satellite in orbit after the launching of the United States of America's Application Technology Satellite (ATS-6), which was launched into geostationary orbit on 30 May 1974, and positioned at 94° W longitude. This report 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, Swanson, and Heffernan, 1975].

Simultaneous observations in the first series of tests (June 1974) discussed here, were carried out at other observatories, particularly the National Radio Astronomical Observatory at Greenbank, USA; and with these tests, were reported in a publication of the National Academy of Science of the United States.

The first test (June 1974) was designed to determine the spectral power flux-density laid down by the satellite transmitter, especially in the region of the radioastronomy band, and careful calibration procedures were used to obtain the flux in absolute terms. The second test (April 1975) was designed to determine the relationship between the input signal to the satellite and the amount of out of band radiation needed to ascertain whether a significant reduction in the radiation in the radioastronomy band could be obtained by increasing the input level to the satellite transponder. Calibration for absolute flux determination in this second test was not carried out, nor was it needed. The measured values had good relative stability as determined by noise tube calibration of the receiver.

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 ATS-6 configuration used for the HET experiment is shown in Figure 1. The TV-FM signals from earth stations were received at C-band on the Earth Coverage Horn (ECH). 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 metre paraboloid antenna from its prime focus. Table I summarizes the principal performance characteristics.

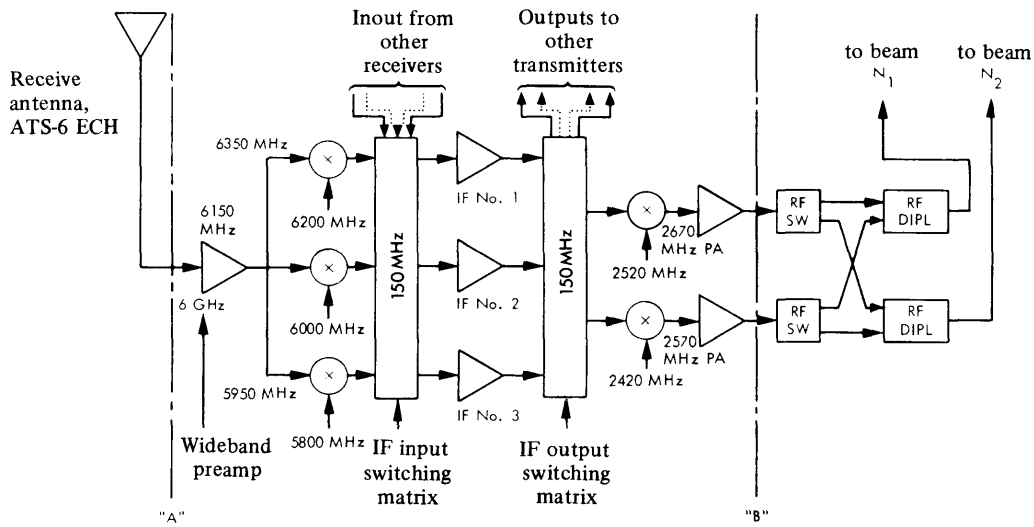

FIGURE 1 – *Simplified block diagram of the ATS-6 HET system*

TABLE I – *ATS-6 HET System Parameter Summary*

	Receiver centre frequency MHz(1)	Receive antenna	Repeater type	Repeater band-width MHz (3 dB)	Transmit centre frequency MHz	Transmit antenna(2)	Repeater e.i.r.p. dBW, peak	3 dB contour of beam foot print
Repeater channel 1	5950 6150 6350	ATS-6 Earth coverage horn 17° HPBW	Hard limiting dual conversion no spectrum inversion	40	2569.2	ATS-6 30' reflector S-band beams N_1 or N_2	+ 53.2 either beam	⩽ 0.9°
Repeater channel 2	(same)	(same)	(same)	30	2670	(same)	+ 53.0 either beam	(same)

(1) Selected by command.

(2) Either channel can drive either beam; both channels can drive either beam simultaneously; channel power cannot be divided between the two beams; all functions selected by command. See Figure 4 for typical S_1 and S_2 "footprints". The S_1 and S_2 elements create S-Band beams N_1 and N_2 respectively.

The diplexer in the 2670 MHz band was specifically designed to reduce the ATS-6 emissions in the 2690 to 2700 MHz band. This diplexer provides 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 power flux spectral 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 224-4.

Preflight and in-orbit ATS-6 9.1 metre paraboloid antenna patterns are given in Fig. 2.

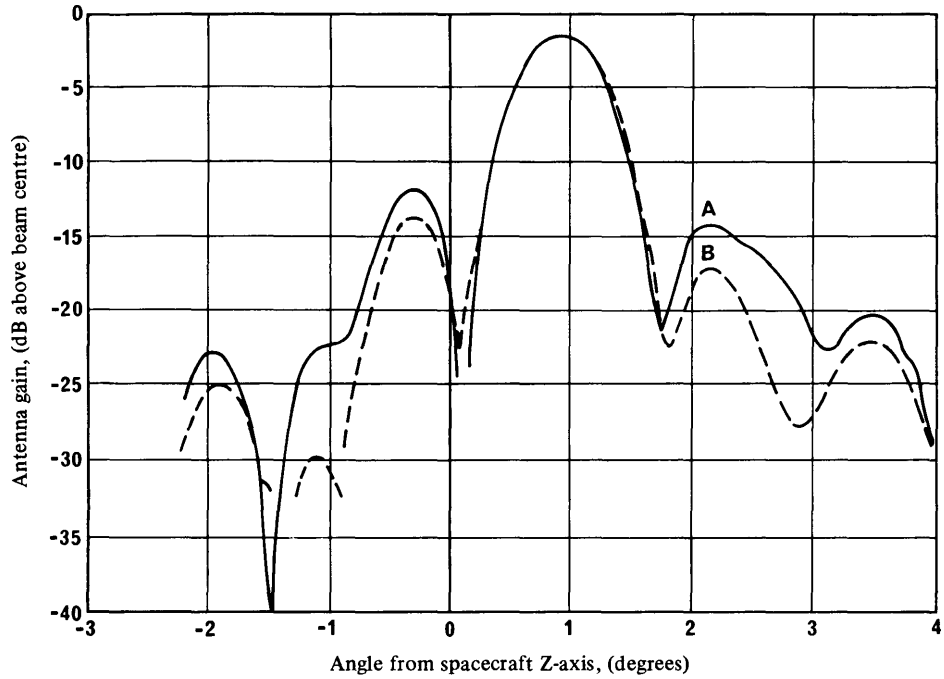

FIGURE 2 – *ATS-6 antenna patterns*

A : In orbit

B : Preflight

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 224-4). 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 frequency response, determined primarily by the filter, is illustrated in Fig. 3.

The rms fluctuation temperature was approximately 0.5 K for a one second integration time. With the receiving antenna used, this corresponds to a power flux spectral 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 pyramidal horn. The half-power beamwidth was approximately 1° in the H plane.

3.1 *Received power flux spectral density determination*

The radiometer output can be viewed as a convolution of the received spectrum with the spectral characteristics of the radiometer. The deconvolution of the radiometer output and the receiver bandpass characteristics, in order to derive the incident power flux spectral density, is summarized as follows. The received signal, $C(f_r)$ can be written:

$$C(f_r) = \int_0^\infty S(f)\, H_{f_r}(f + f_r)\, df \qquad (1)$$

where $S(f)$ is the received power flux spectral density, and $H_{f_r}(f)$ is the receiver frequency response when tuned to frequency (f);

or,

$$C(f_r) = S(f) * H(f) \qquad (2)$$

The index f_r is dropped since (2) represents the set of all integrals of the type (1) for each f_r of interest. Equation (2) is deconvolved numerically to solve for the unknown $S(f)$ in the region of the 2690-2700 MHz radioastronomy band.

A trial received flux-density, S^0, (f), was chosen and the following convolution was performed numerically:

$$C^0(f) = S^0(f) * H(f) \tag{3}$$

The calculated $C^0(f)$ was compared with $C(f)$, the measured ATS signal. A corrected received power flux spectral density:

$$S^1(f) = S^0(f) + C(f) - C^0(f) \tag{4}$$

was generated and fed back into Equation (3) giving:

$$C^1(f) = S^1(f) * H(f) \tag{5}$$

The solution rapidly converges to $S^n(f)$ when $C^n(f) \simeq C(f)$.

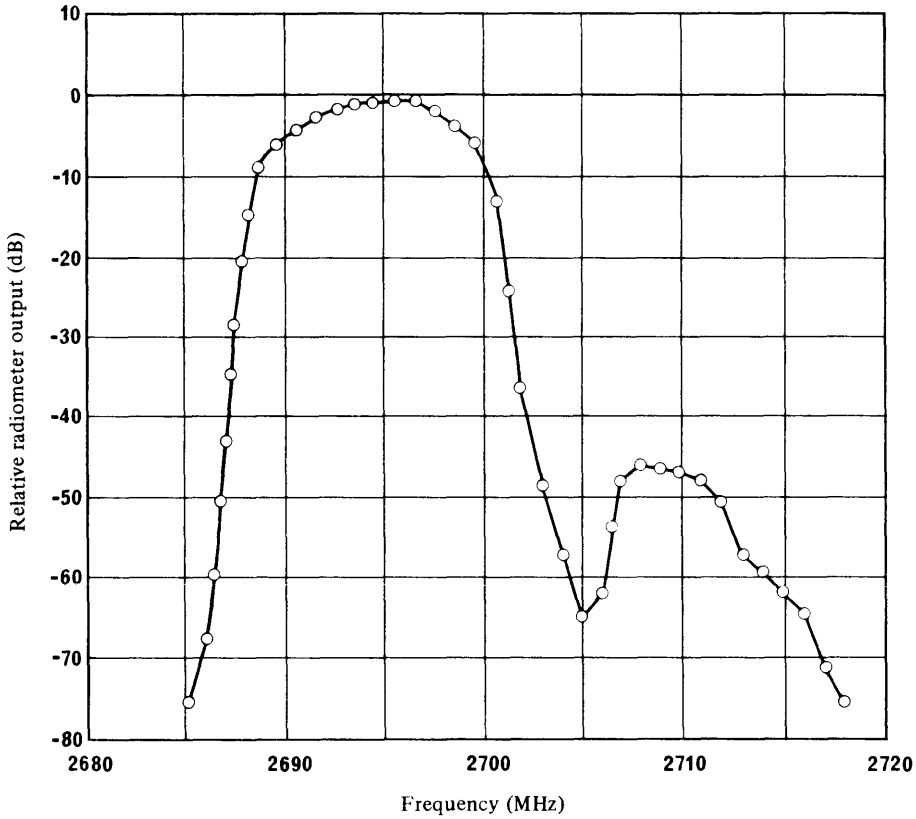

FIGURE 3 – *PSURAO radiometer bandpass characteristics when tuned to 2695 MHz*

4. June 1974 test programme

The ATS-6 broadcast area coverage or "footprint" used in the June 1974 tests is shown in Figure 4. PSURAO was located near the 4.5 dB beam contour. 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 radio astronomy 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 Figure 5, 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.

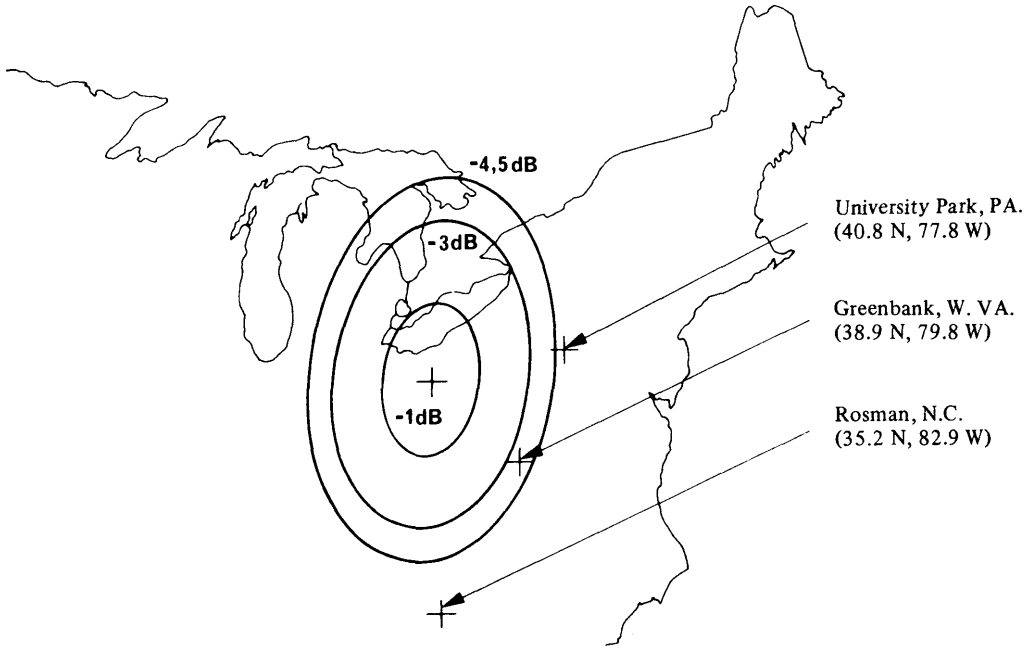

FIGURE 4 – *ATS-6 footprints for June 1974 test*

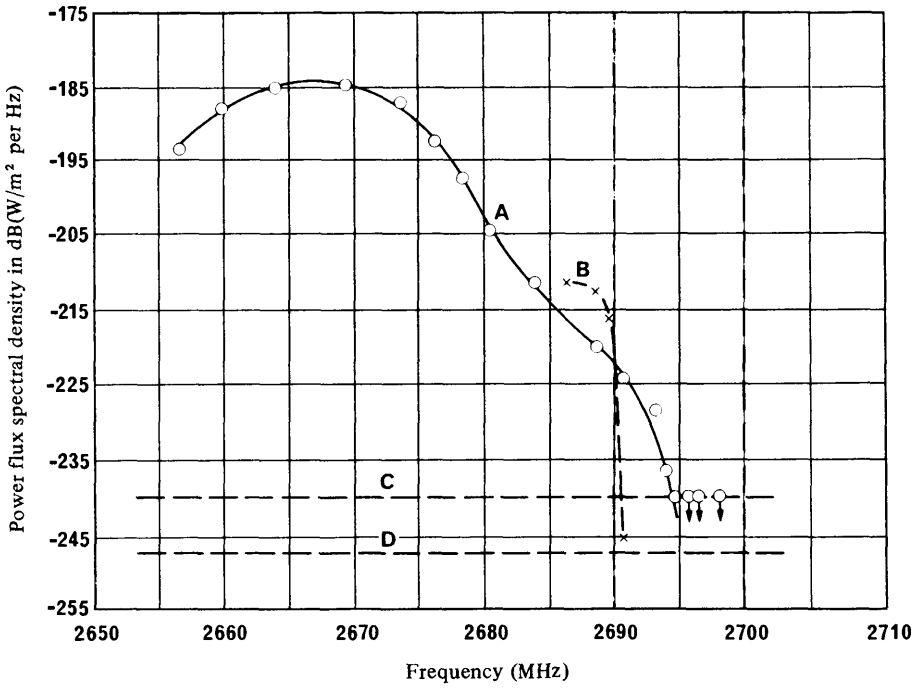

FIGURE 5 – *Radiometer output and ATS-6 flux-density*

A : radiometer output, $C(f_r)$

B : ATS-6 flux density, $S(f)$

C : PSURAO minimum fluctuation level

D : CCIR criterion

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. 5). 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.

From Figure 5, 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.

5. The April 1975 test programme

The purpose of the 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 (C/N). 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. For these tests the ATS-6 repeater receiver was switched from the ECH (Earth Coverage Horn) (+16 dB gain) to the 9.1 metre parabolic reflector (+46 dB gain).

The pointing of Figure 6 was chosen to permit the relatively narrow footprint of the ATS-6 reflector (diameter, 9.1m) at 6 GHz to point close to Rosman while the 2670 MHz antenna footprint pointed close to PSURAO.

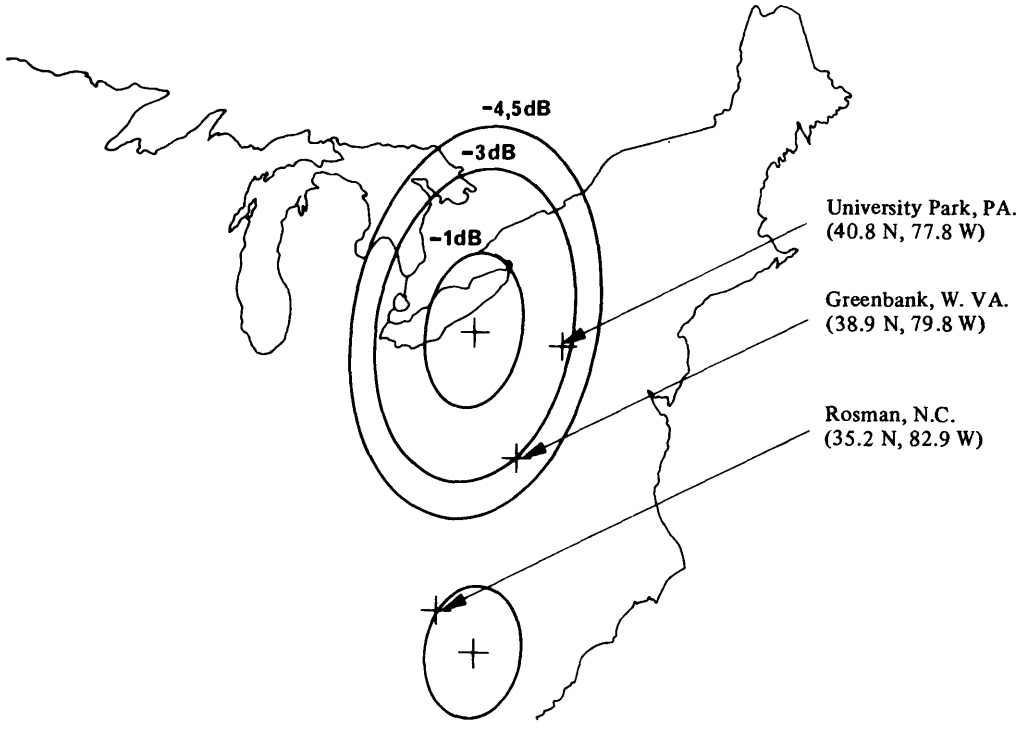

FIGURE 6 – *ATS-6 footprints for April 1975 test*

Radiometer output versus frequency was measured under a variety of ATS-6 signal conditions, providing satellite received signals varying in 5 dB steps from −110 dBW to −75 dBW and using both CW and a $\sin^2$ window video test pattern.

Figure 7 is a summary of the mean flux-density at 2690 MHz versus the up-link signal strength at the satellite under various test conditions. No corrections have been made for actual radiometer receiver bandpass characteristics. The radiometer output data was corrected for polarization effects (+3 dB) and differences in the ATS-6 footprint contours (1.5 dB) so that the data could be compared directly with the results of the June 1974 tests. Also illustrated in Figure 7 is the predicted flux versus the up-link signal strength.

The effect of carrier modulation on the out-of-band emission is characterised by the three data points taken at an up-link signal strength of −90 dBW. The application of the $\sin^2$ window increases the power flux spectral density by 5 dB.

The data points taken at −85 dBW may be spurious. The data discrepancies among ECH, 9.1 metre reflector and the predicted values is due to experimental uncertainties (for example, in the absolute calibration of the PSURAO radiometer and the ATS-6 analogue telemetry, antenna pointing error, etc.).

An apparent anomaly observed in the test was an increase in ATS-6 mean flux in the 2697-2703 MHz region of the spectrum at up-link signal strengths above −80 dBW. Unfortunately, insufficient quantitative data exists to draw any meaningful conclusions.

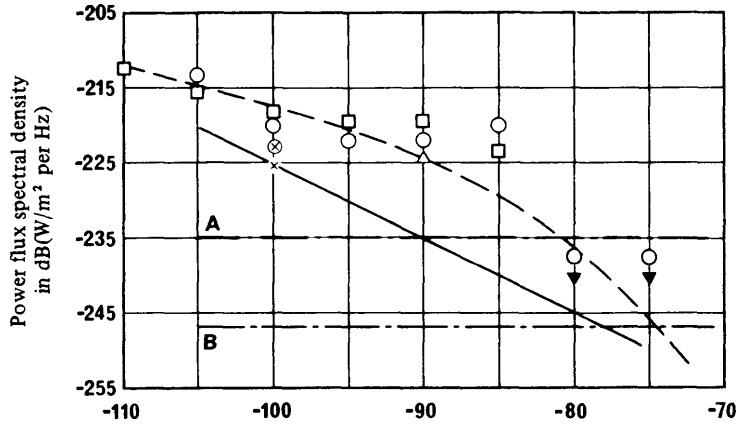

FIGURE 7 – *Radiometer output vs ATS-6 received signal strength at 2.69 GHz; comparisons with other data*

A : Psurao measurement limit
B : CCIR guideline
○ : April '75, PFF, $\sin^2$ TP
□ : April '75, ECH, $\sin^2$ TP
△ : June '74, ECH, video
⊗ : April '75, ECH, CW
× : NASA pre-launch data, extrapolated

6. Conclusions

The series of ATS-6 measurements taken by radioastronomy observatories whose locations ranged from the −3 to the −4.5 dB contours 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. 5, 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 minimise 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.

As noted in Section 4 the power flux spectral density is about −223 dB(W/(m^2 · Hz)) at the band edge with the use of a filter, and falls off at a rate of about 25 dB/MHz. In this case the interference would have been well below the CCIR limit (−247 dB(W/(m^2 · Hz))) * had the carrier frequency of the transmitter been 2 or 3 MHz lower than that used.

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HAGEN, J. P., SWANSON, P. N., and HEFFERNAN, P. J. [1975] The effect of the ATS-6 satellite on the 2690-2700 MHz radioastronomy band. Report X-410-75-283, NASA Goddard Spaceflight Centre, October 1975.

WHALEN, A. A. [1975] Health, Education, Telecommunications experiment. Proceedings of International Communications Conference, San Francisco, IEEE, 1975.

* See Recommendation 314-4.

RECOMMENDATION 517 *

PROTECTION OF THE RADIOASTRONOMY SERVICE FROM TRANSMITTERS IN ADJACENT BANDS

(1978)

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 224-4;

(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 Nos. 89, 90, 91, 92, and 116 of the Radio Regulations;

(e) that No. 116A 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 World Administrative Radio Conference in 1979.

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* This Recommendation is brought to the attention of Study Groups 4, 7, 8, 9, 10 and 11.

REPORT 699 *

IONOSPHERIC LIMITATIONS TO GROUND-BASED RADIOASTRONOMY BELOW 20 MHz

(1978)

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 antennae at short wavelengths, the development of low noise pre-amplifiers and the succession of important discoveries at high frequencies have contributed to this trend.

There are, however, many phenomena of astrophysical interest which manifest themselves only at the long radio wavelengths. Free-free absorption in ionized regions of the Galaxy, self-absorption in extragalactic radio sources, low-frequency emission mechanisms from tenuous plasmas in clusters of galaxies are some phenomena which require extensive investigation. To date (1975), extensive astronomical measurements below 20 MHz have been limited to two source surveys [Bridle and Purton, 1968; Braude *et al.*, 1969] with resolution of a few degrees; measurements of galactic background emission [Ellis and Hamilton, 1966; Reber, 1968] with resolution 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 Figure 1.

The lack of high resolution instruments below 20 MHz is evident. There are three main technical reasons which account for this:

- Antennae of several kilometres extent are required for resolution better than 1 degree. Dashed lines in Figure 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 frequency allocations for radio astronomy 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 sites on the Earth sufficiently remote from interfering signals. It is significant that the few ground-based measurements made below 10 MHz, have been made from Tasmania which from an interference point of view can be regarded as in an advantageous situation.

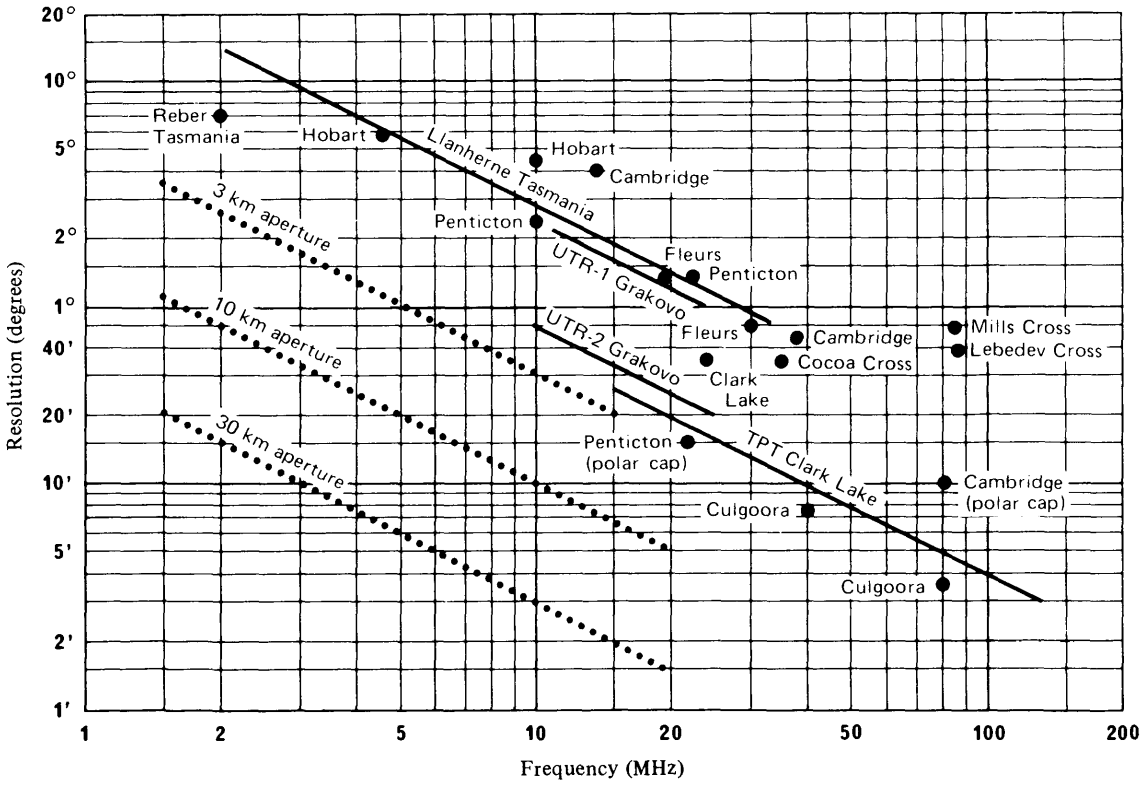

FIGURE 1

* This Report is brought to the attention of Study Group 6.

DESCRIPTION OF FIGURE 1

This Figure shows the resolution of fixed frequency radio telescopes (points) and broad-band telescopes (lines) in current and past use. Dotted lines indicate the resolution obtainable with apertures of various extents. These telescopes are described in the following references.

Fixed frequency telescopes

Reber Tasmania:	REBER, G. J. [1968] J. Franklin Inst. **285**, 1.
Hobart 4.7 MHz:	ELLIS, G. R. A., GREEN, R. J., HAMILTON, P. A. [1963] Aust. *J. Phys.* **16**, 545.
Hobart 10 MHz:	HAMILTON, P. A., HAYNES, R. F. [1968] *Aust. J. Phys.* **21**, 895.
Penticton 10 MHz:	GALT, J. A., PURTON, C. R., SCHEUER, P. A. G. [1967] Publ. Dominion Obs. 25, **10**.
Cambridge 13 MHz:	ANDREW, B. H. [1969] *M. N. Roy. Ast. Soc.* **143**, 17.
Fleurs 19.7 MHz:	SHAIN, C. A. [1958] *Proc. IRE*, **46**, 85.
Penticton 22 MHz:	CONSTAIN, C. H., LACEY, J. D., ROGER, R. S. [1969] *IEEE Trans. Ant. Prop.*, **AP-17**, 162.
Penticton Polar cap:	DEWDNEY, P. E. [1975] Dominion Astrophy Obs.
Clark Lake 26 MHz:	ERICKSON, W. C. [1965] *IEEE Trans. Ant. Prop.*, **AP-13**, 422.
Fleurs 30 MHz:	FINLEY, E. A., JONES, B. B. [1972] *Proc. Astr. Soc. Aust.*, **2**, 115.
Cocoa Cross:	CRONYN, W. M., SHAWHAM, S. D. [1975] Univ. of Iowa Physics and Astronomy, 75-12.
Cambridge 38 MHz:	COSTAIN, C. H., SMITH, F. G. [1960] *M. N. Roy. Ast. Soc.*, **121**, 405.
Culgoora 43 MHz:	SHERIDAN, K. V., LABROM, N. R., PAYTEN, W. J. [1973] *Proc. IEEE*, **61**, 1312.
Cambridge Polar cap:	BRANSON, N. J. B. A. [1967] *M. N. Roy. Ast. Soc.*, **135**, 149.
Mills Cross:	MILLS, B. Y, LITTLE, A. G., SHERIDAN, K. V., SLEE, O. B. [1958] *Proc. IRE*, **46**, 67.
Culgoora 80 MHz:	See Culgoora 43 MHz.
Lebedev Cross:	VITKEVICH, V. V., KALACHEV, P. D. [1965] Radio Telescopes Trudy Fiz. Inst. Lebedeva 28.

Broadband telescopes

Llanherne, Tasmania:	ELLIS, G. R. A. [1972] *Proc. Astro. Soc. Aust.*, **2**, 135.
UTR-1 Grakovo:	BRAUDE, S. Ya., LEBEDEVA, O. M., MEGN, A. V., RYABOV, B. P. ZHOUK, I. N. [1969] *M. H. Roy Ast. Soc.*, **143**, 289.
UTR-2 GRAKOVO:	DOUBINSKI, B. A., SLISH, V. I. [1973] Radioastronomy, Soviet Radio, Moscow.
Clark Lake TPT:	ERICKSON, W. C., FISHER, J. R. [1974] *Radio Science*, **9**, 387.

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 [Cole, 1973] the years 1985 to 1990 and 1996 to 2001 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 [CCIR, 1970]. 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 are possible 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 always 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,

$$\varphi_c(\nu) \simeq \arccos\left(\frac{\nu_c}{\nu}\right) \tag{1}$$

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 1.5°.

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 antennae 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 extent 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 Data, 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 parenthesis 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.

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)

6. Scintillation and the quality of observations

The major factor limiting the quality of observations at times of sufficiently low density and no interference is the phenomenon of scintillation [CCIR, 1974]. 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 antennae 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 antennae, 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.

Because of the transient nature of scintillations, it is important to make full use of the best conditions. This implies use of antennae 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 539-1

THE PROTECTION OF RADIOASTRONOMY OBSERVATIONS IN THE SHIELDED ZONE OF THE MOON *

(Question 7-1/2)

(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 co-ordinated 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.

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 area of the Moon in Recommendation (Spa2 – 8) 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.

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* Propagation aspects of this subject are discussed in Report 336-1, of Study Group 5.

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 co-ordinate 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 479-1

PROTECTION OF FREQUENCIES FOR RADIOASTRONOMICAL MEASUREMENTS IN THE SHIELDED ZONE OF THE MOON

(Question 7-1/2)

(1974 - 1978)

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 Recommendation No. Spa2 – 8 of the Radio Regulations expresses the desirability of maintaining the shielded area of the Moon as an area of maximum value for observations by the Radioastronomy Service and by passive space research and consequently as free as possible from transmissions;

(g) that the same Recommendation also invited the CCIR to study the frequency bands most suitable for radioastronomy observations on the shielded area of the Moon and work out Recommendations concerning these bands as well as criteria for their application and protection;

(h) that earth satellites with high apogees, deep-space probes and transmitters located on the Moon may each illuminate the shielded zone;

(i) that Report 539-1 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 539-1.

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.

REPORT 226-4

FACTORS AFFECTING THE POSSIBILITY OF FREQUENCY SHARING BETWEEN RADAR ASTRONOMY AND OTHER SERVICES

(1963 - 1966 - 1970 - 1974 - 1978)

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 antennae 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 terrestrial 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.

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 antennae, sensitive receivers and low tracking rates.

Many similarities exist between radar astronomy systems and deep-space tracking facilities. These, or similar facilities on Earth, may also be used in a bistatic mode, where the other 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

$$R^2 = Const.\ PA/T \tag{2}$$

Both relations point to the fundamental importance of large powers, large antennae and sensitive receivers.

The detectability of the planets and of the asteroids Icarus and Toro 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].

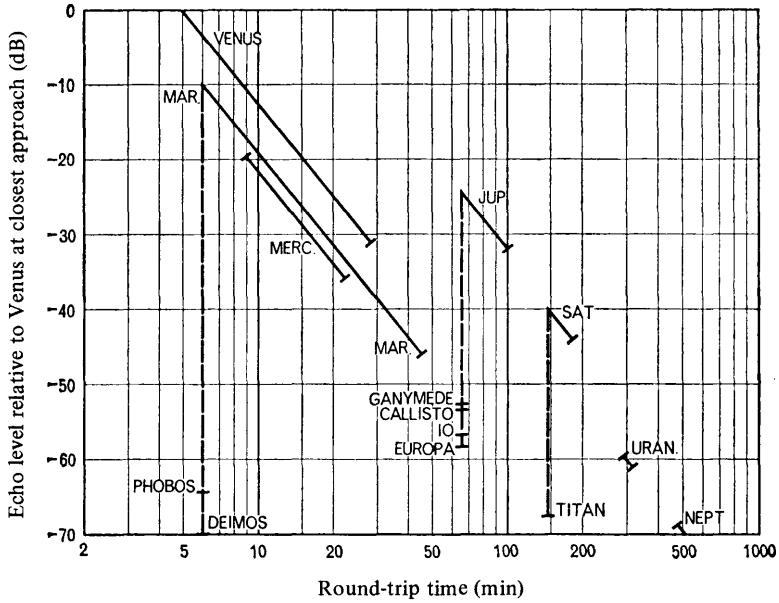

FIGURE 1 – *Guide to the detectability of the planets by radar; atmospheric absorption has not been considered in the figures and will greatly reduce the actual detectability of the giant planets*

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. For greater discrimination, the accumulated data of many hours of actual observation can be processed over many more hours by analogue and digital computers.

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.

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* 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 224-4).

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 465-1.) 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.

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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 power	System noise-temperature (K)
			Diameter (m)	Gain (dB)					
Calif. Inst. Tech. JPL	Goldstone Lake, Calif.	2.4×10^3	64	62	2100	400	400	CW(1)	20
Cornell Univ. National Astronomy and Ionosphere Center	Arecibo, Puerto Rico	2.4×10^3 4.3×10^2	304 304	72.0 60.0	20 000 39 000	450 150	450 2500	CW 0.03-10.0 ms	40 120
Mass. Inst. Tech. Lincoln Lab.	Tyngsboro, Mass. (Haystack)	7.8×10^3	36.5	66.1	482	350	350	CW	45
Institute de Geofisica de Peru	Jicamarca Radar Observatory Lima (Peru)	50	285 (Square array)	42.6	84 000	250	6000	0.01-1000 ms	2000-3000
Stanford Univ. Research Inst.	Stanford, Calif.	24	365 (array of 48 log Periodic antennae)	25	6880	300	600	10 μs	Cosmic noise

(1) Radiates unmodulated carrier.

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SECTION 2E: AMATEUR SATELLITE SERVICE

Report

REPORT 542-1 *

TECHNICAL FEASIBILITY OF FREQUENCY SHARING BY THE AMATEUR SATELLITE SERVICE

Interference potential of amateur satellites in shared bands

(1974 - 1978)

1. Introduction

It was shortly after the first demonstration of the practicability of electromagnetic wave communication without wires that radio amateurs began to experiment with radio transmission. Over the years since 1896 radio amateurs around the world have contributed significantly to the development of radio communication. Today they are involved in a wide range of communication activities which include some of the most modern techniques [CCIR, 1974-78]. In particular they are communicating via satellites.

In recent years several amateur radio organizations, with the active support of the International Amateur Radio Union and its member societies, have made contributions to the development of space techniques and experience. Project OSCAR, Inc. (Orbiting Satellites Carrying Amateur Radio), an organization formed in 1960 by amateurs on the west coast of the United States, developed and arranged launches for four amateur radio satellites of the OSCAR series. A fifth OSCAR satellite was constructed by Project Australis, an amateur group in Melbourne, Australia, and the flight qualification tests and launch were arranged by the Radio Amateur Satellite Corporation of Washington, D.C., with the co-operation of the National Aeronautics and Space Administration.

A sixth OSCAR satellite (AMSAT-OSCAR-6) was launched in October 1972, after assembly in the United States, using systems built by amateurs in Australia, the Federal Republic of Germany and the United States AMSAT-OSCAR-7 was launched in November 1974 into an orbit very similar to that of AMSAT-OSCAR-6.

This Report treats questions concerning the administrative control of satellites in the amateur service and the interference potential of amateur satellites operating in shared bands.

Annex I summarizes the characteristics of OSCAR-6 and OSCAR-7.

Annex II is a report on the results of AMSAT-OSCAR-6 and AMSAT-OSCAR-7 experiments as of October 1975.

2. Administrative control of satellites in the amateur service

No. 1567A of the Radio Regulations requires that, in the case of amateur satellites to be operated in shared bands, the authorizing Administration should ensure that a sufficient number of capable, reliable and responsible amateur command stations are established before launching is effected, so as to be able to guarantee that any harmful interference that might be reported can be terminated by group command. (It may be noted that the possibility of harmful interference being received from a non-geostationary satellite will last no more than a few minutes, on any one occasion and will not reappear for several hours, if not days, depending upon the location at which the interference occurs.)

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

3. Effects of amateur satellites on other services in shared bands

Annex III contains an approach to the analysis of the interference potential of amateur satellites in the bands shared with television broadcasting, radiolocation, and fixed and mobile services. The problem of sharing with the radiolocation service, in particular, requires further study.

General information on protection ratios and sharing criteria for the use of space techniques in the amateur radio service is presented in [CCIR, 1970-74]. Among other things, it provides data on earth receiver signal-to-noise ratios produced by satellites in the amateur satellite service, and tabulates the technical characteristics of all OSCAR satellites.

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ANNEX I

TECHNICAL CHARACTERISTICS OF THE AMSAT-OSCAR-6 AND AMSAT-OSCAR-7 SPACECRAFT

AMSAT-OSCAR-6

Launch:	October 15, 1972 from the Western Test Range, Lompoc, Calif., by NASA with the NOAA-2 meteorological satellite on a two-stage Thor-Delta launch vehicle.
Orbit:	1460 km circular, polar orbit, 101.6° inclination, 114.9945 minute period; sun-synchronous orbit, with passes repeating on a two-day cycle around 9 AM and 9 PM local time.

Transponder characteristics:	145.9 to 146.0 MHz input passband, 29.45 to 29.55 MHz output passband, 1 to 1.3 watts output; linear transponder, input signal of −100 dBm produces 1 watt output.
Beacons:	29.45 MHz at 100 to 200 milliwatts. 435.10 MHz at 300 milliwatts (this beacon is no longer operative).
Antennae:	Ten metre half-wave dipole made of standard carpenter's rule. Two metre quarter-wave monopole made from piano wire. 70 cm quarter-wave monopole made from piano wire.
Telemetry:	24 channels, transmitted sequentially in Morse code at 20 or 10 words per minute. Battery and regulator voltages, solar array and experiment currents, RF outputs and temperatures are telemetered approximately every 90 or 180 seconds, depending upon code speed.
Codestore:	896-bit digital shift-register message storage unit capable of storing and playing back 18 word Morse code and 22 word teletype messages loaded by selected ground stations.
Telecommand:	21 function telecommand system capable of turning on and off the transponder, 435 MHz beacon, selecting between telemetry and Codestore, and between 20 and 10 word per minute Morse code telemetry rate.
Power:	n-on-p silicon solar cells and rechargeable 6 ampere hour nickel-cadmium battery (24 volt system). Approximately two watts of average prime power available at beginning of life.
Stabilization:	Passive magnetic attitude stabilization along the longest axis, achieved by means of a 20.3 cm long 50 000 pole-cm aluminium-nickel-cobalt (Alnico 5) magnet. Spin is dampened by twelve 0.32 cm diameter permalloy rods.
Size:	16.3 × 30.5 × 44.0 cm rectangular solid, 50 per cent covered with solar cells.
Weight:	18.2 kg.
Lifetime objective:	one year.

AMSAT-OSCAR-7

Launch:	November 15, 1974 from the Western Test Range, Lompoc, Calif; by NASA with the NOAA-4 meteorological satellite on a two-stage Thor-Delta launch vehicle.
Orbit:	1450 km near-circular, polar orbit, 101.7° inclination, 114.9448 minute period; sun-synchronous orbit, with passes repeating on a two-day cycle around 8 to 9 AM and 8 to 9 PM local time.
"Mode A" transponder characteristics:	145.85 to 145.95 MHz input passband, 29.40 to 29.50 MHz output passband, 1 to 2 watts output; linear transponder, input signal of −100 dBm produces 1 watt output.
"Mode B" transponder characteristics:	432.125 to 432.175 MHz input passband, 145.975 to 145.925 MHz inverted output passband, 6 to 8 watts or 3 to 4 watts output; linear transponder, input signal of −106 dBm produces 2.5 watts output.
Beacons:	29.502 MHz at 100 to 200 milliwatts (associated with Mode A transponder). 145.972 MHz at 100 to 200 milliwatts (associated with Mode B transponder). 435.103 MHz at 300 milliwatts. 2304.091 MHz at 40 milliwatts.
Antennae:	Ten-metre deployable "STACER" half-wave dipole. Two-metre quarter-wave circularly polarized canted turnstile made of standard carpenter's rule (used also as three-quarter wave canted turnstile at 432 and 435 MHz). 2304 MHz circularly polarized quadrifilar helix.
Telemetry (Morse code encoder):	24 channels, transmitted sequentially in Morse code at 20 or 10 words per minute. Battery and regulator voltages, clock count, solar array and experiment currents, RF outputs and temperatures are telemetered approximately every 90 or 180 seconds, depending upon code speed.

Telemetry (teletype encoder):	60 channels, transmitted sequentially in five-level (Baudot) code at the rate of approximately one parameter per second. Two lines of digital status data are also encoded, including readings of the spacecraft clock and the contents of the command storage registers. The encoder can be commanded to dwell on any desired channel.
Codestore:	896-bit digital shift-register message storage unit capable of storing and playing back 18 word Morse code and 22 word teletype messages loaded by selected ground stations.
Telecommand:	35 function redundant telecommand decoders capable of turning on and off the two transponders, 435 and 2304 MHz beacons, selecting between high and low speed Morse code telemetry, teletype telemetry (in either "commutate" or "dwell" modes), Codestore, and other functions.
Power:	n-on-p silicon solar cells and rechargeable 6 ampere hour nickel-cadmium battery (14 volt system). Approximately 14 watts of average prime power available at beginning of life.
Stabilization:	Passive magnetic attitude stabilization, achieved by means of four 15.2 cm long, cast aluminium-nickel-cobalt (Alnico 5) magnets. Spin is dampened by permalloy rods. Slow spin maintained by effect of solar pressure on white/black paint patterns on canted turnstile antenna elements.
Size:	Octahedral in shape, 36 cm high, 42.4 cm diameter.
Weight:	28.9 kg.
Lifetime objective:	three years.

ANNEX II

RESULTS OF THE AMSAT-OSCAR-6 AND AMSAT-OSCAR-7 AMATEUR SATELLITE EXPERIMENTS

1. Introduction

The principal objectives of the AMSAT-OSCAR 6 and 7 satellites (A-O-6 and A-O-7) are:

- to experiment with multiple-access communications operating techniques, using large numbers of small terminals operating simultaneously in the amateur service.
- to conduct store-and-forward communications tests using an on-board digital message storage unit.
- to study radio propagation from the satellites at their operating frequencies of 29.5, 146, 432 and 435 MHz.
- to demonstrate the operation of small, deployable amateur earth terminals with the AMSAT-OSCAR 6 and 7 satellites, suitable for use in the event of natural disasters, epidemics, famines and similar emergencies.
- to experiment with satellite signals as an instructional tool in the classroom in order to directly involve and motivate youngsters towards seeking careers in engineering and the sciences.
- to experiment with voice bulletin and other special transmission techniques, such as slow-scan television, ranging, and radio-control.
- to investigate the feasibility of operating Earth-to-satellite and satellite-to-Earth links at frequencies shared with the Radiolocation Service.

2. Multiple-access communication experiments

Well over 3000 amateur radio operators in at least 100 different countries have demonstrated their communication capabilities with the AMSAT-OSCAR 6 and 7 satellites, with often as many as 50 signals heard through the transponder simultaneously. The linear transponders aboard A-O-6 and A-O-7 permit mixed-mode, random access operation. Approximately 75% of the communications has been by Morse code telegraphy (1A1 emission), 20% by single-sideband voice (3A3J) and the remainder by AM voice (6A3), direct printing radiotelegraphy (1F1), slow-scan television and various experimental transmission modes.

One objective of the transponder experiments has been to determine the effectiveness of linear, frequency-translating transponders in random, multiple-access applications, and to establish user power-sharing criteria for various types of amplitude-modulated user signals. It was found that much of the signal variations occuring on the Earth-to-satellite and satellite-to-Earth links can be compensated for by the user during transmissions. This is facilitated by the nearly universal adoption of an operating procedure whereby each satellite user monitors his or her own downlink signal to correct for Doppler shift and varying signal levels as a function of satellite position, orientation, and transponder loading. The fact that as many as 50 users have been observed operating through the transponder at the same time tends to verify the hypothesis that random variations in the amplitude-modulated user signals, when averaged over the passband, provide each user with a larger percentage of the transponded power than might be predicted if one were to divide the power proportionately among the users. This characteristic is best exhibited by single-sideband (3A3J) users, since single-sideband transmissions have lower average power characteristics than do on-off Morse code (1A1), or constant-power techniques such as narrow-band FM (12F3) [Klein and King, 1974].

3. Message-store and forward experiments

Both AMSAT-OSCAR 6 and 7 have digital message storage units capable of storing messages in Morse code up to 18 words in length. This system, called "Codestore" can be loaded by telecommand stations in Australia, Canada and the United States. A message typical of those stored in the Codestore system is:

"DUE TO LOW BATTERY VOLTAGE OSCAR 6 WILL BE OUT OF SERVICE UNTIL JUNE 28".

The operation of Codestore has also been demonstrated in a real-time regenerative mode in which Morse code characters transmitted via the spacecraft telecommand system are reconstituted and retransmitted character-by-character over the spacecraft telemetry beacon transmitter.

4. Inter-satellite propagation experiments

The frequency plans of the communications transponders aboard A-O-6 and A-O-7 are such that output signals from A-O-7 can be retransmitted through A-O-6 when the two spacecraft are within range of one another. This makes possible inter-satellite propagation tests involving stations in the amateur service. The two spacecraft are in nearly identical orbits and have a difference in period of 0.05 minutes per orbit. As a result, the two satellites pass close together for several weeks each six months [Klein and Soifer, 1975]. The sensitivity of the A-O-6 transponder is such that it should be capable of repeating signals from the A-O-7 transponder out to separation distances of the order of 5000 km.

The possibility of inter-satellite propagation was realized two months after the launch of A-O-7 as observations of successful A-O-6/A-O-7 linked communications began to be received. Two-way inter-satellite communication reports were received from 15 radio amateurs who successfully used both telegraphy (1A1) and single-sideband (3A3J) transmission modes. Fifty-five amateur stations in 12 countries were involved in these contacts, which occurred out to satellite separation distances of up to 2000 km. Successful two-way communication was accomplished between stations transmitting through different satellites at the same time, i.e., one station transmitting through A-O-7 and the other transmitting through A-O-6, and also between stations where both operators were transmitting through A-O-7 and listening to their signals retransmitted through A-O-6.

5. Small terminal and emergency communication experiments

The 1400 to 1500 km orbital altitudes of AMSAT-OSCAR 6 and 7, and the 29.5, 146 and 432 MHz frequencies used for the transponder links permit small portable or mobile terminals to be used for two-way, Earth-satellite-Earth communication. Transmitting equipment costing under 100 US dollars has been available, as have high-frequency receivers and very high-frequency receiving converters. Complete satellite earth terminals can be obtained for under 1000 US dollars made up of completely "off-the-shelf" equipment manufactured in several countries. The wide availability of solid-state transmitting and receiving equipment for the frequency bands employed makes battery operated suitcase size terminals feasible, and these terminals can be hand carried and easily transported. Several such terminals have been constructed and are in use.

Mobile terminals installed in automobiles, aircraft and boats by amateur radio operators in the United States, Japan, France and the Philippines have been quite successful in providing two-way communication with AMSAT-OSCAR 6 and 7.

The potential application of OSCAR spacecraft to assist in communication in the event of natural disasters, epidemics, famines and similar emergencies was demonstrated in September 1974, in an emergency test conducted to simulate an earthquake in the state of Alaska. During this test, several messages were passed between Alaska and other areas of the United States via AMSAT-OSCAR 6.

Besides the factors of availability, reliability, portability, ease of operation and the low cost of OSCAR portable user terminals, the amateur radio community in many countries represents a resource of radio operators experienced and trained in emergency communication procedures [ITU, 1971].

6. Instructional applications

Experimental curriculum material has been prepared by educators and distributed to teachers in a number of countries. These guides contain lesson units describing how AMSAT-OSCAR 6 and 7 can be received in schools on shortwave receivers, and used to teach concepts of orbital mechanics, Doppler shift, fading, communications range, telemetry and the physics of the environment. Telemetry signals are transmitted as a series of numbers in Morse code, so that only pencil, paper, a telemetry decoding sheet, and a knowledge of the ten Morse code digits are needed for receiving and decoding the data [Dunkerley, 1974]. On several mornings each week during the school year, volunteer amateur radio operators serving as bulletin stations transmit condensed lessons intended for use by teachers and students in classrooms.

7. Multiple-address bulletin experiments

Bulletins have been transmitted through the OSCAR transponders on a regularly scheduled basis, generally under single-access conditions in which the bulletin stations employ the full power output of the spacecraft transponder. Bulletins in this "broadcast" mode generally include orbit ephemeris information, the current operating schedule, and announcements of planned experiments and demonstrations. Additional bulletin stations have regularly transmitted hurricane watch information during the hurricane season.

8. Other communications-related experiments

AMSAT-OSCAR 6 and 7 have been used with a number of different satellite range and range-rate measurement techniques involving tones, pulses, measured delays in speech, slow-scan television line synchronization time delays, feed-back tones, and Doppler shifts [Meinzer, 1973]. Radio control of model aircraft via OSCAR satellite links has also been demonstrated; as has the successful transmission of electro-cardiograms, facsimile data and slow-scan television pictures.

One of the two transponders in AMSAT-OSCAR 7 employs a novel, high efficiency technique called "Envelope Elimination and Restoration" to achieve linear operation. The successful demonstration of this technique in space, along with the successful demonstration of low cost techniques for fabricating spacecraft hardware, is of importance for a number of non-amateur applications.

9. Shared band experiments

AMSAT-OSCAR 7 contains a transponder which relays Earth-to-satellite signals in the frequency range 432.125 to 432.175 Mhz (see Annex I). As this band is shared between the amateur and radiolocation services, special pulse-limiting circuitry was incorporated in the transponder design to suppress the effects of interference from radiolocation transmitters. In spite of the high sensitivity of the receiver portion of this transponder (-106 dBm input produces 2.5 watts output, and signals 20 dB weaker can still be received), no reports of significant interference from the radiolocation service have been received from the users of this transponder, although weak signals attributable to radiolocation have been observed occasionally.

The 435.1 MHz telemetry beacon in AMSAT-OSCAR 6 produced approximately 300 mW e.i.r.p. during the several months period in which it functioned. The AMSAT-OSCAR 7 435.1 MHz beacon produces approximately 300 mW for one orbit on command. 300 mW e.i.r.p. corresponds to a maximum power flux density at the Earth of -140 dB(W/m^2) at the subsatellite point. There have been no known reports of interference to the radiolocation service due to the operation of these beacons or any other system in the two spacecraft. On occasion, interference to amateur receiving stations has been reported due to radiolocation transmitters situated within several hundred kilometres of an amateur receiving station, but these incidents have generally been of a localized, relatively minor nature.

10. Telecommand station automation

Because a large number of commands is required to maintain AMSAT-OSCAR 6's operation, several amateur telecommand stations in Australia, Canada, Germany and the United States have been equipped with automated equipment capable of sending sequences of preprogrammed commands. The command signals are transmitted at regular intervals, as controlled by timers and punched paper tape. More sophisticated automated telecommand equipment has also been developed in which microcomputers are employed to send programmed commands, point antennae and log transmitted commands, permitting fully unattended telecommand station operation.

11. Conclusion

11.1 *Interference to other services*

In-orbit experience with the AMSAT-OSCAR 6 spacecraft since October 1972, and AMSAT-OSCAR 7 since november 1974 in a number of experimental applications, has resulted in no known reports of interference to other services, including the radiolocation service which shares the 430 to 440 MHz amateur band.

11.2 *Interference from other services*

Interference to amateur receiving stations from transmitters in the radiolocation service has been reported, but these generally have been local problems limited to regions near amateur receiving stations.

11.3 *Interference between amateur and amateur satellite operations*

There have been some cases of interference to amateurs from stations transmitting to amateur satellites, and from amateurs to stations receiving satellite transmissions. Generally, these cases have been solved by informal band-planning and agreements not requiring action by government telecommunication authorities.

11.4 *General*

The results of operations with AMSAT-OSCAR 6 and AMSAT-OSCAR 7 indicate that sharing between the amateur satellite and radiolocation services is feasible for OSCAR spacecraft operating in the 430-440 MHz band.

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ANNEX III

INTERFERENCE POTENTIAL OF AMATEUR SATELLITES IN SHARED BANDS

1. General

To date, amateur satellites have been in low, i.e. non-geostationary, orbits. While some use of the geostationary orbit can be expected, it is anticipated that the lower orbits will be the more common for the following reasons:

- amateurs must usually use simple techniques, to keep the cost and scale of effort to attainable bounds;
- amateurs must arrange launching on the basis of "as available" capacity; since a given size rocket has a greater payload capability when used to attain low orbits, there are more opportunities for spare capacity to be available;
- amateurs generally prefer low orbits, since the resulting motion makes world-wide use of a single satellite possible, giving more opportunity for experiment and communication.

However, the following comments take account of both moving and geostationary orbits.

2. Review of low orbit characteristics

A satellite in a low orbit appears to rise and set. The presence or absence of visibility, the visible duration and the interval between passes are functions of orbital height, inclination and location of the observing point. For a point on the equator, the following data are obtained for a direct equatorial satellite.

Height (km)	True period (min)	Apparent period (min)	Half arc of visibility (degrees)	Max. slant range (km)	Visibility time (min)	Probability of being visible P_v (%)	Surface visibility (%)
1 853	126	143	39	5 190	30	21	17·2
3 706	162	183	51	8 150	52	28	18·2
7 412	264	324	62·5	11 300	112	34	26·8
12 971	444	640	71·5	17 975	254	40	32·8
18 330	606	1 280	75	24 090	532	40	37·1
35 792	24 hr.	00	81·5	41 320	Continuous	100 or 0	42·3

If the observation point is not on the equator, the probability of the satellite being visible decreases, becoming zero if the latitude of the point is greater than the half arc of visibility angle.

With inclined orbits, the maximum duration of visibility is the same as the visibility time in the table. However, on some passes, the time will be shorter, and on other passes a low satellite will not be visible at all.

For a number of satellites in orbits of various inclinations and a number of points at various latitudes, the probability of visibility, P_v, is approximately equal to the "% surface visibility" column in the above table.

3. Probability of signal arrival

Let θ_H and θ_v be the horizontal and vertical beamwidths of a terrestrial antenna, i.e. the main-lobe angles. The probability that an amateur satellite is in the main lobe is given by:

$$P_m = P_v \frac{\theta_H}{360} \cdot \frac{\theta_v}{90} \qquad (1)$$

where the angles are measured in degrees, and where P_v may be determined by exact or approximate methods.

Let Φ_H and Φ_v be the horizontal and vertical angles at which the antenna pattern is some number of decibels below the on-axis gain; in interference studies, this number is often taken as equal to the on-axis gain; i.e. the interference is received by an isotropic antenna. The probability that an amateur satellite is received "off main lobe" or not at all, is then:

$$P_b = 1 - \left(P_v \frac{\Phi_H}{360} \cdot \frac{\Phi_v}{90} \right) \quad (2)$$

For the special case of equal horizontal and vertical angles, these probabilities are:

Angle (degrees)	P_m	P_b
1	$3{\cdot}1 \times 10^{-5} P_v$	1·0
3	$2{\cdot}78 \times 10^{-4} P_v$	1·0
10	0·0031 P_v	1–0·0031 P_v
30	0·0278 P_v	1–0·111 P_v
90	0·25 P_v	1–0·25 P_v

As a specific example, assume that P_v is 0.25, that $\theta_H = \theta_v = 25°$ and $\Phi_H = \Phi_v = 60°$ (values for Band III television from Recommendation 419). Then the probability of reception of an amateur satellite via the main lobe is less than 0.5%, and the probability that reception is either at or below the level of an isotropic antenna exceeds 97%.

4. Amateur satellites and television broadcasting

The present frequency bands for which amateur service and television broadcasting are authorized but not necessarily in the same regions are:

50 to 54 MHz:
- amateur service in Region 2;
- broadcasting service (television, Band I) in Region 1;
- amateur service in Region 3, subject to the provisions of Nos. 244, 245, 246 and 247 of the Radio Regulations.

220 to 225 MHz:
- amateur service in Region 2;
- broadcasting service (television, Band III) in Region 1 up to 223 MHz, plus limited amateur use under No. 301 of the Radio Regulations;
- amateur service, 220 to 225 MHz.

Recommendation 417-2 gives the following as values to be protected 90 to 99% of the time:

Band	dB (μV/m)
I	+48
III	+55

Recommendation 419 gives the antenna directivity as:

Band	Off-axis angle (degrees)	Discrimination (dB)
I	50 to 70	0 to 6
III	25 to 60	0 to 12

From the above relations, the probability of the occurrence of interference for a typical moving satellite (P_v = 25%) is:

Band	Main lobe (%)	Back lobes (%)
I	1·9	96
III	0·5	97

Given that the interference is not steady, and assuming that the frequencies will not be specially selected, the protection ratio deduced from Recommendation 418-3 for either CW or sound signal interference has the value of 50 dB. Since the sound signals may be amplitude or frequency modulated, this value also is probably satisfactory for such types of amateur signal. No data are available for single-sideband emissions and a common assumption is to assume that the interference is related to the average signal power.

The allowable power flux-density, W_a is given by:

$$W_a = U - P_r + G_D - 146 \qquad \text{dB(W/m}^2\text{)} \tag{3}$$

where

U is the signal level to be protected (dB(μV/m)),

P_r is the protection ratio (dB),

G_D is the antenna discrimination (dB).

Using the values developed above, the allowable amateur satellite signal to protect a television service becomes, for the strength outside an allocated region:

Band	Frequency (MHz)	Max. allowable power flux-density (dB(W/m²))	Field strength equivalent (dB(μV/m))
I	50 to 54	−142	+ 4
III	220 to 223	−129	+17

Since for a radio amateur satellite in the geostationary satellite orbit, the signal would be steady, the signal strength outside an allocated region should be 10 dB lower, i.e. −152 and −139 dB(W/m²) for Bands I and III.

These values correspond to:

Band	Allowable e.i.r.p.	
	Stationary orbit (dBW)	Synchronous orbit (not stationary) (dBW)
I	10	20
III	23	33

or to about 0 dBW for Band I and +13 dBW for Band III; these values being established for the worst case values and for an orbit of 2000 nautical miles.

Formerly, amateur satellites operated at an average value of e.i.r.p. of about −10 dBW, with some future units planned for an average value of e.i.r.p. of approximately 4 dBW. In view of the fact that these are all non-geostationary satellites it appears that the probability of harmful interference is negligible, and that the probability of detectable interference at any time is small.

5. Sharing between amateur satellites and the radiodetermination service

Sharing with the radiodetermination service has not hitherto been studied by the CCIR. The following study combines data from several sources to determine the allowable sharing criteria.

For a pulse system, the minimum detectable, or threshold, signal at the receiver input is related to the receiver noise by:

$$P_D = kTB + NF + L_{BT} \qquad \text{dB} \tag{4}$$

where

P_d is the threshold signal (dBW),

kTB is the theoretical noise over the receiver bandwidth B (dBW),

NF is the receiver noise figure,

L_{BT} is the threshold power factor, to allow for the effect of the receiver passband on the pulse shape.

For square pulses and a double-tuned intermediate-frequency amplifier, L_{BT} is [Reference Data for Radio Engineers, 1968]:

BT	L_{BT} (dB)
0·01	20
0·1	10
0·8	3
1·0	4
10·0	13

where the bandwidth, B, is in MHz and the pulse width, T, is in μs. If the equipment is of a normal design, $BT = 1.0$. In this case, for an interfering signal, B can be taken as the bandwidth of the interfering signal, and T as the design pulse width.

The threshold signal power flux-density W_0 for a fixed antenna and a fixed signal source is related to the receiver input by:

$$W_0 = P_D + L_L + L_D - A \qquad \text{dB(W/m}^2\text{)} \tag{5}$$

where

L_L is the line loss (dB),

L_D is the duplexer loss (dB),

$A = 10 \log S$ where S is the effective antenna area (m^2).

A is related to the antenna gain, G, by the equation:

$$A = \frac{\lambda^2}{4\pi} G \tag{6}$$

and as an approximation is often taken to be 50% of the physical area.

If the antenna is scanning, there is an additional loss, L_S, introduced by the fact that the indicator integration time period is reduced. This loss is approximately:

Percentage of maximum integration time, t (%)	Loss, L_s (dB)
100	4
30	7
10	10
3	12
1	14
0·3	17
0·1	20

The percentage integration time, t, is given by:

$$t = \frac{F\theta_H}{6000\,\omega} \qquad \% \tag{7}$$

where

F : pulse rate per second,

θ_H : half-power beamwidth in horizontal plane,

ω : scan rate per minute.

Note that the loss, L_S, includes an allowance for the variation of antenna gain with angle, and that it is essentially based on a 100% probability of visibility; the values for a 50% probability are approximately 3 dB less.

If vertical scanning is also used, the time percentage should be multiplied by the ratio of the vertical beamwidth to the vertical scan angle; the result being used to determine L_S.

In addition, there is a loss, L_p, if a long-persistence indicator is used, as in a pulse position indicator, and a further loss, L_i, if the target is moving.

The interfering power flux-density W_i for a moving signal source which is just detectable on a scanning radar is therefore:

$$W_i = kTB + NF + L_{BT} + L_L + L_D + L_s + L_p + L_i - A \qquad \text{dB(W/m}^2\text{)} \qquad (8)$$

As an example, assume a typical airport surveillance radar, with:

B = 1 MHz (T = 1μs)

NF = 9 dB,

Antenna = 3 × 6 m,

θ_H = 1.2°,

Scan = 360° horizontal,

Pulse rate = 1000/s,

Scan rate = 3 r.p.m.

Typical values for the other losses would be:

L_L = 1 dB

L_D = 2 dB

L_p = 3 dB

L_i = 5 dB

The scan percentage is 1000 × 1.2/6000 × 3 or 7%, giving L_s equal to 13 dB. S is approximately 9 m^2, or A = 10 log S is approximately 10 dB.

For an interfering frequency-modulated signal occupying a bandwidth of 25 kHz, BT is 25 × 10^{-3}, giving a value of L_{BT} of approximately 16 dB. The power flux-density to produce a just detectable response is:

$$W_0 = (-204 + 60) + 9 + 16 + 1 + 2 + 13 + 3 + 5 - 10 = -154 + 49 = -105 \text{ dB(W/m}^2\text{)}$$

An amateur signal of the above characteristics and strength would appear as a just visible brightening of the trace at the azimuth of the satellite. If modulated, small intensity changes might be observed. The signal would not appear often, the probability of its appearance being approximately $2P_t \cdot \theta_t/90$, or less than 2% of the time in the above example. The signal could not be confused with a target.

Anti-clutter circuits would reduce detectability. One that is effective against narrow-band signals is a fast time-constant circuit; with this, only rapidly changing portions of the signal, as for keyed CW, would be visible. The interference reduction provided by such circuits is approximately the same as their effectiveness in the reduction of clutter.

The presence of the interference would reduce maximum range by a small amount over an azimuth of 3° for about 2% of the total time. With a moving satellite, this reduction would occur at any azimuth for only a short period; typically, for one or two scans.

Other types of radar exist. However, the general principles of bandwidth and scanning loss apply in a similar manner, with, of course, different numerical values.

The probability of amateur satellite interference to radar systems appears to be very small. For the above example, the allowable signal would be 5 dB less if the satellite were stationary, or −100 dB(W/m^2). This corresponds to an e.i.r.p. of +52 dBW from the synchronous orbit. Former amateur satellites operated at about −10 dBW, with some units planned for an average e.i.r.p. of approximately +4 dBW. Thus, the margin against interference is such that detectability could not be achieved unless transmitter power were increased by at least 23 dBW and about 25 dB of the satellite antenna gain employed. Since this corresponds to a beamwidth of about half the visible Earth, or less for lower orbits, the probability of interference is small.

6. Sharing with fixed and mobile services

Report 358-1 (New Delhi, 1970) gave the following values as median field-strengths to be protected (mobile service) *:

Frequency band (MHz)	Urban noise only (dB(μV/m))	Receiver noise only) (dB(μV/m))
30 to 50	24	8
50 to 100	24	14
100 to 200	19	20
200 to 400	14	26
400 to 500	11	29

* These figures should be used with caution pending the result of further studies by Study Group 8.

The bulk of land mobile operation is in urban or traffic-generated noise, and some fixed services in these bands are among or near noise sources, and it may be reasonable in some instances to use the larger of the two values in the table.

Report 358-3, also gives protection ratios, typical values being 8 dB for the protection of frequency modulation services, and 17 dB for the protection of amplitude modulation services.

Combining these values, and converting them into values of power flux-density gives the following signal levels:

Frequency band (MHz)	Max. signal for the protection of mobile services in urban areas	
	Frequency-modulation services (dB(W/m²))	Amplitude-modulation services (dB(W/m²))
30 to 50	−130	−139
50 to 100	−130	−139
100 to 200	−134	−143
200 to 400	−128	−137
400 to 500	−125	−134

Under rural noise conditions, the allowable signal would be less in some bands, by 12 dB in the band 30 to 50 MHz, and by 6 dB in the band 50 to 100 MHz.

These values are for co-channel operation.

For an amateur satellite in a synchronous orbit, the band 100 to 200 MHz would allow an e.i.r.p. of +28 dBW or +19 dBW when sharing with frequency or amplitude modulation services respectively.

It may be noted that the probability of reception with full antenna gain is higher in the mobile services than in others. This is due to extensive use of simple antennae, $\theta_H = 360°$ and $\theta_v = 50°$ being typical. However, the antennae rarely have gain, and may show a loss compared to an isotropic antenna.

Formerly, amateur satellites operated with an e.i.r.p of about −10 dBW with some future units planned for an e.i.r.p. of approximately +4 dBW (a power flux-density of about −135 to −145 dB(W/m^2) depending on orbit). In view of the fact that these are moving satellites, it appears that the probability of harmful interference is not great.

7. Conclusions regarding the proposals emanating from the CCIR Special Joint Meeting (Geneva, 1971)

The amateur proposals of § 5.4 of the Report of the Special Joint Meeting endorse positive shut-off as the interference control measure (see No. 1567A of the Radio Regulations), noting that further additional developments are expected to provide for change in frequency, power and/or mode of emission.

In view of the margin between signal levels which cause interference and the present and projected power levels of amateur satellites, and considering further, that the low-orbit satellites which seem to be desired in the amateur service have low or very low probabilities of causing interference; it appears that provisions for change in frequency, power and emission mode should be developed, since these would allow a choice of the most favourable conditions of operation.

If this step were taken, and considering the proposals made by the amateurs for the provision of means to change frequency, power, and mode of emission, and further considering that such steps as channel interleaving or frequency offset can be used to reduced effects of interference, it would appear satisfactory to:

- establish a limitation of the power flux-density (band by band) which would give a low risk of detectable interference and negligible risk of harmful interference;
- allow, as an alternative to power flux-density limits, operation under No. 115 of the Radio Regulations in the regionally allocated bands.

Since most, if not all, countries place a power limit on amateur transmission which is equivalent to a limit on the power flux-density in the practical sense; on the basis of available data, special limits for the power flux-density do not appear to be required in bands above 450 MHz.

REFERENCE

REFERENCE DATA FOR RADIO ENGINEERS [1968] 5th Edition, Howard Sams, Co.

QUESTIONS AND STUDY PROGRAMMES, DECISIONS, RESOLUTIONS AND OPINIONS

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?

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. 93 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 Reports 684, 685 and 686.

STUDY PROGRAMME 1D/2

THE FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE RESEARCH SATELLITES AND TERRESTRIAL SYSTEMS

(1978)

The CCIR,

CONSIDERING

(a) that space research satellite systems will require extensive use of the radio-frequency spectrum;

(b) that in the interest of efficient use of the spectrum, the feasibility of sharing with terrestrial systems should be investigated;

(c) that specific frequency bands may be preferred for some space research,

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 antennae 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 possible need for limits on the e.i.r.p. of space research satellites in frequency bands shared with other Services;

8. 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;

9. the determination of the technical criteria that may be used for coordination purposes to avoid mutual interference.

Note. – See Report 687.

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.

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 antennae 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 antennae 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 Report 222-4.

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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 222-4 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.

Note. – See Recommendation 367.

QUESTION 5-1/2

TECHNICAL FACTORS INVOLVED IN THE PROTECTION OF RADIOASTRONOMICAL OBSERVATIONS

(1961 - 1963 - 1970 - 1974)

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?

Note. – See Report 223-4.

STUDY PROGRAMME 5A/2

CRITERIA FOR EVALUATION OF INTERFERENCE TO RADIOASTRONOMY

(1974)

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 the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, in Recommendation Spa2 – 12, has requested information relating to harmful interference to radioastronomy,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the practical interpretation for the Radioastronomy Service, of harmful interference as defined in Article 1, No. 93 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;

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 Reports 224-4, 696, 697, 698 and Recommendations 314-4 and 517.

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, antennae 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?

Note. – See Report 226-4.

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* Propagation data which may be needed for this study would result from the work of Study Groups 5 and 6. The existence of Study Programme 29C/6 (Man-made radio noise) should also be noted.

QUESTION 7-1/2

FREQUENCY UTILIZATION ABOVE THE IONOSPHERE AND ON THE FAR SIDE OF THE MOON *

(1965 - 1966 - 1970 - 1974)

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;

(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 the World Administrative Radio Conference, Geneva, 1971, has noted in Recommendation No. Spa2 – 8 the desirability of maintaining the shielded area of the Moon as an area of maximum value for observations by the Radioastronomy Service and for passive space research and, consequently, as free as possible from transmissions;

(g) that the World Administrative Radio Conference, Geneva, 1971, has recommended that the CCIR study the frequency bands most suitable for radioastronomy observations on the shielded area of the Moon and work out recommendations concerning these bands as well as criteria for their application and protection,

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;

1.3 two spacecraft above the ionosphere;

2. in what frequency bands would radioastronomical measurements carried out:

2.1 on a station above the ionosphere,

2.2 on the far side of the Moon,

have marked advantages compared with observations from the surface of the Earth;

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 7A/2 **

SHIELDING EFFECTS DUE TO THE IONOSPHERE

(1978)

The CCIR,

CONSIDERING

Question 7-1/2, and the fact that optimum utilization of frequencies above the ionosphere requires better understanding of the shielding effects due to passage through the ionosphere,

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* Information in Report 336-1 of Study Group 5 is relevant to this Question.

** This Study Programme is brought to the attention of Study Group 6.

UNANIMOUSLY DECIDES that the following studies should be carried out:

determination of the attenuation of terrestrial radio signals when they travel through the ionosphere to the region beyond, and the degree to which this attenuation varies with frequency, zenith angle, time of day, season of year, phase of the sunspot cycle, and the location of the source of the signals.

Note. – See Report 699.

STUDY PROGRAMME 7B/2 *

SHIELDING EFFECTS DUE TO THE MOON

(1978)

The CCIR,

CONSIDERING

Question 7-1/2, 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 Report 539-1 and Recommendation 479-1.

QUESTION 10-1/2

PREFERRED FREQUENCY BANDS FOR SPACECRAFT TRANSMITTERS USED AS BEACONS

(1968 - 1970 - 1978)

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:

- orbital elements of satellites;
- terrestrial distances, particularly intercontinental distances over oceans, to a high degree of accuracy,

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 geodetic and 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;

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* This Study Programme is brought to the attention of Study Group 5.

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 also under Question 12-2/2.

Note 2. – See Report 456-2 and Recommendation 513.

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 364-3),

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 11-1/2

SPACE RESEARCH RADIO LINKS BETWEEN EARTH STATIONS AND SPACECRAFT BY MEANS OF SPACE STATIONS

(1970 - 1978)

The CCIR,

CONSIDERING

(a) that some space research spacecraft, particularly those in low orbit, 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 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 Space Research Service, 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 space research 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 space research spacecraft by means of geostationary data relay satellites;

3. what interference problems may arise within the Space Research Service 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 space research satellites to enable frequencies to be shared with other Services?

Note. – See Reports 537-1, 689, 690, 691 and Recommendations 510, 511 and 512.

STUDY PROGRAMME 11A/2

DATA RELAY SATELLITE SYSTEM AND FACTORS WHICH AFFECT THE FREQUENCY SHARING WITH TERRESTRIAL SERVICES

(1978)

The CCIR,

CONSIDERING

(a) that continuous communication with research spacecraft is 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 research 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 537-1 concludes that with a few strategically located earth stations, utilization of a data relay satellite (DRS) can provide continuous or near continuous communication between research spacecraft and the Earth;

(f) that experiments and studies, such as those mentioned in Report 537-1, have demonstrated the feasibility of a DRS system;

(g) that frequency requirements between the mission spacecraft and the data relay satellite are 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 telemetering maintenance data from sensors, 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 antennae with substantial gain and directivity;

(k) that use of the DRS could reduce future frequency requirements for near-Earth space research;

(l) that use of a DRS could result in a reduction of the number of required near-Earth satellite earth stations;

(m) that Report 537-1 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. determination of power flux-density limits for the DRS in the Space Research Service which will adequately protect terrestrial services sharing bands 9 and 10;

2. determination of values for the DRS and user spacecraft off-beam discrimination especially in the direction of shared terrestrial services in bands 9 and 10.

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?

STUDY PROGRAMME 12A-1/2

RADIOCOMMUNICATION SYSTEMS FOR EARTH EXPLORATION SATELLITES (NOT INCLUDING METEOROLOGICAL SATELLITES)

(1970 - 1978)

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.

Note. – See Reports 535-1, 692 and Recommendation 514.

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* This Question cancels Question 4/2.

STUDY PROGRAMME 12B/2

SENSORS USED BY EARTH EXPLORATION AND METEOROLOGICAL SATELLITES

(1978)

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 requirements for spectrum space for the operation of such sensors will increase rapidly during the next decade;

(g) 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 Reports 540, 693, 694 and Recommendations 515 and 516.

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,

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* This Study Programme replaces Study Programme 4A/2 which is therefore cancelled.

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 Reports 395-3 and 541-1 and Recommendation 362-1.

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 538-1.

QUESTION 13-1/2

TECHNICAL FEASIBILITY OF FREQUENCY SHARING BY THE AMATEUR SATELLITE SERVICE

(1972 - 1974)

The CCIR,

CONSIDERING

(a) that the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, established an Amateur Satellite Service, allocated frequencies to it in bands already allocated to the Amateur Service on an exclusive or shared basis, and adopted No. 1567A of the Radio Regulations concerning cessation of emissions from amateur satellites;

(b) that the Amateur Service, and particularly the Amateur Satellite Service, has made significant contributions to the observation and understanding of propagation phenomena especially in bands 7, 8 and 9;

(c) that amateur stations generally, including those used for satellite communication, are typified by simple terminals with small antennae;

(d) that the desire for widespread use and experimentation has led to extensive use of low, non-geostationary orbits, for which any given area of the Earth is exposed to the transmissions of the satellite for relatively short periods,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the techniques and operating modes of the Amateur Satellite Service in frequency bands shared with other Services, and what are the preferred frequency bands for this Service;

2. what is the potential interference from and to the Amateur Satellite Service in frequency bands shared with other Services; what sharing criteria should be applied in these bands; and what are the differences in these criteria that should be applied with satellites in geostationary and non-geostationary orbits?

Note. – See Report 542-1.

QUESTION 14-2/2

FEASIBILITY OF FREQUENCY SHARING WITHIN AND AMONG SPACE RESEARCH SYSTEMS

(1972 - 1974 - 1978)

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,

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;

4. what are suitable calculation and prediction methods to be used by system designers in complying with the applicable criteria for interference? *

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,

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* See Recommendation No. Spa – 15 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971.

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/2

FREQUENCY SHARING BETWEEN DEEP-SPACE AND OTHER SPACE RESEARCH SYSTEMS

(1978)

The CCIR,

CONSIDERING

(a) that, with one exception, 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,

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 antennae 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.

Note. – See Reports 544, 545 and 688.

QUESTION 15/2

SPACE SYSTEMS TECHNOLOGY IN THE SPACE RESEARCH SERVICE

(1974)

The CCIR,

CONSIDERING

(a) that advances in space technology will affect the application of space systems in most, if not all, of 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 telecommunications technology in such areas as attitude control, station keeping, antennae, primary and secondary power systems, generation of radio-frequency power, thermal control, modulation problems, and problems of the space environment;

2. what improvements in performance are foreseen in these areas?

Note. – See Reports 546-1, 672, 673 and 674.

STUDY PROGRAMME 15A/2 *

ANTENNAE FOR SPACE RESEARCH SYSTEMS

(1978)

The CCIR,

CONSIDERING

(a) that the limitations on the physical size and beamwidth of antennae 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 antennae 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 antennae with improved side-lobe and back-lobe characteristics;

4. what are the polarization characteristics of antennae, 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 antennae usable gains, aperture and pointing accuracy.

Note. – See Reports 675, 676, 677 and Recommendation 509.

STUDY PROGRAMME 16A/2 **

SAFETY ASPECTS OF RADIO-FREQUENCY RADIATION FROM SPACE RESEARCH STATIONS

(1974)

The CCIR,

CONSIDERING

(a) that radio-frequency energy is known to have harnmful effects on the human body when absorbed in sufficient quantity;

(b) that determination of hazardous radiation levels have been made by competent authorities;

(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 hazarduous radio-frequency radiation.

Note. – See Reports 543 and 682.

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* This Study Programme is brought to the attention of Study Groups 5 and 6.

** This Study Programme relates to Question 52-1/1 of Study Group 1.

*** 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.

STUDY PROGRAMME 16B/2 *

PROTECTION OF TELECOMMUNICATIONS EQUIPMENT FROM RADIO-FREQUENCY RADIATION FROM SPACE RESEARCH EARTH STATIONS

(1978)

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 17/2

RADIOCOMMUNICATION REQUIREMENTS FOR SYSTEMS TO SEARCH FOR EXTRATERRESTRIAL LIFE

(1976)

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;

(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 while the search for radio signals from extraterrestrial civilizations has already begun, more sensitive systems will be in use by the 1980's which could receive harmful interference from very weak man-made signals;

(h) that it is necessary to share the bands in which the search is conducted with other Services;

(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;

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* The attention of Study Groups 1, 4, 7, 8, 9, 10 and 11 is drawn to this Study Programme which derives from Question 52-1/1.

3. what protection is necessary for receiving systems conducting a search for artificial radio signals of extraterrestrial origin;

4. what criteria will make 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

FEASIBILITY OF FREQUENCY SHARING BETWEEN SPACE OPERATION AND OTHER SERVICES

(1978)

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;

(d) that no criteria have yet been recommended for the protection of the Space Operation Service;

(e) 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 the Space Operation Service in the frequency bands allocated to this Service;

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 Reports 396-3, 678 and Recommendation 363-1.

QUESTION 19/2 *

SPURIOUS EMISSIONS RADIATED FROM AND RECEIVED BY STATIONS OF SPACE SERVICES

(1978)

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;

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* This question is brought to the attention of Study Groups 1, 4, 7, 8, 9, 10 and 11.

(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 transmitters operating on fundamental frequencies above 235 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? *

QUESTION 20/2

CHARACTERISTICS AND EFFECTS OF RADIO TECHNIQUES FOR THE TRANSMISSION OF ENERGY

(1978)

The CCIR,

(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, and harmful interference to radiocommunication systems,

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 radiotransmission 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 21/2

CHARACTERISTICS AND TELECOMMUNICATIONS REQUIREMENTS OF SYSTEMS FOR SPACE RESEARCH

(1978)

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;

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* This question is mainly concerned with the research and exploration services.

(c) that the purpose of technological space research is the development and testing of new space techniques;

(d) that space research systems often lead to space applications;

(e) that radiocommunication is presently the only practical means of communication between the Earth and objects in space;

(f) that space research utilizes sensors of many types;

(g) that for some sensing techniques involving certain natural phenomena, operation of the sensors at specific frequencies is required;

(h) 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 536-1 and 548-1.

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?

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 Report 683 and Recommendation 365-3.

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 364-3.

QUESTION 23/2

USE OF SATELLITE SYSTEMS FOR DISASTER WARNING AND RELIEF OPERATIONS

(1978)

The CCIR,

CONSIDERING

(a) that geostationary satellite systems can provide telecommunication services to help minimize losses caused by natural disasters, epidemics, famines, and similar emergencies (see Recommendation No. Spa2 – 13);

(b) that, for economic viability, such systems should perform a variety of functions including voice disaster warning, field reporting, data collection, and coordination of relief operations, thus requiring multiple links and frequency assignments;

(c) that signal attenuation due to propagation factors is important when selecting frequencies for the required space-to-Earth links;

(d) that large area coverage with selective addressing to small areas is required in the disaster-warning mode;

(e) that the cost of the equipment needed to receive the disaster-warning transmissions should be minimal,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the performance requirements of the different types of links to be provided by a multifunction disaster-warning satellite system;

2. what are the technical and economic tradeoffs involved in the design of these links;

3. what are the preferred system technical characteristics, including preferred frequencies of operation for disaster-warning satellite systems;

4. what are the sharing criteria appropriate to operating such systems in the preferred frequency bands?

ISBN 92-61-00671-X