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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 IV

FIXED SERVICE USING COMMUNICATION SATELLITES



Geneva, 1978



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**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.

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*

Number	Volume	Number	Volume	Number	Volume
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80	X	355-359	IX	463	IX
100	I	361	VIII	464-466	IV
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162	III	368-370	V	473, 474	XII (CMTT)
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205	X	374-376	VII	478	VIII
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		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

Number	Volume	Number	Volume	Number	Volume
2	IV	18	XII (CMTT)	28, 29	VII
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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
4	VI	33	XIII	65	XI
14	VII	39	XIII	66	XII (CMV)
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20	VIII	61	XIII		
23	XII (CMV)	62	I		
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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 IV

FIXED SERVICE USING COMMUNICATION SATELLITES

(Study Group 4)

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FIXED SERVICE USING COMMUNICATION SATELLITES

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FIXED SERVICE USING COMMUNICATION SATELLITES

STUDY GROUP 4

Terms of reference:

To study questions relating to systems of radiocommunication for the fixed service using satellites (including the associated tracking, telemetry, and telecommand functions).

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 4 (1974-1978)

1974-1978

Chairman: W. KLEIN (Switzerland)

Vice-Chairman: E. R. CRAIG (Australia) _____

1978-1982

Chairman: E. R. CRAIG (Australia)

Vice-Chairman: E. HAUCK (Switzerland)

The use of the Fixed Satellite Service by the public for long distance communications – competing with new developments in submarine cables – is continuing to grow fast. This is partly due to its great structural and operational flexibility, but also due to development of new and improved technologies and system concepts, with decreasing costs per unit of information capacity or per telephone channel. Active satellite systems are mainly using the geostationary-satellite orbit with large earth-station antennae and working in the frequency bands below 10 GHz with analogue transmission over one single-satellite hop. However, the future trend in communications, based on present semiconductors, integrated circuit and computer development, is clearly directed toward digital signal processing and digital transmission systems and their application in satellite communication networks seems imminent.

On the other hand, there is hardly any doubt that frequencies below 10 GHz are best suited for the purpose and will therefore be used as long as the foreseeable congestion in certain parts of the geostationary-satellite orbit will allow it. These frequency bands have to be shared with existing terrestrial services and to some extent with other new satellite services which are just beginning to develop, thus creating coordination problems of great complexity and requiring agreed technical and operational characteristics and restrictions on both sides. The situation concerning the frequency bands above 10 GHz, which are gradually coming into use, will of course be quite similar, with the additional difficulty of increased attenuation and scatter-effects by atmospheric precipitation.

With this background, the work of Study Group 4 has evolved in the past and will progress further, most certainly for another decade or more.

Communication satellites have opened a new dimension for regional and global extensions of existing telecommunication facilities; they are part of a more general network and must comply with already established or still developing general requirements based on agreed end-to-end transmission characteristics for each communication mode. Starting on these premises we may distinguish four important areas of activity in Study Group 4:

- A. Baseband characteristics and earth station operational aspects, including interface problems with terrestrial networks (with CCITT).
- B. Orbital system and overall transmission characteristics (earth station to earth station), including signal processing and propagation factors.
- C. Frequency sharing and interference problems among similar and dissimilar satellite networks, based on relevant system, antenna radiation and propagation characteristics (with Study Groups 2, 5, 8, 10/11).
- D. Frequency sharing and interference problems with terrestrial services, including system, antenna radiation as well as propagation characteristics (with Study Group 5 and, in particular, with Study Group 9).

These areas are not independent of each other, but strongly correlated. Area A sets minimum requirements to be fulfilled by the others, the strong interdependence of areas B, C and D becomes evident by citing one single example, the 3-dimensional antenna radiation properties which are a determining factor in all these fields. Therefore many, if not all, texts contain important material for more than one field, a difficulty which cannot be avoided, whatever criterion for the subdivision may be chosen. Fortunately, the constraints given by areas C and D are not contradictory but mostly convergent with respect to area B. The following lines are meant to be a short summary of progress achieved since the last Plenary Assembly in 1974.

A. Baseband characteristics and operational aspects

An attempt was made, in accordance with CCITT practice, to improve and define more realistic *noise objectives* in the relevant CCIR Recommendations (Recommendations 353-3, 356-4 and 357-3). The relative merits and constraints of higher noise allowance in national or regional satellite networks for telephony are discussed in Report 208-4. In view of the increasing interest in data- and PCM speech-transmission, short noise-bursts and *circuit-interruptions* are given much higher attention than before and allowable bit error-rates are defined on the basis of measuring intervals of 1 second, 1 minute and 10 minutes. Four new texts may be mentioned in this connection:

Question 27/4, Study Programme 24A/4, Recommendation 522 and Recommendation 558.

Studies on the efficient use of the available frequency-spectrum have shown that the allocation of a higher fraction of the overall noise allowance in the hypothetical reference circuit to *interference-noise* would result in a significantly higher total capacity of the geostationary-satellite orbit. Recommendation 466-2 has been completely revised and amended to prepare the way in that direction; this needs further careful study. The detailed new Report 706, in reply to Question 24/4, attempts to define and apply the concept of *circuit availability*, having in mind the findings of CCITT and Study Group 9 on the subject; a proposal for provisional availability objectives to be recommended is offered together with experimental results.

Switching channel groups or even single telephone-channels in a satellite seems possible in the near future, and the use of *short-hop inter-satellite links* has received great attention, mainly for two reasons: A better use could be made of the available earth station capacity in many cases, thus postponing or avoiding the need for a new antenna and improving operational flexibility, and a more efficient use of the orbit/frequency spectrum might be achieved simultaneously. A new Study Programme 2Q/4, was agreed and Report 451-2 was given a new shape to include these aspects. The frequency bands above 54 GHz, near to atmospheric absorption bands, allocated to inter-satellite-links in the Radio Regulations, are considered most suitable for the long-term planning. However, present technology and reliability arguments favour the use of frequencies below about 30 GHz for the near future. Interference studies suggest that even frequencies in the range of 3 to 7 GHz might be shared with terrestrial services without serious difficulties (Report 387-3). Two non-contiguous frequency bands should therefore be allocated for inter-satellite links shared with suitable terrestrial services operating below 35 GHz.

For economic reasons partially unattended earth stations (Report 553-1) and *earth-station antennae with limited steerability* (Report 390-3), are beginning to find increasing interest, and new and improved data on radio-stars may facilitate the calibration of the quality-factor for large earth-station antennae (Report 390-3).

B. Orbital system and overall transmission characteristics

The rapid growth of intercontinental satellite communications and the increasing importance of regional satellite networks is reflected in the highly condensed and amended Report 207-4. Up to the present, these operational networks use well established analogue transmission techniques (in frequency bands below 10 GHz); experiments are under way with digital multiplex systems and *time-division multiple access (TDMA) in frequency bands above 10 GHz*. Most recent studies in this area are also devoted to:

- the development and future introduction of digital systems (including data transmission);
- more efficient signal processing methods which are mainly digital;
- and to specific problems connected with the use of frequency bands above 10 GHz.

For instance, revised Report 552-1, "Use of frequency bands above 10 GHz", now includes a comparison between analogue and digital system qualities in general, and suggests methods for improving the performance of digital transmission during poor propagation conditions due to hydrometeor attenuation and scattering; also, typical operational characteristics for a 11/14 GHz digital satellite link with site diversity are discussed in detail. In particular, considerable progress has also been made in the field of *modulation and multiple access techniques*, where the virtually new Report 708 is presented, replacing both former Reports 211-3 and 213-3. The most important factors determining system and access qualities and the relative merits of various solutions are critically discussed and compared, and the most advanced signal processing methods are taken into account, such as digital speech interpolation, combined amplitude phase modulation or spread spectrum multiple access. *Energy dispersal techniques*, suitable for minimizing interference probabilities under various operating conditions, have been further improved and extended to new systems (Report 384-3); their maximum use is recommended for all new designs (Recommendation 446-2).

A great number of new texts and amendments to existing ones are devoted to *digital systems*, where the bit error-rate in the baseband signal has a significance similar to the signal-to-noise ratio in the analogue case; there is, however, no linear relationship with the carrier-to-noise or interference level ratio. A new hypothetical reference circuit for systems using digital transmission, including site diversity and inter-satellite-links as the case may be, is proposed in Recommendation 521; there are also three related Recommendations concerning: the admissible total bit error-rates (Recommendation 522), the partial contributions to bit error-rate due to

interference from other satellite networks (Recommendation 523) and those from terrestrial networks (Recommendation 558). Some of the underlying philosophy may be found in new Reports 710 and 793. There is some probability that digital transmission will be introduced in satellite networks before it comes into general use in terrestrial networks and, therefore, an extensive new Report 707 has been elaborated dealing with characteristics and constraints of various *earth-station interface* problems, and a proposal was made to CCITT Study Group XVIII to clearly separate responsibilities at the interface; this proposal was made in answer to various suggestions made by the CCITT (Opinion 56).

C. Frequency sharing with other geostationary satellite networks

As mentioned earlier, the limited capacity of the geostationary-satellite orbit will be used up in a foreseeable future, in a first stage certainly in the more crowded parts of the orbit and in the most favourable frequency bands below 10 GHz. Measures to improve the communications capacity of this unique orbit, and there are many possibilities, have been and will remain one of the prime subjects in our studies. The problem is in fact of an extraordinary complexity and does involve not only technical and propagational but economical and operational aspects as well. A special Interim Working Party (*IWP-4/1*) was formed nine years ago to explore this topic in depth and has since provided very valuable results; however, much remains to be done until a clear picture of the whole situation can be obtained; for this purpose IWP-4/1 shall continue to function (Decision 2-2).

The basic Report 453-2 has been completely revised and amplified, presenting a condensed survey of all known parameters and their evaluation with respect to the *efficient use of the geostationary-satellite orbit* by networks operating in the same frequency band. A great deal of new material has been added in the field of signal processing, of system and orbital planning constraints, of improved antenna characteristics and possible new options in geosynchronous, nearly stationary orbits. In particular, it would be worthwhile to mention the urgent studies and steps required for the progress of work and for the technical guidance of WARC-1979. A considerable effort has also been made to define a criterion for the optimum use of the geostationary-satellite orbit, but at this stage it is not possible to make a final proposal (Report 711).

Report 454-2 has been significantly improved with respect to the need for *coordination between two satellite networks* using simple satellite transponders, but the case of signal processing transponders needs further study to comply with Recommendation Spa2 – 15 of the Radio Regulations. System homogeneity and the amount of tolerable interference levels, together with other factors, have a great effect on the efficient use of the geostationary-satellite orbit and this is explained in detail in revised Report 454-2, where also the need for further studies in this domain is stressed. A similar remark is justified for possible improvements in *satellite antenna techniques*, such as better sidelobe suppression, use of spot and shaped beams, depending on operational requirements, use of co-channel multi-beam and cross-polarized radiators, where significant progress in theory and experiment has been achieved. These problems are extensively discussed in revised Reports 558-1 and 555-1. In this context Study Group 4 wants to *inform Administrations* that it would be useful and highly desirable that measured satellite antenna radiation patterns could be used as early as possible in the process of coordination under Article 9A of the Radio Regulations. A new Recommendation limits the absolute power-density levels for off-main-beam angles greater than 2.5° , for earth stations transmitting in the 6 GHz band. Modern station keeping techniques allow closer satellite spacing and attitude control; after careful examination the position tolerance has been reduced from 1° to 0.5° (Report 556-1 and Recommendation 484-1).

The World Administrative Radio Conference for planning the *Broadcasting-Satellite Service* in the 12 GHz frequency band (WARC-BS, 1977) gave new impetus to a number of activities in the CCIR, mainly in connection with frequency sharing and mutual interference protection, problems which still require intensive studies before satisfactory answers can be given. The impact on the work of Study Group 4, of the Maritime Mobile- and Radionavigation-Satellite Services needs is less severe than that of the broadcasting-satellite, because much lower transmission capacities and powers are involved here.

A new Question 26/4, adopted by correspondence, clearly demonstrates the difficulties raised by using the up-path channels of the Fixed-Satellite Service for feeder links to satellites of other services. A provisional answer to the problem for the particular case of *broadcasting feeder links* is contained in Report 561-1. This revised Report is virtually new and also takes account of ideas laid down in Reports 453-2 and 809; it may serve as a basis for the study of coordination between dissimilar systems in general. Study Groups 10 and 11 in a memorandum to the Chairman of Study Group 4 refer to the Radio Regulations and to the fact that the total bandwidth allocated to the Fixed and Broadcasting-Satellite Service together is larger for the down-path than for the up-path, and express their concern about the resulting adverse implications; it is urged that additional studies be undertaken by Administrations participating in the work of Study Group 4, in cooperation with Study Groups 10 and 11, with a view to *offer more explicit guidance to WARC-1979 in this particular field*. This wish is strongly supported by Study Group 4.

A contribution from one Administration proposed a draft Recommendation to designate specific frequency bands, in which *maritime mobile satellite feeder links* would have priority of access on the geostationary-satellite orbit. Study Group 4 felt unable at this time to support this Recommendation, but urges Administrations to undertake further studies on this subject and submit proposals to the Special Preparatory Meeting, 1978.

Spurious emissions had so far received little attention, but based on new Question 25/4, two rather important Reports are now available; one deals with the *protection of earth-station receivers* from spurious emissions in the frequency bands adjacent to the 12 GHz satellite broadcasting band (Report 712); the second discusses the problem of *spurious emissions from earth and space stations* in the Fixed-Satellite Service and the possible protection of other services (Report 713). The need for recommended limits of spurious radiation levels in each case is recognized and initial steps to reach this target are proposed.

D. Frequency sharing with terrestrial radio-relay links

Most measures for improving the efficient use of the geostationary-satellite orbit are equally effective in facilitating frequency sharing with terrestrial radio-relay links; the problem is however aggravated in this case by the much higher complexity of terrestrial propagation modes and by system and network dissimilarities. The texts in this area have been studied and prepared in close cooperation with Study Group 9 and are presented in common by the two Study Groups. It is suggested that reference be made to the relevant part of the Report of the Chairman of Study Group 9.

E. Future activities

There is no doubt that studies and efforts for progress in all main areas must continue. The efficient use of the geostationary-satellite orbit, as well as various other geosynchronous-satellite orbits to be developed later on, short-hop inter-satellite links, digital techniques, improved earth- and space-antenna radiation characteristics, multiple spot-beam and orthogonal cross-polarization techniques, multiple frequency and signal-processing satellites, protection limits for mutual interference-levels of various kinds and use of higher frequency bands, all these together with associated operational and frequency coordination problems, are the main topics for the future. Particular items for urgent and important new studies are mentioned in many texts of our Study Group; reference is made in particular to Reports 453-2 and 561-1. But further steps would have to be determined on the basis of the requirements of WARC-1979, as defined in a preliminary programme for the Special Preparatory Meeting of the CCIR. A great effort will be necessary to comply with these requirements and it is hoped that at least provisional limits may be defined and/or recommended in such cases where a final answer would seem premature.

SECTION 4A: DEFINITIONS

Report

REPORT 204-4

TERMS AND DEFINITIONS RELATING TO SPACE RADIOCOMMUNICATIONS

(1963 – 1966 – 1970 – 1974 – 1978)

Terms and definitions concerning space systems, services and stations are included in the Radio Regulations (1976 edition) and are not reproduced in this Report.

Spacecraft

A man-made vehicle which is intended to go beyond the major part of the Earth's atmosphere.

Deep space

Space at distances from the Earth greater than or approximately equal to the distance between the Earth and the Moon.

Space probe

A spacecraft designed for making observations or measurements in space.

Note. – A space probe intended to go into deep space is a deep space probe.

Satellite

A body which revolves round another body of preponderant mass and which has a motion primarily and permanently determined by the force of attraction of this body.

Note. – A body so defined which revolves round the Sun is called a planet or planetoid.

Active satellite

A satellite carrying a station intended to transmit or retransmit radiocommunication signals.

Passive satellite

A satellite intended to transmit radiocommunication signals by reflection.

Primary body (in relation to a satellite)

The attracting body which primarily determines the motion of a satellite.

Orbit

1. The path, relative to a specified frame of reference, described by the centre of mass of a satellite or other object in space, subjected solely to natural forces, mainly gravitational attraction.

2. By extension, the path described by the centre of mass of an object in space subjected to natural forces and occasional low-energy corrective forces exerted by a propulsive device in order to achieve and maintain a desired path.

Unperturbed orbit (of a satellite)

The orbit of a satellite in the idealized condition in which the satellite is subjected only to the attraction of the primary body, effectively concentrated at its centre of mass.

Note. – In a frame of reference whose centre is the centre of mass of the primary body, and whose axes have fixed directions in relation to the stars, the unperturbed orbit is a conic section.

Orbital elements (of a satellite or other object in space)

The parameters by which the shape, dimensions and position of the orbit of a body in space can be defined in relation to a specified frame of reference.

Note 1. – The position of the centre of mass of the body, in the orbit, is usually given as a function of time with the orbital elements.

Note 2. – The frame of reference used is a direct rectangular co-ordinate system OXYZ, in which the origin is at the centre of mass of the primary body and the third axis OZ is perpendicular to the principal reference plane, also called the basic reference plane, or simply the reference plane.

Note 3. – For an artificial earth satellite, the reference plane is the Earth's equatorial plane and the third axis OZ has a South to North orientation.

Visible arc

The common part of the arc of the geostationary satellite orbit over which the space station is visible above the local horizon from each associated earth station in the service area.

Service arc

The arc of the geostationary satellite orbit within which the space station could provide the required service * to all of its associated earth stations in the service area.

Orbital plane (of a satellite)

The plane containing the centre of mass of the primary body and the velocity vector of a satellite, the frame of reference being that specified for defining the orbital elements.

Ascending (descending) node

The point at which the orbit of a satellite or planet intersects the reference plane, the third co-ordinate of the satellite or planet being ascending (descending) on passing through that point.

Direct (retrograde) orbit (of a satellite)

A satellite orbit such that the projection of the centre of mass of the satellite on the reference plane revolves about the axis of the primary body in the same (reverse) direction as (to) that in which the primary body rotates.

Inclination (of satellite orbit)

The angle between the plane of the orbit of a satellite and the reference plane.

Note. — By convention, the inclination of a direct orbit of a satellite is an acute angle and the inclination of a retrograde orbit is an obtuse angle.

Circular orbit (of a satellite)

A satellite orbit in which the distance between the centres of mass of the satellite and of the primary body is constant.

Elliptical orbit (of a satellite)

A closed satellite orbit in which the distance between the centres of mass of the satellite and of the primary body is not constant.

Equatorial orbit (of a satellite)

A satellite orbit the plane of which coincides with that of the equator of the primary body.

Polar orbit (of a satellite)

A satellite orbit the plane of which contains the polar axis of the primary body.

Inclined orbit (of a satellite)

A satellite orbit which is neither equatorial nor polar.

Apoastron

The point in the orbit of a satellite or planet which is at a maximum distance from the centre of mass of the primary body.

Periastron

The point in the orbit of a satellite or planet which is at a minimum distance from the centre of mass of the primary body.

Apogee

The point in the orbit of an earth satellite which is at a maximum distance from the centre of the Earth; the apogee is the apoastron of an earth satellite.

Perigee

The point in the orbit of an earth satellite which is at a minimum distance from the centre of the Earth; the perigee is the periastron of an earth satellite.

* The required service depends upon the system characteristics and user requirements.

Altitude of the apogee (perigee)

The altitude of the apogee (perigee) above a specified reference surface serving to represent the surface of the Earth.

Period of revolution (of a satellite)

The time between two consecutive passages of a satellite through a characteristic point on its orbit.

Note. — In the absence of further information, it shall be understood that the period of revolution is the anomalistic period (see below).

Anomalistic period

The time elapsing between two successive passages of a satellite through its periastron.

Nodal period

The period of time elapsing between two consecutive passages of a satellite through the ascending node.

Sidereal period of revolution (of a satellite)

The time elapsing between two consecutive intersections of the projection of a satellite on a reference plane which passes through the centre of mass of the primary body with a line in that plane extending from the centre of mass to infinity, both the normal to the reference plane and the direction of the line, being fixed in relation to the stars.

Sidereal period of rotation (of an object in space)

Period of rotation, around its own axis, of an object in space, such as a natural satellite or a spacecraft, in a frame of reference fixed in relation to the stars.

Station-keeping satellite

A satellite, the position of the centre of mass of which is controlled to follow a specified law, either in relation to the positions of other satellites belonging to the same system or in relation to a point on Earth which is fixed or moves in a specified way.

Synchronized satellite**Phased satellite (deprecated)**

A satellite controlled so as to have an anomalistic period or a nodal period equal to that of another satellite or planet, or to the period of a given phenomenon, and to pass a characteristic point in its orbit at specified instants.

Attitude-stabilized satellite

A satellite with at least one axis maintained in a specified direction, e.g. toward the centre of the Earth, the Sun or a specified point in space.

Synchronous satellite

A satellite for which the mean sidereal period of revolution is equal to the sidereal period of rotation of the primary body about its own axis.

Geosynchronous satellite

Synchronous earth satellite.

Note. — The sidereal period of rotation of the Earth is about 23 hours 56 minutes.

Sub-synchronous (super-synchronous) satellite

A satellite for which the mean sidereal period of revolution about the primary body is a sub-multiple (an integral multiple) of the sidereal period of rotation of the primary body about its own axis.

Stationary satellite

A synchronous satellite with an equatorial, circular and direct orbit. A stationary satellite remains fixed in relation to the surface of the primary body.

Geostationary satellite

A stationary satellite having the Earth as its primary body.

Note. — The orbit on which a satellite should be placed to be a geostationary satellite is called the geostationary satellite orbit.

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SECTION 4B: FREQUENCIES, ORBITS AND SYSTEMS

Reports

REPORT 205-4

**FACTORS AFFECTING THE SELECTION OF FREQUENCIES FOR
TELECOMMUNICATIONS WITH SPACE STATIONS
IN THE FIXED SATELLITE SERVICE**

(Question 2-3/4)

(1959 – 1963 – 1966 – 1970 – 1974 – 1978)

1. Introduction

The purpose of this Report is to summarize the relationships between frequency and radio propagation and other technical factors which influence radiocommunication in space, to provide a basis for the selection of frequencies for communication between the Earth and a space station in the Fixed Satellite Service.

This Report does not deal with factors affecting the sharing of frequencies, which are the subject of separate reports.

§ 2 of this Report considers, in a general manner, the propagation and environmental factors affecting communication with space stations; while § 3 considers the impact of equipment technology. The propagation effects are considered in greater detail in the texts of Study Group 5 (particularly Reports 564-1, 719, 720 and 721) and of Study Group 6 (particularly Report 263-4), which should be consulted as required.

2. Factors affecting communication with space stations

Systems in the Fixed Satellite Service are designed to operate with minimum necessary transmitter power at both the earth and the space stations, for one or more of the following reasons:

- available power in space stations has, so far, been limited by technology, and launch vehicle constraints;
- in frequency bands shared with terrestrial Services, space stations are power limited by agreement;
- interference between space communication systems and, in shared bands, into terrestrial systems is minimized for low transmitted powers.

At the same time, systems must be designed to meet their traffic and performance requirements. The manner in which these can be met depends on the environmental and propagation effects and on the noise level in earth and space stations, all of which are frequency dependent.

2.1 Atmospheric absorption

The attenuation characteristics of the “normal” atmosphere are frequency dependent allowing energy at certain frequencies to pass through it more readily than at others and such frequency regions are more useful for space communications. The major frequency regions of interest to space communications lie between the ionospheric MUF (maximum usable frequency for reflection by the ionosphere) and the first oxygen absorption line (about 60 GHz). Other windows between gaseous absorption lines above 60 GHz may also prove to be of interest. Two other ranges, below about 300 kHz and in the optical and infra-red regions, are of little current interest for systems in the fixed satellite service.

Fig. 1 shows the one-way attenuation relative to free space between 1 and 300 GHz for a vertical path for a dry atmosphere and for a moderately humid atmosphere (7.5 g/m^3 at the surface). A “clear” atmosphere (free from hydrometeors) is assumed. With this assumption the attenuation (in dB) at arbitrary elevation angles, $5^\circ \leq \theta \leq 90^\circ$, may be calculated approximately from the values for vertical paths by multiplication by the factor cosecant θ . For more details see Report 719.

2.2 Hydrometeor absorption

In the presence of hydrometeors (rain, hail, snow, fog, clouds) atmospheric attenuation increases with increasing frequency; hydrometeor attenuation, especially at frequencies above 10 GHz and during small percentages of the time, may become the limiting factor in systems designed for high reliability. Substantial attenuation will furthermore tend to increase the receiving system noise temperature of an earth station; hence, the carrier-to-noise ratio for a received signal from a space station will deteriorate more than from signal attenuation alone. High hydrometeor densities tend to be sufficiently localized to allow use to be made of diversity techniques which, for a given performance requirement, may result in a reduction of the necessary fade margin.

Further details, including the variation of attenuation effects with elevation angle, are given in Report 564-1 and Report 721.

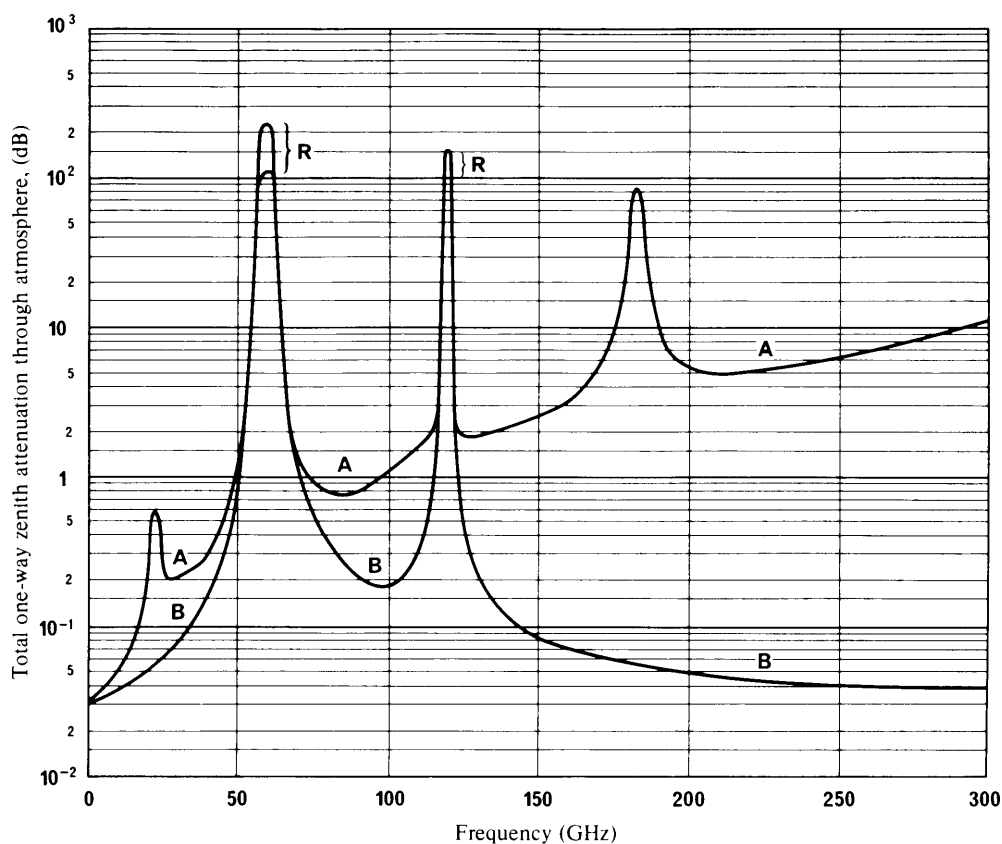


FIGURE 1 — Total one-way zenith attenuation through the atmosphere as a function of frequency

Curves A: 7.5 g/m³ at ground
 B: dry atmosphere (0 g/m³)
 R: range of values due to fine structure

2.3 Other propagation effects

A number of other factors can be related to the effects due to propagation alone. They are:

2.3.1 Ionospheric scintillation

At frequencies below about 1 GHz and, for low elevation angles of a transmission path up to about 7 GHz, fluctuations of amplitude and phase due to refractive inhomogeneities in the ionosphere, called scintillation, cause a variation of the received signal level with time which must be accommodated by an appropriate fading margin in the system design. Additional information on propagation through the ionosphere may be found in Study Group 6 texts (particularly Report 263-4).

2.3.2 Faraday rotation

The interaction of moving electrons in the ionosphere with the Earth's magnetic field gives rise to a rotation of the plane of polarization of a linearly polarized wave called "Faraday rotation". The rotational angle of the electric field due to Faraday rotation depends upon many factors such as the season, the time of day, solar activity, the direction of the incident wave, the conditions of the ionosphere through which the wave passes, frequency and so on. Faraday rotation may occasionally reach a peak value of 150° at 1 GHz, which corresponds to 9° at 4 GHz and 4° at 6 GHz. The direction of rotation is also opposite for transmit (6 GHz) relative to receive (4 GHz). Thus, differential rotation of the plane of polarization for 6 GHz relative to 4 GHz must be provided at the earth station.

The influence of Faraday rotation, however, is not expected to be significant for frequencies above 10 GHz.

2.3.3 Depolarizing effects

Signals above 1 GHz may be subject to depolarization effects which in general increase with frequency when passing through a scattering medium such as rain. This results in a loss of isolation between two orthogonally polarized signals. This loss of isolation may be severe for small percentages of the time. As in the case of absorption in the presence of high hydrometeor densities, diversity techniques may be used to overcome these effects.

2.3.4 Doppler effects

A Doppler frequency-shift is produced if the path length of a radio link varies with time, giving a continuous change of phase. For a low-altitude satellite, the fractional change in received frequency has a maximum value of up to 2×10^{-5} . Second-order difficulties may also arise from the fact that the absolute frequency-shift is not exactly constant throughout the frequency band occupied by the emission.

2.3.5 Tropospheric effects

Propagation effects due to tropospheric scintillation and refraction may be of less consequence, but may have to be taken into account by system designers. More detailed information on tropospheric propagation phenomena may be found in Reports 564-1 and 718.

2.3.6 Atmospheric refraction

For a discussion of the effects of variable atmospheric refraction see § 2 of Report 718.

2.4 Noise

Apart from thermal noise generated in the receiver of an earth or space station, natural noise sources influence practical systems design.

At the lower frequencies, cosmic noise predominates, decreasing with increasing frequency; at the higher frequencies, absorptive constituents of the atmosphere (water vapour, oxygen, hydrometeors) act as noisy radiators and produce corresponding noise increases. Such "absorption" noise is usually described as an increase in the noise temperature of a receiving system which may be computed from equations given in Report 720.

Noise which enters an earth station receiving system through antenna side-lobes directed at the Earth, or a space station receiving system through its earth-oriented antenna is essentially frequency independent but significant.

The Sun is a strong noise source with a noise temperature of about 10^6 K at 30 MHz and of at least ("quiet sun") 10^4 K at 10 GHz. Solar noise entering through the main beam of earth station antennae will produce temporary outages over the entire frequency band of interest (see Report 390-3).

3. Equipment technology

In addition to the frequency dependent propagation and environmental factors affecting communication with space stations there are two important system implementation elements which are also frequency-dependent: the gain of earth and space station antennae, and the excess noise temperature of receivers.

4. Summary

To date, communications with space stations in the Fixed Satellite Service have utilized frequency bands between about 1 GHz and 10 GHz. Higher frequency bands have recently been authorized for this Service, and a number of programmes are under development to exploit these new frequency allocations.

The most interesting frequency bands lie between two limits which are not sharply defined. The upper limit is principally dependent upon conditions in the lower atmosphere. The lower limit, however, is influenced by ionospheric conditions and cosmic noise, and is thus more dependent upon geographical location, time of operation, service availability requirements and implementation constraints.

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REPORT 206-3

GENERAL CONSIDERATIONS RELATING TO THE CHOICE OF ORBIT PARAMETERS IN THE FIXED SATELLITE SERVICE

(Question 2-3/4)

(1963 – 1966 – 1970 – 1974)

1. Introduction

Various orbits have been proposed for use in the Fixed Satellite Service: it is the aim of this Report to categorize the various types from the technical point of view, and to discuss those types that seem most desirable for operational use.

It is noted that, since the development of fixed satellite systems is necessarily an evolutionary process, and because all operational and transmission requirements may not be met by a single type of system, more than one system or type of system may eventually be incorporated into the world telecommunication network. In general, systems in the Fixed Satellite Service are characterized by two elements inherent in their transmission path geometry: propagation between a space station and an associated earth station is line-of-sight, and any number of earth stations within line-of-sight of a space station may communicate with each other via the space station. Problems of potential interference resulting from this geometry between earth, space, and terrestrial stations in shared frequency bands are treated extensively in Reports of Study Group 4 and where applicable, Study Group 9.

2. Types of orbit for systems in the Fixed Satellite Service

Possible orbits of space stations include circular and elliptical orbits, the plane of which may lie in or at an angle to the earth's equatorial plane. Of greatest current interest are orbits with high apogees and relatively long periods; notably the geostationary satellite orbit and a 12-hour highly elliptical orbit of about 65° inclination. These orbits provide large geographical coverage for 24 hours a day; the former with fixed, essentially unvarying geometry, the latter on the basis of periodic "hand-over" between successive space stations by means of multiple antenna systems at the associated earth stations.

In addition, medium altitude orbits can be useful for certain applications. The characteristics of these orbits have been described in the technical literature [Dalglish and Jefferis, 1965; Lutz and Dorosheski, 1966; Jensen *et al.*, 1962; Haviland and House, 1965].

The type of orbit and space station, and the specific earth station design used in a given system are dictated by traffic requirements (type of traffic, volume of traffic, and traffic connectivity and coverage) and by operational considerations (reliability, traffic restoration capability, flexibility in traffic rerouting).

2.1 Systems using geostationary space stations

Such systems have established themselves as highly preferred on the basis of their invariant geometry with respect to their terrestrial service area(s). The advantages of this geometry are:

- continuous unchanging visibility from all points within their terrestrial service area(s);
- minimum operational and implementation requirements at the associated earth stations;
- invariance in transmission parameters and space station implementation, particularly with respect to the use of narrow beam fixed space station antenna systems;
- near maximum potential earth coverage (see Fig. 1);
- nearly constant predictable interference between systems using the same frequencies.

The orbits are, however, characterized by a relatively large two-way transmission delay of 0.6 second (see Report 383-3) and a periodic predictable masking of signals received at an earth station by sun conjunctions.

Studies have shown that the geostationary satellite orbit provides a finite communications capacity relative to a given coverage area, in a given frequency band, due to the limited number of space stations which it can accommodate without undue inter-system interference. This matter is given special attention (Study Programme 2J-2/4 and related texts). Among the techniques considered to alleviate geostationary satellite orbit saturation is the use of geosynchronous space stations in moderately inclined and possibly elliptical orbits, allowing each orbit "position" to accommodate several "quasi-stationary" space stations on a non-interference basis.

2.2 Systems using moving phased space stations

Phased satellite systems — particularly those using closed, i.e. recurrent, earth tracks — can be designed to use a reasonably small number of satellites per system. (A closed earth-track orbit is one in which the earth track is the same from one day to the next. The satellites may be in either equatorial or sub-synchronous inclined orbits.) For communication with earth stations located in the polar areas of the globe, the use of inclined orbits may become more reasonable than the use of equatorial orbits and a geostationary satellite. However, each earth station would need to be equipped with a greater number of antennae than for geostationary-satellite systems if continuous service is to be provided.

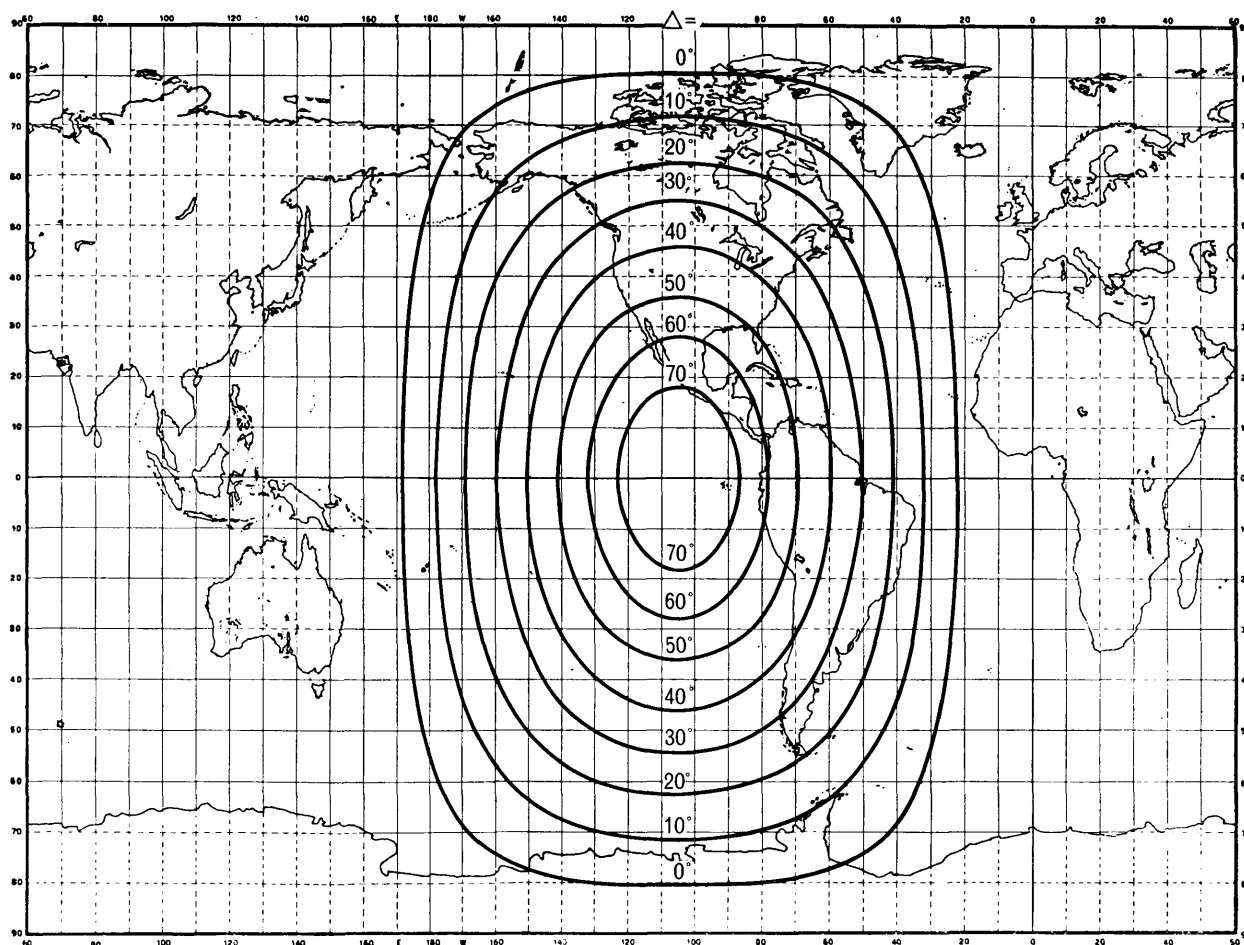


FIGURE 1 — Chart showing a typical coverage area for a geostationary satellite
(with elevation angle Δ as a parameter)

Examples of such systems are those involving the 12-hour and the 8-hour sub-synchronous orbits. In these cases, each satellite would be visible to each earth station either once or twice per day and world-wide coverage would be provided using about six overlapping zones each spanning a few hours of local time. All stations in a given zone might use the same satellite at the same time and be in single-hop communication with each other.

A measure of satellite redundancy which could well have important advantages is also inherent in such systems. On failure of a single satellite, adjacent satellites may be used in a normally non-active part of their orbit, to make good many of the circuits which would otherwise have been interrupted.

Of the possible systems using several moving phased space stations one has shown particular promise and has been implemented: a 12-hour highly elliptical orbit at an inclination of about 65° . This orbit has proven optimal for providing service to earth stations up to polar latitudes which the geostationary satellite orbit is not capable of serving.

The apogee of this orbit is at about the same altitude as the geostationary satellite orbit (about 40 000 km) and a space station's angular velocity near the apogee is low, allowing each space station to be visible over most of its orbital period from a service area which is only slightly smaller than that of a geostationary space station when two or more space stations are suitably phased in the orbit. If the apogee of this orbit is near the orbit's highest sub-satellite latitude (about 65°) the service area will encompass the closer polar regions, and at the orbit inclination of about 65° the apogee will not rotate in the orbit plane as it would for all other inclinations.

For uninterrupted traffic in a system using this orbit, hand-over capability at the associated earth stations is required.

3. Predictable outages occurring in the Fixed-Satellite Service

Interruptions to service may occur in fixed satellite systems under certain conditions of operation. Predictable breaks will occur in random systems on occasions when no satellite is mutually visible to the intercommunicating earth stations, but not in the systems described in § 2. Predictable breaks may occur also in systems because of solar eclipse but only if battery provision is inadequate to provide power during these periods.

Some early satellites were not provided with such batteries, but current practice is to include sufficient reserve for eclipse operation. For satellites in the geostationary orbit, there will be two eclipse periods a year (approximately 40 days each) centred around the equinoxes. The duration of each eclipse increases from a few minutes to about 70 minutes and then back to zero during each period. The eclipses are centred around midnight at the sub-satellite longitude. While this is a time of lowered traffic demand, a given satellite might be relaying traffic between earth stations far to its west, where the local time might be say 2000 hours, a time of greater, but not peak, traffic loading.

In some systems, interruptions will occur due to the transit of the Sun across the earth-station antenna beam (see Report 390-3). The duration and severity of the interference is a function of the earth-station beamwidth, the closeness with which the path of the Sun approaches the centre of the beam and the location of the station. Interference can be expected during a few days around the two equinoxes.

Sun interference experienced on geostationary satellites to date using large antennae (20 to 25 m) has been limited to a maximum of about four days per year. The effect of the interference is high noise or, at the worst, a complete outage. High noise and total circuit outages have been experienced for maximum periods of about 15 and 7 minutes respectively.

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REPORT 207-4

CHARACTERISTICS OF SOME TYPICAL EXPERIMENTAL AND OPERATIONAL COMMUNICATION SATELLITE SYSTEMS

(Question 2-3/4)

(1963 - 1966 - 1970 - 1974 - 1978)

1. Introduction

The first phase of experimentation with communication satellites has been completed; transmission of commercial traffic through communication satellites commenced in 1965.

This Report contains references to the experimental communication satellites launched prior to January 1965 and more detailed information on some typical satellite systems initiated subsequently.

2. Early satellite projects

Active communication satellite experiments prior to January 1965 were SCORE [IRE, 1960], COURIER [Ratcliffe, 1961], TELSTAR [BSTJ, 1963], RELAY [Abramson and Brady, 1962; Schreiner, 1963] and SYNCOM [Gatland, 1964].

3. INTELSAT system

3.1 General

The initial satellite, INTELSAT-I, was launched in 1965 as part of a programme for commercial operation. This operation was highly successful in transmitting multi-channel telephony, monochrome and colour television.

The first satellite in the INTELSAT-II series was launched in January 1967. Several space stations of this type were subsequently put in commercial service and used in a supplementary fashion well into the INTELSAT-III era. They no longer bear commercial service.

The first in the INTELSAT-III series of satellites was put into service in January 1969, and subsequent space stations of this type were placed in orbit to provide service to the Atlantic, Pacific and Indian Ocean regions, initially supplemented by operational space stations of the INTELSAT-II type.

The INTELSAT-IV series of satellites was first put into service in March 1971 to serve the Atlantic Region. In addition, two INTELSAT-IV spacecraft (one operational and one spare) now serve the Pacific Ocean Region and two others serve the Indian Ocean Region.

The first INTELSAT-IV-A satellite which was launched in 1975, began operation as the primary satellite in the Atlantic Ocean Region in February of 1976. A second satellite in the INTELSAT-IV-A series was launched in January of 1976 and now serves as the contingency satellite for the Atlantic Service.

A new generation of high capacity satellites, INTELSAT-V is currently under development with a planned launch date for 1979. The capacity of INTELSAT-V when used as the Atlantic primary satellite will be approximately 24 500 circuits plus two SPADE and television channels. The INTELSAT-V will introduce operation at 14/11 GHz in the INTELSAT system, as well as providing 6/4 GHz capacity.

3.2 The satellites

All the satellites are in geostationary orbits, at a nominal altitude of 35 800 km. Data on some of these satellites are given in Table 1.

TABLE 1 — *INTELSAT spacecraft data*

Characteristics	INTELSAT				
	I	II	III	IV	IV-A
Mass (kg) in orbit	39	83	127	700	790
Size (cm): diameter	73	142	142	240	—
height	59	67	104	530	—
Number of repeaters	2	1	2	12	20
Bandwidth of repeater (MHz)	25	125	225	40	40
Total bandwidth used (MHz)	50	125	450	480	800 ⁽²⁾
Total e.i.r.p. (dBW)	13	15,5	25,8	26/37 ⁽¹⁾	26/29 ⁽¹⁾
Polarization	linear	linear	circular	circular	circular
First launch of series	6.4.65	11.1.67	18.12.68	26.3.71	1975

(1) Values shown are for earth coverage/spot transmit antenna beams and refer to the on-axis main lobe power for a single carrier saturated condition for each repeater.

(2) Frequency re-use techniques used.

3.3 Earth stations

The initially small number of earth stations has now increased considerably, with stations in operation on all continents. As of the end of 1976, the network of earth stations accessing INTELSAT satellites consisted of 157 antennae at 126 earth stations in 82 countries.

Typical earth-station characteristics are: 5 kW of transmitter power radiated from an antenna having a reflector of between 26 m and 32 m diameter. Reception is by the same antenna. The overall receiving-system noise temperature is about 60 K at 5° elevation angle.

4. MOLNIYA, ORBITA and RADUGA satellite systems

4.1 MOLNIYA-I system

The first satellite MOLNIYA-I was launched in an elliptical orbit on 23 April 1965 for providing television, telephony and phototelegraphy services.

The technical characteristics of the spacecraft and the earth stations are shown in Tables II and III respectively.

4.2 ORBITA distribution system

The ORBITA distribution system is used for the transmission of central television programmes. It consists of one transmitting station, situated near Moscow, and a large number of receiving stations, located at distances of 3000-7000 km, all over the territory of the Soviet Union. Sound transmission is carried out by means of a special system of pulse-duration modulation, disposed within the limits of the back porch of line-blanking pulses. The ORBITA system permits the transmission of colour television programmes using the SECAM system together with sound by means of the above-mentioned method, as well as newspaper pages and central broadcasting programmes either instead of the television signal or simultaneously with it.

The parameters of the MOLNIYA-I satellite used in the ORBITA system are given in Table II. The parameters for the earth stations are given in Table III.

TABLE II — *Spacecraft characteristics*

Characteristics	Satellite				
	MOLNIYA-I	MOLNIYA-II	MOLNIYA-III	RADUGA	STATSIONAR-T
Orbit:	Elliptical	Elliptical	Elliptical	Geostationary	Geostationary
– inclination (degrees)	65	63	63	—	—
– apogee (km)	40 000 ⁽¹⁾	40 000 ⁽¹⁾	40 000 ⁽¹⁾	35 800	35 800
– perigee (km)	500 ⁽²⁾	500 ⁽²⁾	500 ⁽²⁾	35 800	35 800
Period (hour)	12	12	12	24	24
Frequency band (MHz)					
– of the transmitter	3700 to 3900	3400 to 3844	3650 to 3900	3400 to 3900	6188 to 6212
– of the receiver	6025 to 6225	5725 to 5987	5975 to 6225	5725 to 6225	
Total peak power (W)	—	7	30	9,5	
Maximum antenna gain (dB)	18	17	17,3	23	
Noise temperature of the receiving space station (K)	3000	3000	3000	3000	3000

⁽¹⁾ Above northern hemisphere.

⁽²⁾ Above southern hemisphere.

TABLE III — *Earth station characteristics*

Total peak power (kW)	2 to 6
Antenna gain (dB)	
– Transmitting	54.8
– Receiving	51.9
System noise temperature (K)	100

4.3 MOLNIYA-II system

At present the MOLNIYA-II satellite system is in regular operation providing communication in the 4 and 6 GHz bands.

The first MOLNIYA-II satellite was launched into a high elliptical orbit in 1971 to distribute colour and monochrome television programmes to the ORBITA-2 network and to transmit sound broadcast programmes; it also provides multi-channel telephony in the multiple access mode and other types of message transmissions throughout the U.S.S.R.. Quality parameters of the system conform to the appropriate CCIR Recommendations.

The characteristics of the satellites in the MOLNIYA-II system are given in Table II, and the characteristics of the earth stations are given in Table III.

4.4 INTERSPUTNIK international communication satellite system

The international communication-satellite system "INTERSPUTNIK" is intended for telephone, telegraph and phototelegraph communications and also for the exchange of radio and television broadcast programmes between the participating countries. The system was set up in 1971 by an inter-governmental agreement between the Socialist countries: People's Republic of Bulgaria, Hungarian People's Republic, German Democratic Republic, Cuba, Mongolian People's Republic, People's Republic of Poland, Socialist Republic of Roumania, Czechoslovak Socialist Republic and the U.S.S.R..

At present, "INTERSPUTNIK" leases transponders in a satellite belonging to the U.S.S.R.

Frequency modulation is used for colour television broadcasting by the SECAM-III.B system. The accompanying sound is broadcast by two different methods: time- and frequency-division multiplexing of the television channel; with time-division multiplexing, the sound signals are converted into a sequence of duration-modulated pulses located in the line blanking intervals. With frequency-division multiplexing of the television channel, the sound signal is organized by means of an FM sub-carrier above the television signal spectrum (7.5 MHz).

With the "INTERSPUTNIK" system, telephone communication is effected by frequency modulation of the signals of the individual carriers, each carrier being modulated by the signal of one telephone channel.

The guidance systems of the "INTERSPUTNIK" stations are designed for three types of operation – programmed guidance, autotracking (using a wideband information signal) and automatic programme correction.

The "INTERSPUTNIK" system uses MOLNIYA III-type satellites, the parameters of which are given in Table II. The earth station parameters are given in Table III.

The "INTERSPUTNIK" system has been in regular operation since November 1973 after the earth stations were brought into service in the U.S.S.R. and Cuba. In 1977 the system included six stations and a number of new stations are under construction.

The quality standards of the telephone and television channels are in keeping with the CCIR and CCITT Recommendations.

4.5 *RADUGA satellite system*

As part of its programme, the Soviet Union launched "RADUGA", the first satellite in the "STATIONAR" series, on to a geostationary orbit on 29 December 1975. The "RADUGA" satellites are designed for telephone, telegraph and phototelegraph communications in the territory of the Soviet Union, and also for monochrome and colour television and radio programme broadcasting and for the transmission of newspaper pages.

The second satellite in the "STATIONAR" series was launched on 11 September 1976.

Frequencies in the 6 GHz and 4 GHz range are used on the Earth-to-space and space-to-Earth segments respectively.

The RADUGA satellite characteristics are given in Table II, and the earth station characteristics are given in Table III.

The system using "RADUGA" satellites has been in regular operation since August 1976. The system already includes many stations, and they will increase in number in the course of time.

One of the "RADUGA" RF channels is assigned to television transmission, using FM signals for monochrome and colour television and TDM and FDM for the accompanying sound signals.

The other satellite channels are used for telephone, telegraph and phototelegraph communications. Some of the channels are designed for TDMA and others for FDMA.

The quality standards of the telephone and television broadcasting channels are in keeping with the CCIR and CCITT Recommendations.

The FDMA channels are used for multiple-channel group transmission by FM as well as for separate telephone channels, so that the channels can be effectively allocated among the earth stations to fit the variations in traffic density throughout the day.

In addition to multiple-channel telephone groups, the TDMA system handles a large number of radio programme broadcasts, which are received by specially equipped earth stations.

4.6 *STATIONAR-T satellite system*

The STATIONAR-T satellite was launched by the U.S.S.R. to a geostationary orbit on 26 October 1976 at a point with co-ordinates 99° E, 0° N. One transmitting earth station located in the town of Gus-Khzustalny is used to provide the programme to the satellite in the 6 GHz band in the fixed satellite service (Table II), [CCIR, 1974-78].

5. **TELESAT satellite system**

The Canadian domestic system was put into service in 1973 by TELESAT, Canada to provide television, radio programme and message communications throughout Canada. In 1977 the system has in service three ANIK satellites and 76 earth stations operating in the 4 and 6 GHz bands. Each operating satellite has the capability of transmitting up to 12 RF channels. In the single access mode, each RF channel is capable of transmitting either one NTSC colour television signal as well as two sound channels and a network cue and control channel or one FDM/FM carrier with a capacity of up to 960 voice channels.

In the frequency-division multiple-access mode, carrier capacities range from one to 120 voice channels using both analogue and digital modulation techniques.

The overall ANIK-A satellite characteristics are shown in Table IV, and the earth station characteristics are shown in Table V.

6. **Applications Technology Satellite project**

6.1 *The satellites*

The Applications Technology Satellite (ATS) programme includes six satellites. ATS-1 and ATS-3, launched 6 December 1966 and 5 November 1967 respectively, are spin-stabilized satellites in geostationary satellite orbits. ATS-1 employs electronically-despun antennae for both SHF (6 and 4 GHz) and VHF (135 and 148 MHz) transponders, whilst ATS-3 employs a mechanically-despun antenna for SHF and an electronically-despun antenna for VHF. ATS-2 is a gravity-gradient stabilized satellite intended for a circular inclined orbit (11 000 km, 28°). However, due to a malfunction of the launch vehicle, ATS-2 is in an elliptical orbit (perigee 185 km, apogee 11 000 km).

TABLE IV — *ANIK-A satellite characteristics*

Orbit	geostationary
Station keeping relative to nominal (inclination and longitude)	$\leq 0.1^\circ$
Number of RF channels	12
Bandwidth of RF channels	36 MHz
e.i.r.p. per RF channel (max.)	36 dBW
Polarization	linear
Diameter of spacecraft	1.9 m
Height of spacecraft	3.5 m
Antenna	Canadian coverage, elliptical pattern nominal $3^\circ \times 8.5^\circ$

TABLE V — *TELESAT earth station characteristics*

Transmitter power output	5 W to 3 kW
Diameter of antennae	4.5, 8, 10 and 30 m
System noise temperature	125 K-450 K

ATS-4, ATS-5 and ATS-6 satellites are gravity-gradient stabilized satellites intended for the geostationary satellite orbit. ATS-4 launched 20 July 1968, is in an elliptical, inclined orbit due to a launch vehicle malfunction. ATS-5 launched in 1969 is in geostationary orbit and was the subject of early propagation experiments at 15.3 and 31.65 GHz in addition to 4 and 6 GHz communications. ATS-6, launched in 1974 is a 3-axis stabilized satellite with a 10 m unfurlable antenna. It is designed to provide not only 4 and 6 GHz communications but also up-link communications at 148 MHz, 1650 MHz and 2250 MHz, and down-link communications at 136 MHz, 1550 MHz, 2025 MHz, 2570 MHz and 2656 MHz. Propagation experiments were carried out with down-link frequencies of 20.15 GHz and 30.15 GHz using the 6 GHz up-link. Further propagation experiments were carried out for up-link frequencies of 13 GHz and 18 GHz using the 4 GHz down-link.

6.2 Earth stations

Three earth stations provide the main support of the Applications Technology Satellite missions. These earth stations are located at Rosman, North Carolina and Goldstone, California in the United States; and at Cooby Creek in Australia. The principal characteristics of the three prime stations are shown in Table VI. The programme is also supported by the operations of the Radio Research Laboratory station at Kashima, Japan, and the Department of Atomic Energy station at Ahmedabad, India. Special communication terminals to access the TV broadcast feature of ATS-6 have also been built in Colorado and Utah in U.S.A., in India, and in Brazil. For the 20 and 30 GHz communication experiments earth terminals with 3 to 9 m antennae were used in the United States and Europe (See Report 564-1 of CCIR Study Group 5).

TABLE VI — *Supporting earth terminals*

	Rosman	Goldstone	Cooby Creek
Type of antenna	Parabolic reflector	Parabolic reflector	Parabolic reflector
Diameter	26 m	12 m	12 m
Type of feed	Cassegrain or prime focus	Cassegrain	Cassegrain
Mount	X-Y	X-Y	Az-El

6.3 Summary of experiments

As of 1977, ATS-1, ATS-3, and ATS-6 are still in considerable use. All are used for communications experiments; ATS-1 has been the subject of UHF satellite experiments with inexpensive transceivers using whip antennas in remote sites. ATS-6 has been involved in tasks for maritime communications which preceded MARISAT; and in the use of TV for educational purposes in the Rocky Mountain States of the US and in India and Brazil.

7. SYMPHONIE system

The experimental Franco-German SYMPHONIE system consists of two satellites SY 1 and SY 2 which were placed in geostationary orbit on 19 December 1974 and 27 August 1975 respectively; they operate in the 6/4 GHz bands.

In 1977 about forty earth stations of different types installed in 19 countries use or have used the SYMPHONIE system permanently or occasionally.

The principal missions performed by the system are:

- technical and scientific tests on FDMA and TDMA telephone transmission (analogue or digital), digital videophone and TV transmission, inter-connections between computers for the benefit of Administrations of various countries,
- demonstrations of high-quality TV transmission (black and white and colour),
- cultural and humanitarian transmissions (educational TV — UNESCO — United Nations),
- pre-operational radio, telephone, videophone and TV transmissions.

The satellite and earth station characteristics are shown in Tables VII and VIII respectively.

TABLE VII — SYMPHONIE satellite data

Mass in orbit (kg)	235
Size (cm): diameter	170
total height	200
Stabilization	3 axes
Orbital position: SY-1	49° E
SY-2	11.5° W
Station-keeping (N-S/E-W)	< 0.25°
Number of repeaters	4
Repeater bandwidth (MHz)	90
e.i.r.p. at edge of coverage area (dBW)	29
Figure of merit (G/T) at edge of the coverage area (dBK)	— 13
Antennae: one receiving	global coverage
two transmitting	regional coverage
	14° × 9° at — 4 dB
Polarization	circular
Estimated life	5 years

TABLE VIII — SYMPHONIE earth station data

Figure of merit (G/T) (dBK)	31.5 - 28 - 23 - 20
Diameter (m)	14 to 16 - 8.8 - 4.5 - 3.3
Transmitting power (W)	from 100 to 3000

8. Orbital Test Satellite: OTS, of the European Space Agency

OTS, whose launch is scheduled for 1978 is intended to:

- demonstrate the performance and reliability in orbit of all on-board equipment;
- carry out experiments on the transmission of radio waves through the atmosphere, frequency reuse etc.;
- provide an adequate pre-operational European traffic capacity.

The coverage of the satellite's six SHF antennae will include not only the whole of Western Europe but also the Middle East, North Africa, the Azores, the Canary Islands, Madeira and Iceland. Its capacity will be equivalent to 6000 telephone circuits.

The payload consists of two separate modules; module A for large earth stations and using dual orthogonal linear polarization, and module B for small earth stations using circular polarization.

In the co-ordinated OTS communications test programme, there will be two kinds of experiments: those requiring large earth stations with antennae 15 to 19 m in diameter, of the kind envisaged for the future operational system; and those for which much simpler and cheaper terminals suffice. Four large European stations will have special OTS antennae: Fucino, near Rome (belonging to the Italian operating company, Telespazio); Bercenay-en-Othe, near Troyes (constructed by the French PTT Administration), Goonhilly Downs in Cornwall and Usingen near Frankfurt (belonging respectively to the British Post Office and German Bundespost). In addition, about 50 European institutes, universities and telecommunications authorities will participate in OTS experimentation using more than 30 small terminals, most of which have antennae of approximately 3 m diameter although some go up to 14 m.

The six-sided OTS satellite will weigh 865 kg at lift-off (including apogee boost motor) and 444 kg in geostationary orbit. The spacecraft is 2.39 m high, 2.13 m long and measures 9.26 m with its solar arrays deployed.

The output stages of both module A and module B include 20 watts TWT amplifiers. The satellite design lifetime is three years.

The operating frequencies are shown in Table IX.

TABLE IX — OTS operating frequencies

Module A up-links: TC receiver 40-MHz chains 120-MHz chains	14 125 MHz 14 152.5 to 14 192.5 MHz 14 242.5 to 14 362.5 MHz
Module A down-links: 40-MHz chains TM transmitter 120-MHz chains	11 490.0 to 11 530.0 MHz 11 575.0 MHz 11 580.0 to 11 700.0 MHz
Module B up-links: 5-MHz chains	14 455.0 to 14 460.0 MHz
Module B down-links: beacon transmitters 5-MHz chains	11 786.0 MHz 11 792.5 to 11 797.5 MHz

9. SIRIO Satellite System

SIRIO * is an experimental satellite designed, developed and built entirely in Italy under the authority of the National Research Council (CNR) carrying propagation experiment equipment in addition to the telecommunications equipment, such as television and telephone transmission and reception over an area including Europe, the East Coast of the United States and Canada. The SIRIO satellite was successfully launched on 25 August 1977 and is positioned on the geostationary orbit at 15° W of longitude.

The main objective of the SIRIO Programme is to carry out propagation and telecommunication experiments in the SHF band (at 12 and 18 GHz) in order to measure the attenuations and distortions of the signals under various meteorological conditions.

In particular the following experiments will be performed:

- measurement of the up-link absolute and relative attenuations at 17.0 and 17.8 GHz;
- measurement of the down-link absolute and relative attenuations at 11.3 and 11.8 GHz;
- measurement of the phase distortion in both up- and down-links;
- measurement of the atmospheric depolarization effects;
- analogue and digital television transmission in the wide band mode;
- voice and data transmissions in the narrow band mode.

SIRIO is a geostationary cylindrical shaped spin-stabilized satellite weighing 398 kg at launching and 210 kg in orbit having the characteristics shown in Table X.

* SIRIO is the acronym for Satellite Italiano di ricerca industriale orientata (Italian Satellite for Industrially Orientated Researches).

TABLE X — *SIRIO satellite characteristics*

Receiving frequency range	17.0 to 17.8 GHz
Polarization	left-hand circular
Noise temperature of the receiving space station	3000 K
Broadband experiment bandwidth	35.0 MHz
Narrowband experiment bandwidth	1.5 MHz
Propagation experiment bandwidth	800 MHz
Antenna gain	22 dB
Transmitting frequency range	11.3 to 11.8 GHz
Polarization	right-hand circular
Broadband experiment transmitted power	4.26 W max.
Narrowband experiment transmitted power	3 W max.
Propagation experiment transmitted power	0.2 W max.
Lifetime	2–3 years

Two earth stations, located at Fucino and Lario in Italy, provide the main support of the SIRIO satellite mission.

The principal characteristics are shown in Table XI.

TABLE XI — *Earth station characteristics*

Type antenna	shaped reflector
Diameter	17.5 m
Type of feed	Cassegrain
System noise temperature	250 K
Transmitted power:	
narrowband experiment	27 dBW
broadband experiment	30 dBW
propagation experiment	30 dBW

The Fucino earth station houses also a VHF station and an Operational Control Centre for the maintenance of the satellite synchronous orbit and for the processing of data coming from the satellite. The experiment is also supported by many foreign organizations in Germany, Holland, United Kingdom, France, Finland, USA and Austria which established in their countries earth stations linked with the SIRIO satellite.

10. US Domestic Commercial Satellites

10.1 *General*

In the United States, demand for commercial communication traffic has resulted in three domestic commercial satellite systems each of which is operational at 4 and 6 GHz with two satellites in orbit for each system. These three systems are known as WESTAR, SATCOM and COMSTAR.

10.2 *The Satellites*

The six US domestic commercial satellites in orbit in 1977 are in geostationary orbit. These satellites include the two WESTAR satellites which illuminate both the continental US and Hawaii with 12 transponder channels each 36 MHz wide. Both the SATCOM satellites and the COMSTAR satellites use frequency cross polarization reuse of the 4 and 6 GHz band. This enables each satellite to employ 24 transponder channels. SATCOM illuminates the continental US, Alaska and Hawaii, while COMSTAR illuminates continental US, Hawaii and Puerto Rico.

10.3 *The earth terminals*

WESTAR operates into six 10 m terminals located in the United States and Hawaii. It provides leased channel service to many TV cable systems, and service for remote printing of news; the latter two systems use 10 m and 4.5 m antennae. WESTAR will also interconnect the 165 receive-only earth stations and five regional transmit terminals of the Public Broadcasting Service. Two SATCOMS serve sixteen (10 m) earth terminals in the continental US and Alaska and 100 (4.5 m) terminals in remote sites in Alaska. COMSTAR serves a network of seven (30 m) earth terminals in the continental US and Hawaii, accomplishing frequency reuse by means of dual polarization feeds. This system supplements terrestrial links used for heavy-route traffic.

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REPORT 214-3 *

**THE EFFECTS OF DOPPLER FREQUENCY-SHIFTS AND SWITCHING
DISCONTINUITIES IN THE FIXED SATELLITE SERVICE**

(Question 7-1/4)

(1963 – 1966 – 1974 – 1978)

1. Introduction

In the fixed satellite service system, the received signal will be subject to the following phenomena:

- Doppler frequency-shifts due to the relative velocities between satellite and earth stations;
- discontinuities of transmission delay and of Doppler shift due respectively to the difference in the lengths of the radio paths and in the different relative velocities, on switching from one satellite to another.

This Report considers the probable magnitude of these phenomena and their effect on various types of communication signal.

2. Doppler frequency-shifts (applicable to non-geostationary satellites)

The magnitude of the total Doppler frequency-shift between the terminals of a system in the fixed satellite service depends upon the wavelengths used and the relative velocities of the satellite with respect to the earth stations. The major component of the effect of the Doppler shift, i.e. the shift of the carrier or a reference-frequency of the transmission, can be removed in the receiver; however, it may be necessary also to compensate for the differential shift across the radio-frequency spectrum of the signal that produces a frequency “stretch” or “shrinkage” of the baseband signal. Depending upon the relative locations of the earth stations and the orbit, the Doppler shifts between transmitting earth station and satellite and also between satellite and receiving earth station can either add or subtract. If 5000 km is taken as a probable minimum orbital height for a communication satellite, then the “stretch” or “shrinkage” of the baseband signal will not exceed 2 parts in 10^5 . In most practical cases, the orbital height will be greater and the Doppler shift would be considerably less than this, and in the particular case of the geostationary satellite, there would be no significant Doppler shift.

* Should be read in conjunction with Report 383-3.

The maximum value of the Doppler shift, resulting from transmission to, or from, a space station on a satellite in a circular orbit, can be estimated from the relationship:

$$\Delta F \approx \pm 3.0 \times 10^{-6} \times F \times s \quad (1)$$

where

ΔF : Doppler frequency-shift,

F : operating frequency,

s : number of revolutions per day (24 hours) of the satellite with respect to a fixed point on the Earth.

This relationship may also be used for calculating the maximum differential Doppler frequency-shift over a frequency band. A few values of s for various circular equatorial orbit altitudes are provided below (Table I) to facilitate the calculations for individual cases.

TABLE I

Revolutions per day relative to the Earth, s	Altitude for circular equatorial orbits (km)	Period (h)
0	35 600	24
1	20 240	12
2	13 940	8
3	10 390	6
4	8 080	4.8
5	6 420	4
6	5 170	3.4
7	4 190	3

In a frequency-division multiple-access (FDMA) system, each participating station uses a portion of the frequency band of the satellite repeater. Since the transmissions from each station are independent in time, there is no adverse effect from any relative time-shift. There will, however, be a Doppler frequency-shift in the transmission from each station which varies with time.

For satellites employed to relay signals simultaneously from a number of earth stations, special consideration of Doppler shift may be necessary.

Table II shows the maximum possible Doppler frequency-shifts at the satellite at 6 GHz. The figures are based on equatorial orbits and assume that the satellite moves in the same direction as the surface of the Earth.

To prevent interference between adjacent radio-frequency channels caused by Doppler frequency-shifts, guard bands can be used. Depending on the location of the stations, the signal transmitted by one station may be shifted upward, while that from a station on an adjacent channel may be shifted downward. Alternatively, the frequency shifts may be corrected by available techniques.

For example, allowing a guard band equal to the maximum possible Doppler frequency-shift shown in Table II for a ten-channel system, the total guard bands would then be 18 times the figures shown (at 6 GHz).

TABLE II — Maximum Doppler frequency-shift

Period (h)	6	8	12	24
Approximate altitude (km)	11 000	14 000	20 000	36 000
<i>Minimum elevation of antenna: 5°</i>				
Maximum Doppler frequency-shift at 6 GHz (kHz)	55.4	37.2	18.5	0.24 ⁽¹⁾

⁽¹⁾ The Doppler shift given takes account of various perturbations of the 24-hour orbit, assuming that the actual position of the satellite can be held within 60 km of the true stationary position. In this case, the maximum-velocity of the satellite towards, or away from, an earth station will not exceed 5.8 m/s.

In the time-division multiple-access (TDMA) system, all earth stations transmit on the same nominal carrier frequency. This requires that the transmitter carrier be on only during that interval of the frame assigned to the station. During transmission, the carrier would probably be modulated by phase-shift keying or frequency-shift keying. Because of the Doppler frequency-shift, transmissions will arrive at the satellite and be repeated at frequencies which vary above and below the nominal carrier frequency. To accommodate this shift, the earth-station receivers must be capable of adjusting to the sudden changes in carrier-frequency which will occur. This may impose the requirement for increased interburst guard time and for more time within the burst to be allowed for carrier recovery and burst synchronization for satellites in a non-geostationary orbit [Gabbard, 1968].

2.1 *Telephony*

When frequency-division multiplex telephony is used, it is necessary to limit the bandwidth or the apparent geocentric angular velocity of the satellite to prevent unacceptable differential Doppler frequency-shifts (unless corrections are applied to compensate for the Doppler effects).

According to CCITT Recommendation G.225, the difference between an audio-frequency applied to one end of the circuit and the frequency received at the other end should not exceed 2 Hz. The question of error in reconstituted frequency is still under study in CCITT Study Group XV.

It may be noted that an error of 2 Hz is not exceeded in a single satellite link, if the product of the baseband (MHz) times the number of revolutions per day of the satellite relative to the Earth, s , does not exceed 0.666; however, additional error is likely to be introduced by the multiplex equipment.

Doppler effects will also shift the pilot frequencies used in FDM telephony for satellites with such angular velocities. Possible methods which could be used for correction of these shifts are:

- a suitable variable time-delay device;
- the carrier-frequencies used in the frequency-division multiplex equipment could be automatically controlled to compensate for the effects of Doppler shift and so reduce the overall frequency errors to acceptably small values.

The first of these methods has the advantage of effectively cancelling the errors resulting from the movement of the satellite, in a manner similar to that in which they are introduced (i.e. by change in transmission delay during the pass). This method would, therefore, also eliminate all the effects of Doppler shift on the baseband signals and by suitable arrangements, would avoid switching discontinuities when transferring the information flow from one satellite to the next in the orbital pattern. Control of the variable delay could be performed, either by using predicted orbit information or on a servo basis employing a pilot signal transmitted from the earth station to the satellite and back to the same earth station (loop method). The loop method has the following advantages:

- it would ensure that only the correct frequencies were received at the satellite. This facility could be of particular importance for certain systems, for example, those using closely-spaced channels or blocks of channels with single-sideband modulation in the Earth-to-satellite direction;
- Doppler frequency “stretch” might to some extent be obviated, e.g. by splitting the receiving bandwidth into appropriately separated portions and providing independent compensations for the blocks of circuits arriving from each of the other earth stations.

Alternatively, compensation for the variable delays could be applied only at the receiving end and controlled by pilot signals originating at the distant stations. In this case, the Doppler frequency “stretch” or “contraction” of the baseband would need to be accommodated by adaptations of the frequency-division multiplex equipment at each earth station. Administrations are requested to submit to the CCITT their recommendations, or findings concerning such adaptations involving control of the earth-station frequency-division multiplex equipment, either on a loop basis, as is described under the first method above, or on a route-by-route basis.

Doppler-shift correction may be necessary in any system in the fixed satellite service using single-sideband amplitude modulation.

2.2 *Telegraphy and data transmissions*

If telephone channels comply with the requirement of CCITT Recommendation G.225 this implies that, for telegraph and data channels derived from such telephone channels, the effect of Doppler frequency-shift may be ignored or has been adequately compensated for (see § 2.1).

2.3 *Phototelegraphy*

If phototelegraphy channels are derived from telephone channels complying with the requirement of CCITT Recommendation G.225, the effect of Doppler frequency-shift may be ignored as being adequately compensated for.

2.4 *Wide-band data*

It should be noted that Doppler correction would need to be provided for carrier-derived phototelegraphy or data channels requiring wider bandwidths than a single telephone channel (e.g. group or supergroup bandwidths).

2.5 *Television*

The change in field frequency introduced by Doppler frequency-shift is very small. In normal monochrome television practice, the accuracy of the field frequency at the programme source is likely to be the limiting factor as far as disturbance to domestic receivers is concerned and Doppler shift will not be of concern.

It may ultimately be desirable to correct for the effects of Doppler shift on colour television signals, but the initial tests made with the satellites have demonstrated that standard colour receivers and, in particular, those using crystal controlled sub-carrier oscillators, will operate satisfactorily, with the order of Doppler frequency-shift likely to be encountered in a practical system in the fixed satellite service.

3. Switching discontinuities (applicable to non-geostationary satellites)

Satellites which rise and set can be used by any two or more earth stations only while mutually visible. These stations must then switch or "hand-over" to another mutually visible satellite, to maintain communication with some orbit systems, or with excessively separated earth stations; relatively long interruptions may occur when mutual visibility of the first satellite is lost before another satellite has been acquired. Such interruptions can be avoided by the use of controlled, equally separated satellites of sufficient number in orbits having a recurrent earth-track [Dagleish and Jefferis, 1965]. Such satellite orbit systems are often referred to as systems of phased satellites. The phased circular equatorial orbit system is the simplest and best-known such system.

Even though such systems can prevent hand-over interruptions, there will generally be slight discontinuities of overlap of communication between two stations at the instant of hand-over, depending on whether the propagation path via the new satellite is shorter or longer than that via the former satellite. The calculation of these propagation path lengths or delay times, and their difference, is dependent upon simple geometric relationships which are explained in Report 383-3 on the effects of transmission delays.

In the case of multi-hop connections, the switching discontinuities in the different hops will not often be coincident in time, so that the number of discontinuities per 24 hours will be approximately $n \times m$, where n is the number of hops and m the mean number of switching discontinuities per 24 hours per hop. With systems employing phased satellites, the time differences for some pairs of earth stations would not exceed 10 ms; whilst for other pairs of earth stations, the time differences would be up to 20 ms or even more. In unphased satellite systems, the time differences would have durations between 0 and 30 ms or more. It should be noted that these discontinuities are predictable and that counter-measures are possible. The use of variable delay devices could reduce these switching discontinuities to negligible proportions.

Note — An earth station using any satellite, non-geostationary or geostationary, may have its circuits interrupted for predictable periods when the satellite in use has approximately the same orientation from an earth station as the Sun or another satellite at the same frequency, or when the satellite uses a solar power supply without batteries and is eclipsed by the Earth. To avoid interruptions of these types, alternate routing via surface circuits or via a different satellite may be used during periods of outage.

3.1 Telephony

Time differences, of up to perhaps 20 ms during transfer from one satellite to another, should not cause difficulty with telephone conversations. However, a discontinuity in transmission of this duration can cause errors in existing telephone MF signalling systems such as the Intercontinental CCITT No. 5 and TASI. Signalling techniques, (such as CCITT No. 6), that employ high-speed pulsing rates, may be much more susceptible to errors from this source.

3.2 Telegraphy and data transmissions

The effects of present interest are those due solely to differences in transmission time between one satellite path and another, and these are of two types:

- lengthening or shortening of telegraph elements when the transmission time differences are relatively large, i.e., exceeding a significant part of an element;
- phase discontinuities of voice-frequency tone, sometimes giving rise to telegraph distortion, whenever the transmission time differences exceed a fraction of the time occupied by one cycle of the highest baseband frequency utilized by a telegraph channel of a broadband system carrying voice-frequency telegraphy [Zuhrt, Reger and Vollmeyer, 1959].

According to preliminary information from one source (see Annex I), it appears that, in an unprotected 50-baud start-stop telegraph channel the average number of character errors caused by discontinuities of up to about 7.5 ms may not exceed about 0.25 per discontinuity. The average number of character errors increases probably to about 1.0 for discontinuities of duration about 10 to 12 ms, whilst it may approach 2.0 or more for discontinuities of duration up to 20 ms or 30 ms.

Time duration of the discontinuities likely to be encountered in non-geostationary satellite systems would cause character errors in synchronous telegraph systems and in time-division multiplex telegraph systems. Time discontinuities can falsify selection signals such as used in telex, causing incorrect routing and, particularly on automatic systems, the possibility of incorrect charging might arise.

Automatic error-correcting (e.g. ARQ) equipment is used on some telegraph circuits, for example when the traffic is extended over HF radio links. It may be noted that ARQ would not only protect against errors arising from switching discontinuities, but also against errors arising from other causes. Justification for any special treatment of circuits routed through systems in the fixed satellite service should take into account the relative frequency of error producing disturbances in the satellite links and in their terrestrial extensions as well as in international circuits using other means. If, after account has been taken of the various sources of error in telegraph channels, it seems necessary to take special measures to deal with errors caused by satellite switching discontinuities, then it appears that consideration might be given to the possibility of using some device such as a buffer store. This might commence to store the telegraph signals on receipt of a "satellite change" signal, and would retransmit at a slightly higher rate after the satellite switching operation.

Another method of reducing the number of errors due to satellite switching would be to use a suitable variable delay device.

Switching discontinuities of up to perhaps 20 ms would affect data transmission by causing:

- errors to occur in one or more blocks,
- loss of block phase.

Provided the switching from one satellite to another is fairly infrequent, the errors of the first type would not be serious, and would in fact be similar to the effects of occasional switching or noise disturbances to be expected on normal line circuits. The loss of block phase results directly from the time discontinuity and has no equivalent in line systems.

Block phase would thus need to be re-established on data circuits each time a switch from one satellite to another occurs, unless means are adopted to compensate for the delay discontinuity. However, if the switch-overs are not unduly frequent, and re-phasing of the data transmission system is arranged to take place automatically, the loss of circuit time due to this cause would not be a serious disadvantage.

3.3 *Phototelegraphy*

The effect of these discontinuities would be an immediate displacement (either in an advance or a retard direction) of any succeeding elements of the picture, relative to the position before switching. For equipment conforming to CCITT standards and using a drum speed of 60 r.p.m., a delay discontinuity of 20 ms would produce a displacement of about 2% of the picture width, e.g. 0.5 cm displacement in a picture 25 cm wide. This displacement would be a serious defect in most pictures or in typescript, meteorological charts, etc. With higher scanning rates, the displacement would increase in proportion. The amount of such displacement that could be accepted as tolerable is, of course, a matter to be decided in consultation with the CCITT. It seems likely, however, that switching discontinuities of the order of 20 ms would produce unacceptable distortion in the majority of cases, and would, therefore, need to be avoided, either by suitable delay-compensation techniques or by arranging that the picture transmissions do not occur during switching times.

3.4 *Television*

Switching from one non-geostationary satellite to the next is very similar to, and will generally produce the same effects as, switching between "non-synchronous" programme sources, and can result in temporary disturbance to the receiver field time-base. The actual time over which the disturbance exists will vary in practice depending upon the relative phase relationship at the moment of switching, but will normally lie between 0.5 s and 2.0 s.

The change in transmission delay on switching may introduce a small discontinuity in the sound signal which, although noticeable, should not be disturbing.

As switching in a system in the fixed satellite service will be infrequent, the effect on both vision and sound signals would not prove too serious.

4. *Summary*

The significance of Doppler frequency-shift and switching discontinuities in systems in the Fixed Satellite Service varies with the type of service or signal transmitted, and with the characteristics of the satellite orbit. In general, geostationary satellites are not expected to introduce significant Doppler frequency-shifts or switching discontinuities. Non-geostationary satellite systems will introduce greater Doppler frequency-shift and switching discontinuities.

The major component of the Doppler frequency-shift can be removed in the radio-frequency receiver, but there will remain a "stretch" or "shrinkage" of the baseband spectrum due to differential frequency shift. The effect on monochrome television will be insignificant and the effect on colour television will probably be tolerable. In telephony, with the general use of broadband single-sideband frequency-division multiplexing techniques, the changes in baseband spectrum (differential Doppler) will require compensation in the form of transmission delay equalization of the entire baseband or of automatic control of the carrier frequencies used in the multiplex equipment. It is felt that such compensation is feasible. Telegraph, data and phototelegraphy channels, derived from channels adequately corrected for telephony, should not require any further consideration of Doppler effects.

It appears that, unless special steps are taken, time discontinuities due to satellite switching may lead to error rates on telegraph channels which, for certain pairs of earth stations with particular orbital configurations, could exceed the desirable limit suggested in CCITT Recommendation R.54 of 2 errors per 100 000 telegraph characters. Some discussion of this matter, and of possible means of mitigating the effects on telegraph transmission, is given in Annex I.

The attention of the CCITT and the CMTT is drawn to the problems which may arise in systems in the fixed-satellite service due to Doppler frequency-shifts and switching discontinuities; the CCITT with regard to telephony, telegraphy and data transmission and the CMTT for television transmission, including the related sound channel.

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ANNEX I

1. CCITT Recommendations

CCITT Recommendation R.57 calls for a maximum isochronous distortion over a single telegraph link not exceeding 10%.

CCITT Recommendation R.54 suggests, in the considerations, an error-rate not exceeding 2 per 100 000 telegraph characters due to distortion as a desirable overall transmission objective.

2. Telegraph error-rates in 50-baud start-stop telegraph systems

In a preliminary series of experiments, the relationship between the duration of switching discontinuities and telegraph error-rate in 50-baud start-stop telegraph systems has been explored. The error-rate is dependent, to a small extent, on the nature of the transmitted text. It appears that the error-rate may not vary greatly when the duration of the switching discontinuity is varied between 0 and about 7.5 ms; the average number of errors is then about 0.25 per switching operation. For durations exceeding about 7.5 ms, the error-rate increases; this may be explained by the evident fact that, in these circumstances, the lengthening or shortening of the telegraph elements approaches or exceeds 50% of the duration of the elements. The preliminary experiments suggest that the average number of character errors per discontinuity may be about 1.0 for discontinuities of duration of about 10 to 12 ms, whilst it may approach 2.0 or more for discontinuities of duration up to and exceeding 20 ms. These results, as stated above, apply to telegraph signals at a speed of 50 bauds; the duration of each element is 20 ms and it is not unreasonable to find that, for discontinuities of a duration up to about 30 ms, there may not be more than two telegraph character errors.

3. Compensation by means of variable-delay correction devices**3.1 Compensation with moderate accuracy**

It would be possible to greatly reduce character errors due to satellite switching if suitably controlled variable delay devices could be connected in tandem with satellite links, so that the overall signal delay could be kept constant. Compensation to an accuracy of the order of 200 μ s would deal with character errors due to the lengthening or shortening of telegraph elements. The development of such broadband delay devices would have the additional advantage of substantially eliminating differential Doppler-shift effects in the transmitted baseband; these would otherwise call for special control of supergroup and group translation oscillators to preserve the centering of voice-frequency telegraph signals in their appropriate filter bandwidths.

The effects of phase jumps at the instant of satellite switching would remain, and while the character error-rate would be less than that estimated to occur without compensation, a reliable estimate of the probable error-rate would require experimental investigation.

3.2 Compensation with high accuracy

To avoid character errors due to phase jumps at the instant of satellite switching, delay compensation to an accuracy corresponding to $\pm 15^\circ$ at the highest baseband frequency involved appears to be necessary. For telegraph channels carried in the highest frequency telephone channels of a 1200-channel system with baseband frequencies up to 5 MHz, an accuracy of some 0.01 μ s would be required. The probable limit of predicted satellite slant range, and therefore of transmission delay, is of the order of 50 μ s. Consequently, direct compensation on a predicted basis in a single step to an accuracy sufficient to substantially remove telegraph errors is impracticable. Consideration might, however, be given to additional measures, for example, an electronically controlled variable-delay device, which has its delay changed until the baseband signals over the two satellite paths displayed complete correlation in time, the switch – over then taking place.

Another possibility to which attention might be drawn is the employment of a relatively slow “fade-over” instead of an abrupt switch-over. The major effects of sudden phase changes might thereby be avoided and only a small proportion of telegraph channels suffer from amplitude effects. FM voice-frequency telegraph systems can tolerate at least 15 dB reduction of signal level and printed error-rates of the order of one in 80 000 might be achieved, but this possibility requires theoretical and experimental investigation. The effect of such a “fade-over” on telephone, data and facsimile circuits would need to be assessed.

4. Summary of means of compensation

In considering possible methods of mitigating the effects of switching discontinuities on telegraph performance, it must be borne in mind that in any telegraph channel there may be a number of causes of error.

Telegraph errors due to satellite-switching discontinuities might be reduced in number by:

4.1 "buffer store" systems, which would commence to store on receipt of a "satellite change" signal transmitted over the system and re-transmitted at a slightly higher rate after completion of the change;

4.2 time discontinuity correction of moderate accuracy used in conjunction with any of the following measures:

4.2.1 placing of the telegraph channels in the lower part of the baseband spectrum;

4.2.2 inter-satellite switching, which takes place at the point where the telegraph signals are d.c.;

4.2.3 introducing slow "fade-over" devices to mitigate transients caused by rapid switching between satellites;

4.2.4 recoding of the telegraph information into special codes, such as those developed by Hamming, which give correction facilities without the necessity for retransmission;

4.3 precise compensation of transmission delays to minimize the delay discontinuity at change-over.

In addition, it would be possible to use ARQ or some equivalent system; this would be particularly useful in the event that the satellite link is extended by an HF radio link or another type of link liable to introduce a relatively large number of telegraph errors.

REPORT 383-3 *

THE EFFECTS OF TRANSMISSION DELAY IN THE FIXED SATELLITE SERVICE

(Question 7-1/4)

(1966 - 1970 - 1974 - 1978)

1. Introduction

In a system in the Fixed Satellite Service, the transmitted signal will be subject to considerable transmission delay due to the propagation time of the radio path. The magnitude of this effect with various orbits is discussed and it is shown how various types of communication signal may be affected.

2. Transmission delay

Overall transmission delay in a system in the Fixed Satellite Service depends largely on the altitude of the satellites and the number of Earth-satellite-Earth links, or hops, forming the connection.

With geostationary satellites, the transmission delay is essentially fixed for a given circuit, but if the satellites are in motion relative to the Earth, the transmission delay will vary with time; for satellites in the geostationary orbit, the variation in transmission delay will be very small relative to the total delay in the transmission path.

However, under some circumstances, even the very small variations in transmission delay associated with quasi-geostationary satellites in the geostationary orbit may be important.

2.1 Single-hop connection

For a single-hop circuit, the minimum possible transmission delay (t_{min}) occurs when the two earth stations are close together and the satellite is directly overhead. The maximum possible transmission delay (t_{max}) earth station-to-earth station, is obtained when the satellite is at the horizon, as seen by both earth stations. Thus, if h is the altitude of the satellite, r is the radius of the Earth, and c the velocity of light, then let $R = r + h$; further, let θ be the angle subtended at the centre of the Earth between the directions of the satellite and the earth station. Then the one-way transmission delay for the Earth-to-satellite path is:

$$t = \frac{1}{c} \sqrt{R^2 + r^2 - 2Rr \cos \theta} \quad (1)$$

* Should be read in conjunction with Report 214-3.

From this, the minimum and maximum possible transmission delays for one hop between earth stations may be expressed as:

$$t_{min} = 2h/c \quad (2)$$

and

$$t_{max} = (2h/c) \sqrt{1 + 2r/h} \quad (3)$$

The minimum transmission delay will in practice be slightly greater than t_{min} because the earth stations would naturally be some distance apart. Also, the maximum transmission delay would be rather less than t_{max} since the earth stations would, in practice, work to angles of elevation not less than 3° and perhaps generally not less than 5° . However, the above expressions enable the minimum and maximum transmission delays for a single-hop circuit (and the possible range of variation about this mean) to be calculated for different positions of earth stations with sufficient accuracy for present purposes.

To allow for the component of transmission delay in the terrestrial extensions from the satellite-system earth stations, an amount of transmission delay should be added, calculated from the formula (taken from CCITT Recommendation G.114):

$$12 + (0.004 \times \text{distance in km}) \quad (\text{ms})$$

or,

$$12 + (0.0064 \times \text{distance in statute miles}) \quad (\text{ms}).$$

The 12 ms term is an allowance for the probable existing terminal equipment and some loaded-cable facilities, and the velocity factor of the second term, 0.004 (or 0.0064), is based on the use of high-velocity plant for the major transmission distance.

For estimating purposes and since it is improbable that two maximum-delay terrestrial extensions will be used in one connection, it is considered reasonable to take an average value of 30 ms for the total transmission delay of terrestrial extensions, the minimum being of the order of 10 ms, the maximum of the order of 50 ms.

Employing these figures plus the transmission delays computed for the t_{min} and t_{max} formulae above, the range of values for total single-hop transmission delay (one way) for communication-satellite systems have been derived and are given in Table I. It will be noted that Table I shows the case of minimum transmission delay between earth stations plus minimum transmission delay due to terrestrial extensions and the opposite case of maximum transmission delay between earth stations plus maximum transmission delay due to terrestrial extensions. In practice, one may well have a maximum of transmission delay between earth stations with terrestrial extensions of minimum transmission delay, or *vice versa*.

TABLE I

	Overall one-way transmission delay (ms)								
	Non-geostationary satellite (altitude 11 000 km)			Non-geostationary satellite (altitude 14 000 km)			Geostationary satellite (altitude 36 000 km)		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	max.	Mean
	74	109	92	92	128	110	240	280	260
Between earth stations									
Terrestrial extensions	10	50	30	10	50	30	10	50	30
Total	84	159	122	102	178	140	250	330	290

Fig. 1 gives the maximum one-way propagation time of the radio-path and the great-circle distance of the effective earth-coverage of the satellite, as a function of a satellite altitude; assuming that the minimum usable angle of elevation at both transmitters and receivers is 5° . This great-circle distance does not determine the maximum separation distance between earth stations except with a stationary satellite. The hand-over requirement for communication continuity with non-stationary satellites limits the distance between stations to within the coverage overlap of successive satellites. The boundaries for uninterrupted operation of one-hop systems are discussed in Report 206-3.

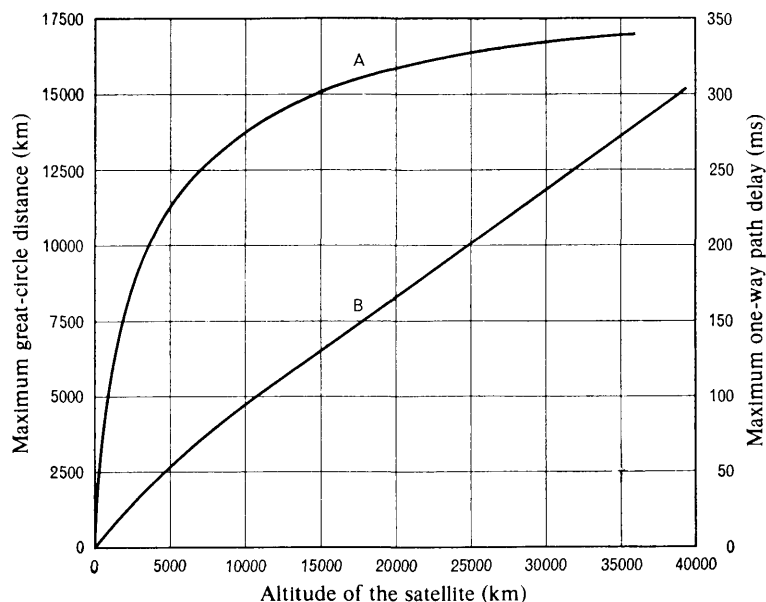


FIGURE 1 — *Single-hop radio link via a system in the fixed satellite service (minimum angle of elevation: 5°)*

Curves A: Maximum great-circle distance (km)
B: Maximum one-way propagation time (ms)

2.2 Multiple-hop connections

Consideration of the geometry of a system in the fixed satellite service shows that the mean transmission delay will increase in proportion to the number of hops. Assuming that the additional transmission delay for the terrestrial extensions (30 ms mean) will be the same for all cases and, assuming essentially zero transmission delay for the intercommunication between continuous hops, the values given in Table II are obtained.

TABLE II

Number of hops	Overall one-way transmission delay (ms)		
	Non-geostationary satellite (altitude 11 000 km)	Non-geostationary satellite (altitude 14 000 km)	Geostationary satellite (altitude 36 000 km)
1	122	140	290
2	214	250	550
3	306	360	

The import of these transmission delays will be discussed in the following sections of this Report.

2.3 Variations in transmission delay as a function of time

In a system using satellites in motion relative to the Earth, the transmission delay in any given circuit will be subject to a gradual change arising from the varying distance between the satellite and the earth stations. In a practical non-geostationary satellite system of the type referred to above, the range of variation would not ordinarily exceed 20 ms per hop.

One method of eliminating, or at least minimizing this change, is to insert a variable delay device in the signal paths at earth stations. The amount of delay thus inserted could be controlled automatically, to maintain the total delay constant at a value slightly greater than the maximum transmission delay of the radio path. The use of such a method could also reduce the effects of switching discontinuities which otherwise could occur at each hand-over of circuits to another non-geostationary satellite. This is discussed in Report 214-3.

The variation in transmission delay is of particular importance in systems employing time division for multiple access (TDMA systems). Even relatively small variations in transmission delay (e.g. less than 1.0 milliseconds in a period of 12 to 24 hours) may be important under some circumstances, for example, when satellite circuits are used for the transmission of data between synchronous data networks and in multiple access systems, such as time-division multiple access (TDMA) and code-division multiple access (CDMA).

In TDMA systems, the transmission from each earth station must be inserted into the pulse train at the satellite at the proper time in each frame. Because of variations in the transmission delay, difficulties arise in synchronizing the transmission from the earth stations. Even though synchronism is obtained at one instant, shifts in the relative positions in time of the transmissions from the various stations will occur, unless the time of start of transmission is regulated.

As an aid in expressing these changes, the "differential transmission delay" will be defined as the difference in time of arrival at the satellite of signals simultaneously transmitted from Stations *A* and *B*.

That is,

if τ_A is the transmission delay from Station *A* to the satellite at any instant,

if τ_B is the transmission delay from Station *B* to the satellite at the same instant, then the differential transmission delay, $\Delta\tau$, is:

$$\Delta\tau = \tau_B - \tau_A \quad (4)$$

This quantity is in itself, however, not of great importance. Of more interest is the "variation in differential transmission delay", $V\Delta\tau$, which occurs over a period of time. Table III gives the maximum values of the "variation in differential transmission delay", $V\Delta\tau$ max., that can occur for satellites in the four different orbits. (Calculation of the values given in the Table is explained in [CCIR, 1963-66]).

TABLE III — Maximum possible variation in differential transmission delay

Orbital period (h)	6	8	12	24
Approximate altitude (km)	11 000	14 000	20 000	36 000
<i>Minimum elevation of antenna: 5°</i>				
$V\Delta\tau$ max. (ms)	30.5	32.0	33.7	0.124 (?)
$V\Delta\tau$ max. (frames) (1)	244	256	269	1

(1) In this case it is assumed that each speech channel is sampled 8000 times a second, and that the frame duration is approximately $\frac{1}{8000}$ s, or 125 μ s.

(2) The indicated time shift takes into account various perturbations in the quasi-geostationary satellite orbit, assuming that it is possible to hold the real satellite position within a radius of 60 km from the exact stationary position, in which case the maximum velocity of the satellite towards, or away from, an earth station will not exceed 5.8 m/s.

It should be noted that these variations occur slowly (e.g. for a satellite in a 10 000 km orbit and using a minimum antenna elevation of 5°, the variation occurs over a period of about 63 minutes). Nevertheless, there will be some variation in delay during the time it takes a signal to travel the distance from the earth station to the satellite and return. The magnitude of this variation for various orbits is indicated in Table IV, as a fraction of the frame time (125 μ s).

TABLE IV — Maximum round-trip variation in transmission delay as seen by one earth station

Period (h)	6	8	12	24
Approximate altitude (km)	11 000	14 000	20 000	36 000
<i>Minimum elevation of antenna: 5°</i>				
Maximum delay variation (frames)	0.004	0.003	0.002	0.00004 (1)

(1) The indicated time shift takes into account various perturbations in the quasi-geostationary satellite orbit, assuming that it is possible to hold the real satellite position within a radius of 60 km from the exact stationary position, in which case the maximum velocity of the satellite towards, or away from, an earth station will not exceed 5.8 m/s.

To the extent that the following perturbations are present, they will cause variations in transmission delay for a quasi-geostationary satellite:

- eccentricity of the orbit will cause transmission delay variations within a period of approximately 24 hours. For example, the result of a variation of 60 km in satellite altitude with respect to the sub-satellite point on the earth because of orbital eccentricity would be a round trip variation in transmission delay of approximately 0.4 ms in a 24 hour period as seen by one earth station;
- inclination of the plan of the orbit relative to the equatorial plane of the earth will cause transmission delay variations within a period of 24 hours. For example, an orbital inclination of 0.5° can cause round trip variations in transmission delay of up to 0.74 ms in a 24 hour period as seen by one earth station;
- east-west drifts in the longitudinal position of the satellite will cause slow variations in transmission delay. For example, a drift of $\pm 0.5^\circ$ in longitude about the nominal position of the satellite can cause round trip variations in transmission delay of up to 0.74 ms, typically over a period of months.

The perturbations noted above would normally be the primary causes of variation in transmission delay. Other perturbations may also be present with associated variations in transmission delay of lesser orders of magnitude.

2.4 Variation in transmission delay due to diversity operation

The signals from the two stations of a diversity pair will have a different time base at the switching point. If the diversity paired stations can be located within $\pm 30^\circ$ azimuth of the satellite and for satellite elevation angles of less than 15° , this time difference can be held to 20 μ s, or less, for spacings of 20 km. Satellite motion will cause this delay to vary by $\pm 0.5 \mu$ s around its nominal value. Other situations requiring greater spacings, azimuths and elevation angle will produce greater differential delay.

FM systems can probably tolerate this delay without correction if only 4 kHz channels or programme material is carried. If medium or high speed data is present in the baseband, a time correction will probably be needed on one of the signal paths so as to align the time bases.

Television transmission requires more stringent synchronization accuracy and this should be given consideration.

3. Telephony

3.1 Transmission delay and echo

Several series of subjective tests have been carried out by members of the CCITT, on the tolerance of telephone subscribers to the combined effects of long delays and the echo effects obtained with modern echo suppressors. Based on these results, a revised Recommendation G.114, on limits for mean one-way propagation time, was adopted at the CCITT IVth Plenary Assembly, Mar del Plata, 1968.

The pertinent Section of CCITT Recommendation G.114 in *Orange Book*, Vol. III-1, Geneva, 1976, is:

“RECOMMENDATION G.114 (P.14) — Mean one-way propagation time

A. LIMITS FOR A CONNECTION

It is necessary in an international telephone connection to limit the propagation time between two subscribers. As the propagation time is increased, subscriber difficulties increase, and the rate of increase of difficulty rises. Relevant evidence is given in the bibliography below, particularly with reference to paragraph (b).

The CCITT therefore *recommends* the following limitations on mean one-way propagation times when echo sources exist and appropriate echo suppressors are used:

(a) 0 to 150 ms, acceptable.

Note. — Old-type echo suppressors may be used; they should be modified for delays above 50 ms.

(b) 150 to 400 ms, acceptable, provided that increasing care is exercised on connections as the mean one-way propagation time exceeds about 300 ms, and provided that echo suppressors designed for long delay circuits are used;

(c) above 400 ms, unacceptable. Connections with these delays should not be used except under the most exceptional circumstances.

Until such time as additional, significant information permits Administrations to make a firmer determination of acceptable delay limits, they should take full account of the Documents referred to in the bibliography in selecting, from alternatives, plans involving delays in the range (b) above.

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Pending further consideration of these limits, the use of systems in the Fixed Satellite Service for telephony is restricted with respect to the number of links that can be operated in tandem. As was apparent from Table II and its associated discussion, not more than one hop via geostationary satellites should be included in one connection. In a system of non-geostationary satellites, the permissible number of links in tandem will depend upon the maximum acceptable delay and the particular orbit characteristics. It is very desirable that the overall transmission delay be held within recommended limits by a suitable combination of satellite and terrestrial links for telephone calls which otherwise would be subject to excessive overall effects of delay and echo, even when used with the echo suppressors giving the best known performance on long-delay circuits.

An approximate assessment has been made of the proportions of telephone traffic which could be accommodated by one-hop, two-hop and three-hop connections, using present knowledge. The results are shown in Table V.

TABLE V

Number of hops	Non-geostationary satellite (altitude 11 000 km)		Non-geostationary satellite (altitude 14 000 km)		Geostationary satellite (altitude 36 000 km)	
	Mean one-way delay (ms)	% total traffic	Mean one-way delay (ms)	% total traffic	Mean one-way delay (ms)	% total traffic
1	122	80	140	80	290	88
2	214	18	250	18	(550)	(12)
3	306	2	360	2		

With geostationary satellites, telephone traffic to points beyond the one-hop coverage area should preferably make use of terrestrial extensions.

3.2 *Echo and echo-suppressors*

New echo-suppressors are available which are designed specifically for the delays associated with geostationary satellite systems. With respect to terrestrial extensions of satellite circuits, the CCITT has stated that the delay on each national chain of extension circuits, equipped with echo-suppressors, beyond the last echo-suppressor in a connection, is an important parameter to be taken into account in the design of echo-suppressors. Tests have indicated that mean one-way end-delays of up to 10 ms can be added with no statistically significant increase in degradation using present designs of echo suppressor intended for satellite-links with long propagation time.

As reported in CCITT Study Group XVI Contribution No. 37 (1964-68), tests have been made by the Telephone Association of Canada, the United Kingdom and the A.T. & T. Co., in which two circuits were connected in tandem, each circuit having a separate pair of echo-suppressors. In each test, values of mean one-way delay for one circuit were taken up to that of a geostationary satellite and these circuits were equipped with echo-suppressors designed for such conditions. The second circuit had modest values of mean one-way delay (up to 30 ms) and was, in each case, equipped with an echo-suppressor intended for such lower delays. Under these conditions there was no statistically significant increase in degradation over that due to the long-delay circuit alone.

Information on three or more interconnected circuits with separate echo-suppressors has not so far been contributed.

3.3 *Transmission delay contrast*

Due to the somewhat longer transmission delay which will be experienced on circuits employing satellite links, a contrast between international telephone calls may be experienced, due to the different facilities employed.

Results submitted to the CCITT by the United Kingdom and the A.T. & T. Co., concerning the use of transatlantic cable and satellite circuits, show no statistically significant effects of this sort over the range of exposure obtained in a four-month period.

4. **Telegraphy and data transmission**

When one-way transmission only is involved, delay would not be important. However, the loop delay is significant when automatic repeat request error correction is applied. Although the circuits provided by systems in the fixed satellite service are unlikely to introduce significant errors in data and telegraph transmission, the earth stations may be linked to more distant terminals by other communication systems, such as HF radio, which are susceptible to errors. It may therefore be advantageous to apply error-correction to the whole circuit, including the satellite link. The loop-delay time is then of importance, since it affects the transfer efficiency and the amount of storage required.

The amount of transmission delay, which may be encountered on such composite circuits, is indicated in §§ 2.1 and 2.2. The most common system of telegraph error-correction (ARQ) now in use should, when using an 8-character repetition cycle, be able to accommodate loop delays of up to 850 ms. Extended storage would be required in a two-hop geostationary satellite system and may be required in a three-hop non-geostationary satellite system.

If the automatic repeat request error correction systems (ARQ) applied are particularly sensitive to the long transmission delay involved in satellite links, the transfer efficiency may be severely impaired. The error-correction system applied in data transmission by satellite should therefore be selected with care.

For data systems, which use automatic repetition of incorrectly received code blocks, the storage capacity of the terminal equipment must clearly be made sufficient to accommodate all delays including propagation delay and switching delay.

Switched telegraph operation may be confronted with some difficulties as far as long-distance automatic selection is concerned; this is a matter which the CCITT should take into consideration.

The smooth variation of delay, arising from the variation of path length, is unlikely to present any difficulty on the transmission of either telegraphy or data.

5. **Phototelegraphy**

The absolute value of transmission delay is of no importance, but the smooth variation will produce a "skew" on the received picture, to an extent depending on the amount by which the delay varies during the time taken to transmit the complete picture, which is of the order of 15 min for equipment conforming to CCITT Recommendations and working at 60 r.p.m. In an operational system in the fixed satellite service, the delay variation over a 15 min period is unlikely to exceed 10 ms, and this would result in a peripheral displacement of the final scanning line from its true position, by about 1% of the picture width. This amount of skew distortion would be acceptable in practice. It should be noted, however, that skew distortion can also arise from difference in drum speed between transmitting and receiving terminal equipment. The CCITT recommends that the terminal equipment should be equalized to within a tolerance of 10^{-5} , which is equivalent to a change of delay of 10 ms over a 15 min period. In the most unfavourable circumstances, the delay variation of the satellite system could increase the effect of this speed difference and increase the total skew to about 3% of the picture width. However, such an unfavourable combination of errors would be unlikely to occur frequently. The foregoing refers to equipment conforming to CCITT Recommendations, but is equally applicable to other types of equipment which provide similar definition standards, despite differences in transmission rate.

For colour pictures, transmitted by the colour-separation process, delay variations may prevent accurate registration.

6. **Television**

The transmission delays summarized in § 2 will in no way limit the transmission of television signals, provided that the accompanying sound signals are subject to the same order of delay.

Only a small overall time difference between sound and vision signals can normally be tolerated before the sound becomes noticeably out of synchronization with the picture. It is therefore, desirable that in a system in the fixed satellite service, facilities should be provided to enable the vision and accompanying sound signals to be transmitted together over the system.

7. **Summary**

Overall transmission delay need not be of concern for services utilizing one-way systems, e.g. television, monochrome phototelegraphy, and those telegraph and data systems not requiring error correction. Telegraph and data systems with automatic error-correction may require adaptation to cope with the transmission delays of communication by satellites, which will ordinarily be greater than those encountered on other transmission media.

For television with an accompanying sound channel which is the usual case, precautions will be required to ensure that their relative transmission delays are within acceptable values. Transmission of the vision signal and sound signal over the same satellite system is desirable.

Transmission delay takes on added significance in telephony. The results of recent tests, considered by the CCITT, Mar del Plata, 1968, and incorporated into Recommendation G.114, indicate that international connections probably will not cause adverse subscriber reaction due to the combined effects of delay- and echo-suppressors, if the mean one-way transmission delay is increased from near zero to the order of 150 ms. As the delay is increased, subscriber difficulties increase, and the rate of increase of difficulty rises also. It should be noted that the satisfactory operation of practical telephony circuits having loop-delays in excess of 300 ms (150 ms one way), is conditional upon the use of echo suppressors designed for long propagation time circuits; such echo-suppressors are dealt with in Recommendation G.161 of the CCITT (see CCITT *Orange Book*, Vol. III-1, Geneva, 1976).

REFERENCE

CCIR Documents
[1963-66]: IV/226 (Canada).

REPORT 451-2

FACTORS AFFECTING THE SYSTEM DESIGN AND THE SELECTION OF FREQUENCIES FOR INTER-SATELLITE LINKS OF THE FIXED SATELLITE SERVICE

(Question 2-3/4)

(1970 - 1974 - 1978)

1. General

The use of radiocommunication links between space stations in the Fixed Satellite Service is a means of interconnecting space networks. It is an alternative to employing multiple earth station antenna systems or multiple-hop circuits. Several experiments using this technique have been successfully conducted.

In recognition of the potential usefulness of inter-satellite links, the 1971 WARC-ST defined the Inter-Satellite Service and allocated to this service frequencies above 54 GHz in the atmospheric absorption bands. It may also be advantageous to operate inter-satellite links at lower frequencies.

This Report considers, in broad terms, some of the concepts involved in the development of inter-satellite links and the technical requirements of inter-satellite link operation.

Although the use of laser beams between spacecraft may be possible, their extremely narrow beamwidths and other limitations tend thus far to favour the use of millimetre wave or other radio links, and only the frequency range of 3 GHz to 300 GHz is considered in this Report.

2. Advantages and disadvantages of inter-satellite links

There are at least four broad benefits provided by inter-satellite connections, viz:

- a reduction in the number of earth stations and/or associated antennae needed;
- better circuit utilization of available capacity on paths between Earth and space may be obtained;
- the provision of extensive (global) connectivity for earth stations accessing satellites through spot beams;
- increased flexibility of network arrangements.

In order to illustrate these points consider the extreme hypothetical example of a system containing, for every earth station, a satellite fully dedicated to connecting with only one earth station (a "tethered" satellite). Circuit connections between earth stations in the system would be made through inter-satellite communication links in the orbital arc. In effect each satellite would be a very long extension of its associated earth station.

In this extreme example of tethered satellites, any inefficiencies in actual capacity utilization of available power and bandwidth due to:

- circuit grouping,
- connection constraints,
- switching,
- multiplex, etc.,

are removed from the earth-space links to the geostationary arc. Within the geostationary arc and removed from the terrestrial links, the greatly increased available spectrum at submillimetre or optical wavelengths would be more tolerant of inefficiencies in utilization generated by real system circuit connection constraints.

Furthermore, since there would be only one earth station for each satellite, the satellite antenna coverage requirement would be minimized. Conceptually, this allows using a very narrow beam earth oriented satellite antenna providing good off-axis rejection of received up-link interference signals from other earth stations, and minimizes generation of down-link interference to other earth stations. With a reduced level of interference flux density generated by low antenna sidelobes, closer inter-satellite spacings could be allowed. Also, with only one bothway connection to an earth station, additional capacity increases beyond that provided by narrow antenna beams would be obtained from the single carrier per transponder mode of operation (i.e., reduced intermodulation and little or no transponder back-off).

Such a system conceptually would allow maximization of the space to earth spectrum efficiency. With the greater spectrum availability at the higher frequencies for the inter-satellite links, it is reasonable to expect that orbital capacity would still be dominated by the capacity achieved on the earth space links even in their most advantageous configuration. Consequently, the idealized model described, would appear to offer an upper limit to achievable geostationary orbital capacity. Less advanced systems using inter-satellite links to connect satellites, each of which serves several earth stations, would give the benefits listed above to a lesser degree.

However when inter-satellite links are employed for transmission between satellites with wide angular separation, (e.g. 80° to 120°), the resulting overall earth-station to earth-station transmission delay would exceed the maximum value specified in CCITT Recommendation G.114.

In the near term, with the object of economically augmenting existing capacity with minimum impact on existing systems, consideration must be given to more limited concepts of inter-satellite link facilities. Typically, such links might provide only limited inter-satellite circuit capacity. Then near-term systems would probably have the following characteristics:

- relatively short inter-satellite spacing,
- limited capacity,
- few systems in service,
- minimum impact on existing spacecraft technology: structure, pointing/orientation, and RF components.

3. Inter-satellite link design considerations

The elements which must be taken into account in the design of an inter-satellite link are the following:

- geocentric satellite spacing ϕ (degrees);
- frequency f (MHz);
- antenna diameter D (metres) of equivalent circular aperture of about 55% efficiency;
- receiving system noise temperature T (K);
- available RF power p (watts);
- required bandwidth b (Hz).

Based on these parameters, the performance of an inter-satellite link may be expressed in terms of its predetection carrier/noise ratio which can be approximated by the equation:

$$C/N = 3.72 \frac{pD^4 f^2}{\phi^2 kTb} 10^{-18} \quad (1)$$

where $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant. This equation holds for small orbital separations. For $\phi > 10^\circ$, the term ϕ^2 should be replaced by the term $1.31 \times 10^4 \times \sin^2(\phi/2)$.

In equation (1), the receiving system noise temperature is a function of frequency. Noise temperatures of about 1000 K are typical for frequencies around 6 GHz, and the following frequency dependence is postulated:

$$T(f) \approx 31.6 (f/6)^{1/2} \quad \text{K} \quad (2)$$

In a real system design the parameters C/N and ϕ are usually system constraints; the former determined by the required system performance, the latter by inter-satellite interference considerations. It is of interest to establish the relationship between power requirements and antenna size in inter-satellite links.

Fig. 1 shows relative available power per unit bandwidth (p/b) as a function of frequency with antenna diameter as a parameter, in dB against an arbitrary reference and for fixed values of ϕ and C/N . Also shown in Fig. 1 are the beamwidths of inter-satellite link antennae for the various combinations of D and f . Increasing the antenna diameter on inter-satellite links reduces power requirements in an inverse 4th power relationship. As antenna size increases, beamwidth decreases and mutual pointing requirements between the two satellites become increasingly more stringent.

For example, with 20 watts of available power, at a satellite spacing of 3 degrees, a 100 MHz wide inter-satellite link at 54 GHz with a postulated carrier/noise ratio of 30 dB would require antennae of 0.68 metre diameter. The beamwidth of such antennae is about 0.56°, and pointing accuracies of about 1/10 of that, or about 0.06°, would be required to utilize the full antenna gain. The carrier/noise ratio of 30 dB has been assumed on the basis that the inter-satellite link noise should not significantly affect total performance.

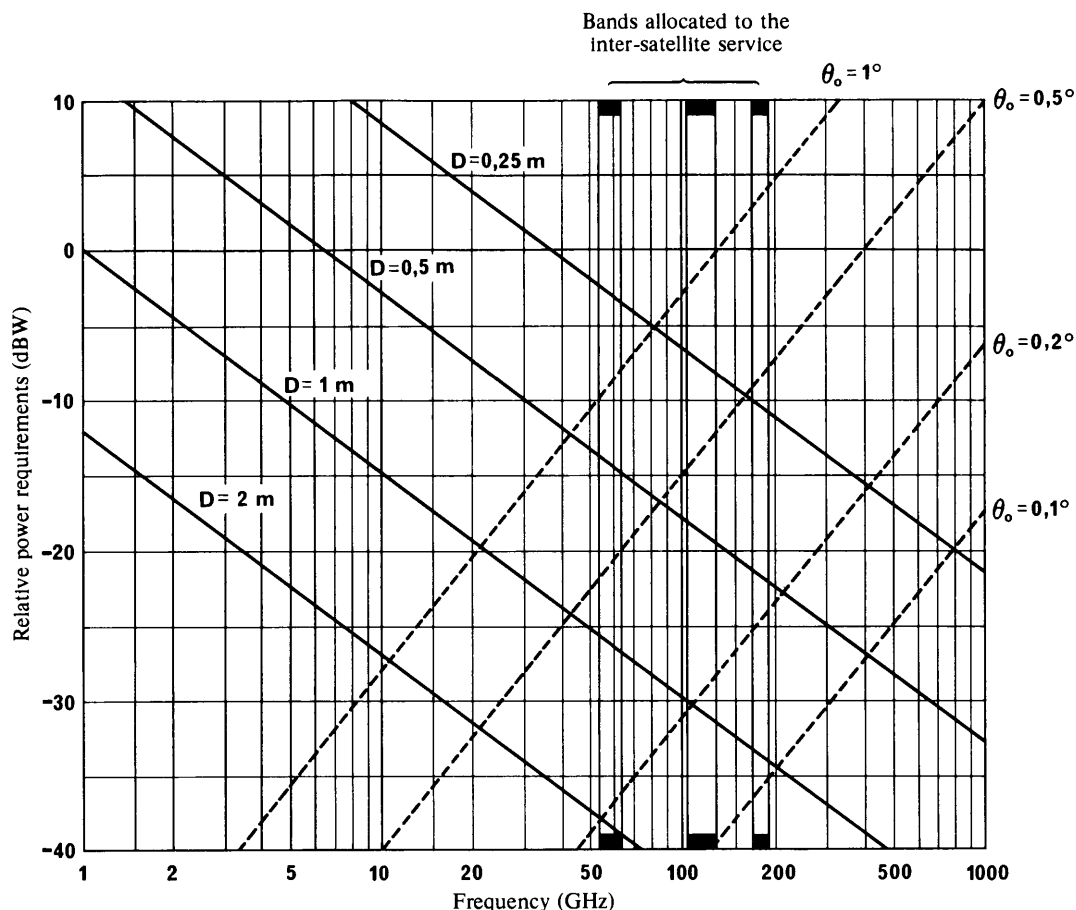


FIGURE 1 — Relative power per unit bandwidth required for an inter-satellite link as a function of frequency for various antenna diameters: no pointing or tracking losses

D : Antenna Diameter
 θ_0 : Half-Power Beamwidth

Hence, the use of reasonably sized antennae to minimize power at 54 GHz or beyond is likely to require mutual tracking between satellites with the present state of the art in spacecraft attitude stabilization and orbital element matching. Tracking and beam steering technology is well developed up to optical frequencies.

Nevertheless, to minimize spacecraft complexity and improve reliability it is attractive to consider, e.g., for INTELSAT applications, inter-satellite links which can be maintained without mutual tracking.

4. Non-tracking inter-satellite links

When considering inter-satellite links the antennae of which do not track each other, two additional system constraints need to be taken into consideration:

- allowable signal level variation on the intersatellite link, ΔC (dB);
- antenna pointing error due to relative attitude tolerances of the spacecraft, δ (degrees).

Typical in-plane and plane-normal pointing error budgets for nominally geostationary spacecraft are derived in Annex I. Within the state of the art net error angles between 0.5° and 1° can be realized.

The main lobe gain degradation due to pointing offset, $g(\theta)/g_0$, for a simple feed antenna may be approximated by:

$$g(\theta)/g_0 \approx 10^{-1.2 (\theta/\theta_0)^2} \quad (3)$$

where θ is the angle off boresight (in degrees) and θ_0 the half-power beamwidth (in degrees) which, in turn, is related to the aperture diameter D by:

$$\theta_0 = \frac{2.14}{fD} \cdot 10^4 \quad \text{degrees} \quad (4)$$

where,

f = MHz
 D = metres.

Considering that the pointing uncertainty involves a boresight error of $\theta = \delta$ and that two antennae are involved, each of which may go through gain variations between g_0 and $g(\theta)$, one may combine equations (3) and (4) to obtain:

$$20 \log (g/g_0) = \Delta C \approx 5.24 (\delta f D)^2 10^{-8} \quad \text{dB} \quad (5)$$

Combining equations (1) and (2), solving the new expression for minimum required power spectral density p/b , and inserting equation(5) as an additional attenuation due to pointing errors, one obtains, in dB notation:

$$10 \log (p/b) = P_0 = C/N + 20 \log \phi - 15 \log f - 40 \log D + 5.24 (\delta f D)^2 10^{-8} - 43.2 \quad \text{dB(W/Hz)} \quad (6)$$

Plots of P_0 versus f for $\delta = 0.5^\circ$ and $\delta = 1^\circ$ and antenna diameters of 0.25, 0.5, 1 and 2 metres (Fig. 2) show that minimum power requirements may be realized at frequencies below 54 GHz, the lowest frequency presently allocated to the inter-satellite service. Fig. 2 uses an arbitrary reference for P_0 and considers C/N and ϕ to be system constants. How close to the optimum (i.e., minimum P_0) frequency an inter-satellite link can be operated depends on the signal level tolerance ΔC one is willing to accept. Limits for $\Delta C = 1$ dB and 2 dB are shown in Fig. 2. The effective optimum frequency is that at which the P_0 and ΔC curves intersect. Absolute minimum power requirements are realized for ΔC of about 3.4 dB; hence, there is no advantage to be gained by allowing a greater level variation than about 3 dB.

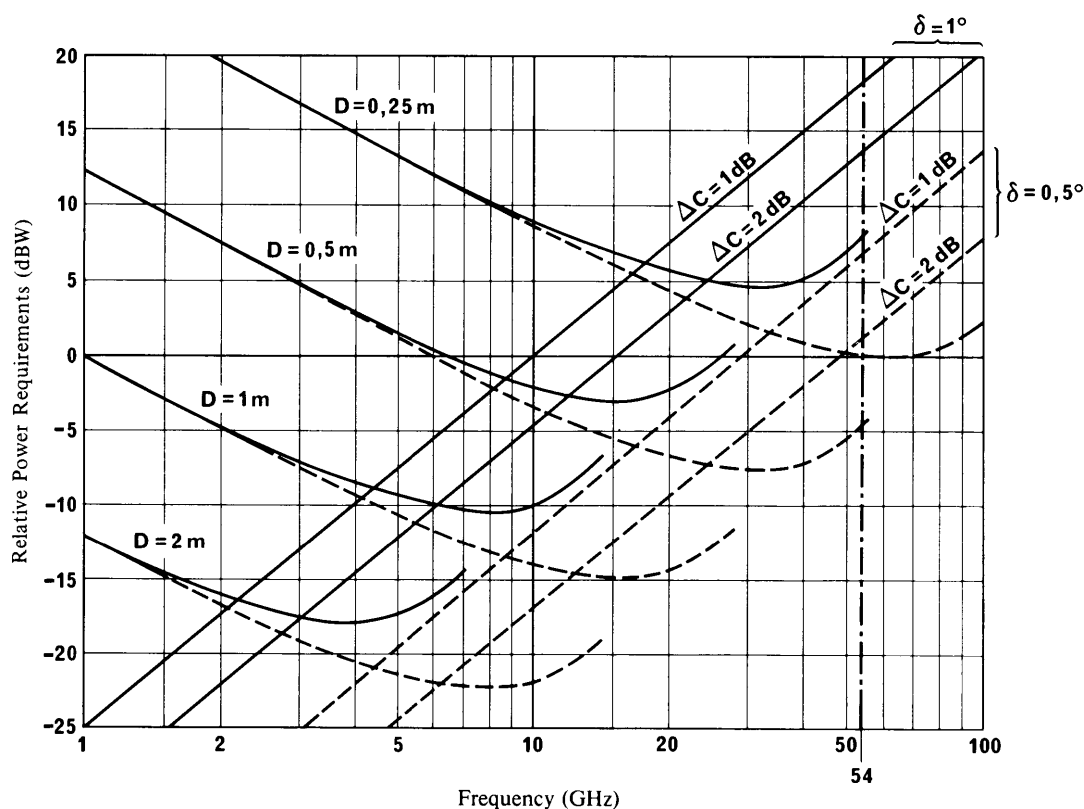


FIGURE 2 — Relative power requirements in a non-tracking inter-satellite link as a function of frequency with antenna diameter (D), net pointing error (δ) and allowable level variation (ΔC) as parameters

— $\delta = 1^\circ$
 - - - $\delta = 0.5^\circ$

These considerations indicate that for antenna sizes greater than 0.25 metres the optimum frequencies for non-tracking inter-satellite links between closely spaced satellites may lie below 54 GHz, the larger antenna sizes favouring the lower frequencies.

5. Choice of frequencies for inter-satellite links

Two distinct categories of use can be envisaged for inter-satellite links operating between geostationary communication satellites:

- (a) Links between satellites separated quite widely in the geostationary satellite orbit (e.g. 60°) to extend the geographical coverage of a system without relaying at an earth station.
- (b) Links between satellites relatively close together (e.g. 3° to 5° orbit spacing) and having virtually the same coverage area, but serving different communities of earth stations.

The optimum technical parameters for these two types of link, which would normally be quite different, are considered below.

5.1 Long inter-satellite links

In category (a) links, a high path loss will exist between the satellites, comparable with the path loss from a geostationary satellite to the Earth, and to keep the link transmitter power to a practicable value it would be necessary to use high gain transmitting and receiving antennae. For a maximum antenna diameter of, say, 1.2 m governed by satellite launch vehicle shroud dimensions, this high gain would call for operation at as high a frequency as possible, typically in excess of 20 GHz, and preferably in the inter-satellite band already allocated at 54.25 to 58.2 GHz. If station-keeping errors and orbital inclination are kept to small, but currently achievable values, variations in the direction from one satellite to the other will be quite small at the wide separation distances involved in these systems, allowing the use of narrow beam antennae even in the absence of antenna tracking facilities.

5.2 Short inter-satellite links

For the short-hop type of link described in category (b) the relative proximity of the satellites results in large angular variations in the link path for quite small values of orbital inclination. For example, the maximum angular variation in a link between satellites spaced 4° apart and each having orbit inclination tolerances of $\pm 0.1^\circ$ will be:

$$2 \arctan \frac{0.2}{4} = 5.7^\circ$$

This assumes a “worst-case” situation where the latitudinal excursions of the two satellites are in complete antiphase. This condition would normally be avoided by suitable choice of orbital parameters and, as shown in Annex I, it should be possible to reduce the angular variation to $\pm 1^\circ$. If antenna tracking were available, high gain antennae could be used for short-hop intersatellite links. However, antenna tracking would involve rather sophisticated satellite devices, probably not currently achievable in a reliable, low-mass form. It is therefore necessary to use antennae with beamwidths equal, in the example quoted above, to 2.0° plus an allowance of perhaps 0.15° for satellite attitude errors.

These results and Fig. 2, indicate that non-tracking antennae one metre in diameter would be best served by frequencies of the order of 10 GHz. If the angular variation could be reduced to a fraction of one degree by an antenna tracking system, the optimum would be raised to somewhere in the region of 20 to 30 GHz. The tracking problem could be relieved to some degree by the use of smaller antennae, but the transmitter power requirement would be substantially increased.

Because of interference considerations it would not be possible to use fixed-satellite space-to-Earth or Earth-to-space bands for space-to-space links. However since link transmission paths will be directed well away from the Earth, there may be no problem in sharing with terrestrial services, and this point is examined in Report 387-3.

5.3 Device technology

Today the 11/14 and 20/30 GHz technology is well-developed for space stations. It would be very desirable for this space-proved hardware or similar equipment to be made usable for inter-satellite links. Frequencies above 50 GHz may be too high for early implementation.

5.4 Interference and co-ordination problems

The following substantial problems have been identified:

- The inter-satellite service will need full duplex capability. Pairs of bands of equal width separated by a gap in frequency, will therefore be necessary.
- The inter-satellite bands should be separated in frequency from the up and the down path bands. It is advisable to have gaps between any two of these bands to minimize the interference problems. An inter-satellite frequency is used on one satellite for transmission and on another for reception. With up or down path frequencies very close to an inter-satellite frequency it would be possible to get very large level differences between a transmitter and a receiver adjacent in frequency. This leads to very severe isolation requirements onboard the satellite, so severe, in fact, that it would be necessary to leave part of the bands unused to create a gap between the transmitting and the receiving frequencies.

- In general the inter-satellite frequency bands should not be shared with other bands used by satellites. However, they can be shared with bands used for some terrestrial services. See Report 791.
- The beams of all inter-satellite links would be aimed in the plane of the geostationary satellite orbit and the angular separation between the beams of inter-satellite links belonging to different systems may be no greater than the angular spacing between adjacent satellites. In order to achieve frequency reuse of the spectrum allocated for inter-satellite links it will be necessary to design for very narrow beamwidths, low sidelobe levels and highly accurate antenna pointing capability in respect of inter-satellite link applications. It is also clear that there is a need to devise techniques and criteria for the co-ordination of frequencies assigned to inter-satellite links.

6. Conclusion

From the preceding discussion, it is reasonable to expect increasing interest in inter-satellite links. Some of the major technical issues identified as requiring further study are:

- design and specification of inter-satellite link transmission parameters, technology and design;
- inter-orbital trunking arrangements and switching concepts/technology;
- impact on spacecraft mechanical design requirements.

A possible demand can be foreseen for “short-hop” inter-satellite links to provide interconnection facilities between communication-satellite networks, and the optimum frequency of operation is found to be substantially below the lowest frequency allocated for the inter-satellite service, and preferably between 15 and 35 GHz.

ANNEX I

GEOMETRY AND POINTING ERRORS FOR NON-TRACKING ANTENNAE IN AN INTER-SATELLITE LINK

The inter-satellite link antennae on each space station are assumed to be fixed to a de-spun platform and are initially aligned so that each space station is in the centre of the other space station antenna's beam pattern under nominal synchronous orbit conditions. The pointing errors caused by deviations from nominal conditions are separated into their in-plane and out-of-plane components in Tables I and II. The total error is the root of the sum of squares (RSS) of the two component classes and affects each satellite independently.

The angular pointing errors contributed by orbital motion are a function of the nominal longitude separation between satellites. The in-plane position error comprises an in-track error, caused by departures from nominal longitude separation, and a cross-track error caused by one or both satellites not being at their nominal altitude. The out-of-plane error arises from motion not taking place in the same plane. These errors are assumed to exist due to tolerances allowed in the orbital elements and not from statistical uncertainty in the individual satellite positions.

The in-track position error makes a relatively small contribution to the angular pointing error since it is equal to half the allowable error in satellite separation. A tolerance of $\pm 0.1^\circ$ in the satellite separation can be maintained at a small additional expenditure of propellant beyond that required for normal east-west station-keeping, if great care is taken. The tolerance is also large enough to allow flexible scheduling of individual manoeuvres.

The cross-track error arises because neither satellite can be maintained in a perfectly circular orbit without daily velocity corrections. Thus the altitude of each satellite will undergo a 24-hour variation about a mean value. The mean altitude of each satellite will be nearly the same as a consequence of the east-west motion being nearly in phase, but the individual variations will, in general, have different amplitudes and phase.

The capability exists to control the amplitudes of the individual altitude variations, or alternatively, to control their phase, such that the cross-track position error never exceeds several kilometres. To do so, however, would require additional velocity corrections in the presence of in-plane velocity coupling from north-south manoeuvres, and would require close co-ordination of the normal east-west manoeuvres performed on the two satellites. Without introducing these additional complexities, it is estimated that the position error can be maintained within 12 km.

The out-of-plane pointing error arises if the two satellites do not move in exactly the same plane. It is estimated that the position error can be maintained within 8 km, which corresponds to an angle of approximately 0.01° between the individual orbit planes. This error reflects the expected uncertainty in the velocity corrections obtained during the individual north-south station-keeping manoeuvres performed on each satellite.

Each north-south station-keeping manoeuvre will alter the inertial orientation of each orbit plane by 0.2° . In order to keep the relative orientation nearly the same, the individual manoeuvres must be closely co-ordinated. For a longitude separation of 3° between satellites, the manoeuvres must be performed within 12 minutes of each other (equal to 4 minutes for each degree of longitude separation).

Pointing error

The various elements in the pointing error budget have been reduced to a single effective value by the following rule:

- All in-plane, long-term contributions are summed algebraically to give a single value. Likewise all cross-plane, long-term contributions.
- The in-plane and cross-plane long-term errors are added on an RSS basis to give a single long-term error value. Since the two contributors are equal and assumed to be uncorrelated, the long-term RSS error is circular.
- The in-plane, short-term contributions are summed algebraically. Likewise the cross-plane, short-term contributions.
- The in-plane and cross-plane contributions and the RSS long-term error are summed on an RSS basis to give the total pointing error.
- Since each term of the total sum is individually a low probability, nominally 3σ , value, the total pointing error is likewise a low probability, nominally 3σ , value.

When the above rule is applied to the error budgets given above, the total error at various satellite-to-satellite spacings is found to be as given in Table III. These are the pointing errors that have been used to estimate transmission performance of the link.

TABLE I — *In-plane pointing errors*

Error source	Error magnitude
1. <i>Long-term variation</i>	
Antenna thermal distortion	$\pm 0.02^\circ$
In-track position error	$\pm 0.05^\circ$
Cross-track position error :	
Nominal longitude separation :	
2°	$\pm 0.47^\circ$
3°	$\pm 0.31^\circ$
4°	$\pm 0.23^\circ$
5°	$\pm 0.19^\circ$
2. <i>Bias</i>	$\pm 0.20^\circ$
3. <i>Short-term variation</i>	
Despun platform pointing	$\pm 0.25^\circ$

TABLE II — *Out-of-plane pointing errors*

Error source	Error magnitude
1. <i>Long-term variation</i>	
Antenna thermal distortion	$\pm 0.04^\circ$
Attitude uncertainty	$\pm 0.01^\circ$
Attitude precession with respect to orbit normal	$\leq 0.10^\circ$
Out-of-plane position error :	
Nominal longitude separation :	
2°	$\pm 0.31^\circ$
3°	$\pm 0.21^\circ$
4°	$\pm 0.15^\circ$
5°	$\pm 0.12^\circ$
2. <i>Bias</i>	
Mechanical alignment	$\pm 0.20^\circ$
3. <i>Short-term variation</i>	
Spin wobble and nutation	$\pm 0.06^\circ$

TABLE III — *Pointing error versus satellite spacing*

Spacing	Effective pointing error
2°	1.01°
3°	0.833°
4°	0.739°
5°	0.693°

The total effective error is assumed to be circular, although this is not precisely true. The computational convenience of making the assumption outweighs the small error involved.

REPORT 552-1

USE OF FREQUENCY BANDS ABOVE 10 GHz IN THE FIXED SATELLITE SERVICE

(Study Programme 2H-2/4)

(1974 - 1978)

1. Introduction

This Report makes a preliminary examination of some of the technical factors which should be considered in the design of systems of the Fixed Satellite Service which are intended for use in frequency bands above about 10 GHz. Since the allocated bandwidth is generally wider at frequencies above about 10 GHz, the use of these frequencies would facilitate the design of high-capacity systems. The use of the 20/30 GHz bands, where 3.5 GHz of bandwidth is available, would facilitate the design of very high capacity systems employing spot beam antennae.

The factors considered in this Report are:

- earth station arrangements to avoid the effects of precipitation,
- frequency sharing with terrestrial systems,
- a system design method.

2. Earth station arrangements

Scatter and absorption by cloud and precipitation increase rapidly at frequencies above about 10 GHz, and this adds considerably to the problems of designing such systems. Without the use of special techniques it may be quite impracticable to provide the large rain margins necessary to meet the required standards of performance.

Three possible ways in which the severe effects of precipitation at the higher frequencies can be overcome are:

- (a) the use of site diversity;
- (b) the use of a lower alternative frequency band to that normally used, and which is much less affected by precipitation;
- (c) the use of adaptive systems which alter the transmission parameters during changing propagation conditions.

For earth stations spaced a suitable distance apart (i.e. 10 to 30 km) the correlation of precipitation between them is almost negligible and the probability that both stations will be affected simultaneously by heavy rain is likely to be very small. The technique is to connect the two earth stations providing the diversity, by a transmission line free from the effects of precipitation, and select for operational use the earth station which is least affected.

In the second approach referred to in (b) above, the assumption is that a number of earth stations within a system normally operate at frequencies which can be severely affected by precipitation, i.e. above about 10 GHz. However, since the probability of more than one station at a time being affected is likely to be small, the technique of switching into use a lower frequency band at the earth station badly affected by precipitation, can be employed.

In the third approach, referred to in (c) above, system performance of digital systems may be improved by reducing the information rate transmitted during poor propagation conditions. Possible methods involve reduction of the information transmitted per symbol (e.g. change from 4-phase PSK to 2-phase PSK), slower clock speed or the use of error correcting codes. An example of the latter approach is given in Annex II.

A site diversity system is likely to have a much wider application than one employing switched frequency bands. In the latter case, for example, one complication is the need for equipment capable of operating at two different pairs of frequency bands; nevertheless, the technique should enable a significant reduction to be obtainable in the rain margins necessary to meet the system performance for small percentages of time.

3. Frequency sharing with terrestrial systems

At frequencies above about 10 GHz variations in the level of the wanted and unwanted signals due to precipitation, and the effects of scatter, have a greater influence on the minimum separation distance obtainable between earth stations of the Fixed Satellite Service, and terrestrial stations of the fixed service.

The effect of scatter can be overcome by careful site selection to avoid beam intersection of the two systems, and by using cross-polarization in the case of linearly polarized waves and, since the basic transmission loss over a given path increases with frequency, the separation distance between stations of the two systems can be less at the higher frequencies. By arranging that the separation angle between an earth station and terrestrial stations is more than about 20 to 30 degrees, the minimum separation distance can be reduced to a few kilometres and the effect of the fluctuation of the wanted and unwanted signals caused by differential rain attenuation of the two systems can be avoided to some extent.

4. A design method for systems in the Fixed Satellite Service

For systems in the Fixed Satellite Service which use frequency bands above 10 GHz, the effects of hydrometeors, especially rainfall, are particularly important and must be taken into account when the systems are designed. The most reliable calculation of the effects of hydrometeors may be made on the basis of experimental distributions of attenuation due to hydrometeors against time. This distribution varies with the frequency and the time of the year and depends on climatic conditions at the site of the earth station and the angle at which the satellite is visible. *

It should also be borne in mind that the correlation between attenuations on the paths of the satellite link declines with the distance between earth stations and increased intensiveness of precipitations. A further de-correlating factor is the frequency difference between the up-path and the down-path.

Annexes I and II contain examples of design methods for PCM systems in the fixed satellite service.

Annex III contains an example of a design method for an FM system based on experimental distributions in the absence of correlation between attenuations on the paths.

In selecting methods of transmission of signals in frequency bands above 10 GHz care should be taken to take into account the fact that variations in signal-to-noise ratio caused by hydrometeors may substantially exceed the difference between the working (nominal) and threshold levels. Since this difference depends on the type of modulation used, the comparative characteristics of the transmission modes will vary in the frequency bands above 10 GHz. Annex IV contains a sample comparison between two multi-channel telephony transmission methods; analogue FDM-FM-FDMA and digital PCM-PSK-TDMA. This indicates that unless care is taken in the selection of system parameters, the advantages of a TDMA system operating in this band may not be as great as can be obtained in the presently utilized 6/4 GHz bands. This subject requires further study, taking into account the particular characteristics of each method of multiple access (i.e. TDMA or FDMA), as well as considering specific techniques to offset their individual disadvantages.

The potential introduction into regular service of the 14/11 GHz bands has resulted in detailed studies being carried out to determine the optimum system characteristics required by earth stations operating in these bands. Annex V presents a summary of those characteristics which impact on earth station design in an FDM/FM/FDMA system, and also indicates those considerations to be examined if site diversity is employed. Since the attenuation due to precipitation varies with frequency, as does the free space loss, the cumulative distribution of attenuation against time will depend upon the locality of the earth station. Hence the allowance to be made for attenuation on the up-path and the down-path may be very different, particularly where cross-strapped links between the 14/11 GHz and 6/4 GHz bands are used. The salient characteristics of the diversity inter-connect link are discussed and it is concluded that its noise contribution can be kept small, and its overall performance compatible, with the satellite link, by careful design.

5. Conclusions

At frequencies above about 10 GHz, scatter and absorption caused by cloud and precipitation have much greater significance. Moreover, there may be an appreciable difference between the up-path and down-path frequencies and careful design is needed to ensure that the necessary performance objectives are met in a balanced way.

* See the sections on Radiometeorology and Space Telecommunications of Volume V.

Certain techniques, such as site diversity, the use of an alternative frequency band or the use of adaptive systems, can overcome the problems met due to large attenuation from precipitation for small percentages of time.

The use of frequency bands around 20 and 30 GHz, where 3.5 GHz of bandwidth is available, would make possible the provision of very high capacity regional and domestic systems using spot beam antennae, and should make it possible for the earth stations of such systems to be located very close to traffic centres.

In the design and planning of systems in the fixed satellite service using frequencies above about 10 GHz, there are a number of areas which require further study. These are, for example, the determination of earth station G/T , and the allowance to be made for propagation, including the effect on cross-polarization discrimination.

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ANNEX I

A DESIGN METHOD FOR A PCM SYSTEM IN THE FIXED SATELLITE SERVICE USING FREQUENCY BANDS ABOVE 10 GHz

The carrier-to-noise-power ratios (C/N) of up-path, down-path and overall-path are designated $(C/N)_u$, $(C/N)_d$ and $(C/N)_t$ respectively, and they can be expressed as follows:

$$(C/N)_u = U - L_{RU} \quad (1)$$

$$(C/N)_d = D - L_{RD} \quad (2)$$

$$(C/N)_t = -10 \log \left(10^{-\frac{U-L_{RU}}{10}} + 10^{-\frac{D-L_{RD}}{10}} \right) \quad (3)$$

where,

U : normal up-path carrier-to-noise power ratio, including operation margin for rainfall and given by:

$$U = (\text{e.i.r.p.})_E - L_{U0} + G_{SR} - kT_s B_s \quad \text{dB}$$

D : normal down-path carrier-to-noise power ratio, including operation margin for rainfall and given by:

$$D = (\text{e.i.r.p.})_S - L_{D0} + G_{ER} - kT_e B_e \quad \text{dB}$$

$(\text{e.i.r.p.})_E$: earth station e.i.r.p., given by:

$$(\text{e.i.r.p.})_E = P_{TE} - L_{FE} + G_{ET} \quad \text{dBW}$$

$(\text{e.i.r.p.})_S$: space station e.i.r.p., given by:

$$(\text{e.i.r.p.})_S = P_{TS} - L_{FS} + G_{ST} \quad \text{dBW}$$

L_{RU}, L_{RD} : up- and down-path margin for attenuation due to precipitation (dB);

P_{TE}, P_{TS} : transmitting powers of the earth station and the space station (dBW);

L_{FE}, L_{FS} : losses due to transmitting feeders and branching filters of the earth station and the space station (dB),

G_{ET}, G_{ST} : transmitting antenna gains of earth station and space station (dB);

L_{U0}, L_{D0} : free space transmission losses of up-path and down-path (dB);

G_{ER}, G_{SR} : receiving antenna gains of earth station and space station (dB);

k : Boltzmann's constant, 1.380×10^{-23} J/K;

T_e, T_s : receiving system noise temperatures of the earth station and the space station (K);

B_e, B_s : equivalent receiving noise bandwidths of the earth station and the space station (Hz).

Equation (3) applies the assumption that transponders are of the frequency converting type.

$(C/N)_i$ may be taken to be the sum of $(C/N)_y$ and A . $(C/N)_y$ is the theoretical carrier-to-noise power ratio required for a bit error rate (BER) of 10^{-x} , and A is a fixed allowance; it includes an allowance for intersymbol interference due to band limitation in the transmission path, an allowance for imperfections of equipments and compensation for interference. Therefore, $(C/N)_i$ can be expressed as follows:

$$(C/N)_i = (C/N)_y + A \quad \text{dB} \quad (4)$$

The value for $(C/N)_y$ and A in equation (4) can be derived from the choice of modulation and demodulation method. For example, for two phase differential modulation and coherent phase detection, the theoretical C/N required for a BER of 10^{-6} is 10.5 dB.

The allowances made in this example are as follows:

- intersymbol interference: 1.5 dB,
- frequency interference from terrestrial systems: 0.5 dB,
- equipment imperfections: 2.0 dB,
- interchannel interference: 0.5 dB.

With these allowances, and from equation(4), $(C/N)_i$ becomes 15 dB. Using equation (3), and neglecting attenuation due to precipitation, Curve A of Fig. 1 is plotted to represent the lowest C/N ratio required on the up-path and down-path to meet a BER of 10^{-x} , normalized to 15 dB.

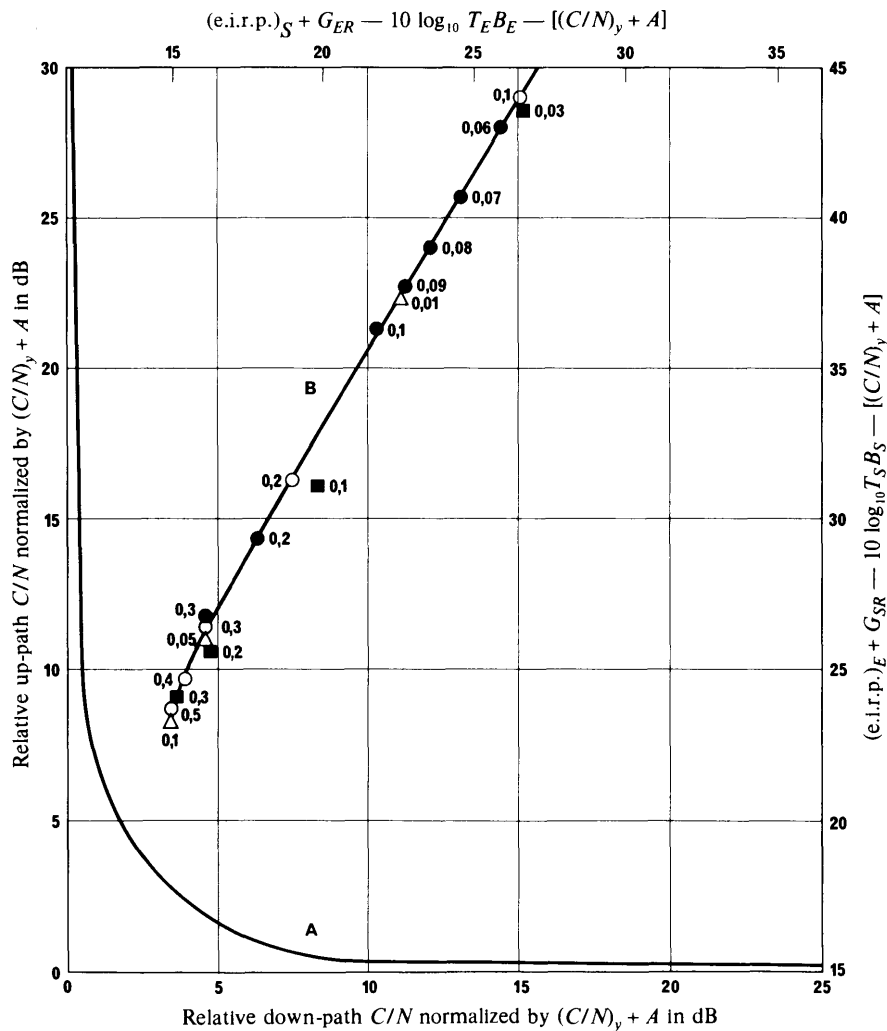


FIGURE 1 — Relation between $(C/N)_u$ and $(C/N)_d$

Rain climate: ○ = 1 ● = 2 ■ = 3, 4 △ = 5

- Curves A: Required C/N for BER of 10^{-6} without considering the effect of precipitation
 B: Required C/N for BER of 10^{-6} when considering the effect of precipitation. (The figures on curve B indicate the time percentage of circuit interruption due to precipitation: % per year)

The effect on Curve A of allowing an up-path margin for precipitation is to move the curve bodily upwards. Similarly, an allowance for down-path margin would be to move the curve bodily to the right. Hence, when the curves have been adjusted in this way the point of intersection indicates the allowance that has been made on each path.

By using the propagation information in Reports 563-1, 564-1 and 720 the appropriate margins for precipitation for defined percentages of time at 20 and 30 GHz can be derived. With this derived information the points indicated along Curve B have been plotted. For example, the lowest point on the Figure (a small triangle) indicates that for rain climate 5 the margin required on the up-path (30 GHz) for 0.1% time is about 7 dB, and on the down-path (20 GHz) about 3 dB. Curve B on Fig. 1 is the best fit line along all the points plotted.

Additionally, for the system parameters defined below, values are set out along the upper abscissa scale of Fig. 1 of:

$$(e.i.r.p.)_S + G_{ER} - 10 \log T_E B_E - [(C/N)_y + A]$$

and along the right-hand ordinate scale of Fig. 1 of:

$$(e.i.r.p.)_E + G_{SR} - 10 \log T_S B_S - [(C/N)_y + A]$$

By using the upper abscissa scale and the right-hand ordinate scale in association with Curve B of Fig. 1, the inter-relation between e.i.r.p. and G/T for selected percentages of time on both the up- and down-paths can be derived.

The system characteristics assumed in this particular example are:

- two-phase differential encoding,
- coherent phase detection,
- signal transmission speed: 100 Mbit/s,
- $BT = 1.0$, where,
 B : radio-frequency bandwidth 3 dB down from the centre frequency (Hz),
 T : pulse width (s),
- BER required: less than 1 in 10^6 ,
- frequency band: 20/30 GHz.

ANNEX II

VARIABLE INFORMATION TRANSMISSION RATE SYSTEM USING ERROR CORRECTING CODES

1. Introduction

System performance of digital satellite communication systems may be improved by reducing the information rate transmitted during poor propagation conditions. Error correcting codes are then employed to maintain the required system performance.

2. Error correction coding scheme

From the viewpoints of simple hardware construction and high speed operation, a system using rate 1/2 self-orthogonal convolutional coding is proposed. During poor propagation conditions, the information bit rate is reduced by 1/2, and a parity check bit is inserted after each information bit. The C/N required for maintaining the same overall bit error rate as that maintained under good propagation conditions is therefore reduced.

For simplicity of hardware construction; rate 1/2 codes with the capability of correcting either single or double errors in each constraint block of the bit stream may be preferable. Implementation of the single-error correcting code will be somewhat simpler than that of the double-error correcting code.

3. Comparison with other variable information rate schemes

Two other variable information transmission rate schemes may be considered.

The adaptive modulation parameter scheme is a technique for PSK systems in which the number of phases transmitted is reduced during poor propagation conditions. The disadvantage of this scheme is that it requires changes in carrier-band equipment configuration, which might lead to hardware complexity and to effective C/N degradation due to residual equipment maladjustment.

The adaptive clock frequency scheme is a technique in which the clock frequency may be reduced, thus allowing a narrow bandwidth to be used in the receiving equipment and therefore improving the required C/N . The disadvantage of this scheme is that filter configuration must be altered, and bit timing adjusted.

Table I shows the theoretical C/N improvement obtainable for each of the systems considered, assuming 4-phase CPSK with 1/2 information bit rate reduction.

TABLE 1 — Theoretical C/N improvement for variable information transmission rate CPSK systems with a reduction rate of $1/2$

Bit error rate	Theoretical C/N improvement in dB			
	Error correction scheme		Adaptive modulation parameter scheme (4 phase/2 phase)	Adaptive clock frequency scheme
	Single error correction capability	Double error correction capability		
10^{-6}	3.0	4.3	3.0	3.0
10^{-4}	2.9	3.9	3.0	3.0

4. Conclusion

An adaptive scheme has been proposed for maintaining the system performance during poor propagation conditions by reducing the information transmission rate and applying error correction coding.

The main advantages of the scheme are:

- hardware implementation is straightforward,
- it can be applied with baseband processing of the signal,
- readjustment of bit timing is not necessary,
- the C/N improvement obtainable is greater than with the other schemes considered.

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ANNEX III

CALCULATION OF THE POWER CHARACTERISTICS OF SATELLITE LINKS IN BANDS ABOVE 10 GHz

In this Annex, the calculation of power characteristics in bands above 10 GHz is based on the example of an FDM-FM-FDMA system.

According to Recommendation 353-3, the psophometrically weighted noise power at a point of zero relative level in any telephone channel should not exceed:

- 10 000 pW0p for more than 20% of any month and,
- 50 000 pW0p for more than 0.3% of any month.

Assuming the use of FM demodulators with improved threshold characteristics, the level of 50 000 pW0p indicated is also taken to correspond to the threshold signal-to-noise level at the demodulator input.

The following two equations may be written on the basis of these standards:

$$\text{— nominal level: } \left(\frac{P_{noise}}{P_{signal}} \right)_{nom} \times \frac{2 \Delta F K_p^2}{m^2 B p W} = 1 \times 10^{-5} \quad (5)$$

$$\text{— threshold level: } \left(\frac{P_{noise}}{P_{signal}} \right)_{threshold} \times \frac{2 \Delta F K_p^2}{m^2 B p W} = 5 \times 10^{-5} \quad (6)$$

where,

$\left(\frac{P_{noise}}{P_{signal}} \right)_{nom}$ noise-to-signal ratio at frequency demodulator input with a nominal level of 10 000 pW0p in the telephone channel;

$\left(\frac{P_{noise}}{P_{signal}} \right)_{threshold}$ noise-to-signal ratio at the frequency demodulator input with a threshold level of 50 000 pW0p in the telephone channel.

ΔF : telephone channel bandwidth, 3.1 kHz;

K_p : relation between multi-channel traffic peak level and peak channel measurement level;

for number of channels $n < 240$,

$$K_p^2 \text{ (dB)} = 4 (\log n - 1) + v \quad (7)$$

v : peak factor of multi-channel traffic, taken as = 10 dB;

m : modulation index;

B : radio frequency bandwidth,

$$B \approx 1.3 \Delta F n (m + 1) \quad (8)$$

p : gain through pre-emphasis;

W : psophometric weighting factor.

A distinction must be drawn between two possible calculation cases.

If the maximum increase in noise in a telephone channel resulting from hydrometeors is known to be less than 50 000 pW0p, as is the case in the frequency bands 6/4 GHz, equation (5) is used in the calculation. Equation (6) is then completed automatically.

However, for the frequency bands above 10 GHz it is the second case which is the most characteristic, and in which the increase in noise in a telephone channel resulting from hydrometeors is known to be greater than 50 000 pW0p (the nominal level being maintained in clear weather conditions). In this case, the calculation must be based on equation (6).

Nominal operation will occur not in clear weather conditions but at a certain level of precipitation.

To obtain the closest approximation to real conditions, it is advisable to base the calculation on the distributions of hydrometeoric attenuations obtained by measurements on satellite links. The present paper uses statistical data obtained at the frequencies 15.3 GHz (down-path) and 30.65 GHz (up-path) [Ippolito, 1971].

In view of the localized character of heavy rainfall, it is assumed that there is no correlation between attenuations by hydrometeors on the up-path and down-path [Kaplunov, 1971].

Hence it follows from a study of these experimental distributions that the up-path and down-path attenuations may be considered to be only weakly correlated. Therefore, Fig. 2 shows the relationship between the maximum losses in hydrometeors on the up-path (L_{m1}) and the down-path (L_{m2}) respectively with a probability $P = 0.3\%$ that the given noise-to-signal level at the satellite link output will be exceeded.

From a study of the power relationships in the satellite link, we may obtain a further relationship between these maximum losses:

$$L_{m2} = 1 + \frac{1}{\left[\left(1 + \frac{T_m}{T_{o.e.} \cdot L_{mol2}} \right) \frac{\left(\frac{P_{noise}}{P_{signal}} \right)_{m.e.}}{\left(\frac{P_{noise}}{P_{signal}} \right)_{r.s.} (L_{m1} - 1)} \right] - 1} \quad (9)$$

where,

T_m : mean atmospheric temperature (K);

$T_{o.e.}$: equivalent noise temperature of earth station receiver in clear weather conditions (K);

L_{mol2} : molecular absorption losses in oxygen and water vapour.

$\left(\frac{P_{noise}}{P_{signal}} \right)_{m.e.}$ maximum noise-to-signal ratio at earth station receiver input

$\left(\frac{P_{noise}}{P_{signal}} \right)_{r.s.}$ noise-to-signal ratio at satellite receiver input in clear weather conditions.

As a convenient example for comparison with existing systems in the frequency bands 6/4 GHz, we have taken the transmission of 750 telephone channels in a repeater band $\Delta f = 36$ MHz on 8 carriers.

Following [Dagleish and Reed, 1969], we have assumed that:

- $p = 2.5$,
- $W = 1.78$,
- noise caused by interference from other sources as well as system amplitude and phase non-linearities (apart from the repeater output stage) amounts to 27% of the total noise in the telephone channel;
- up-path noise amounts to 500 pW.

Substituting these values into (6), we can determine the optimum reduction in satellite transmitter output power, the level of repeater intermodulation noise and the maximum noise-to-signal ratio at the earth station receiver input.

Furthermore, it is assumed that $T_{o.e.} = 540$ K, which corresponds roughly to the earth station receiver designed for the system described by [Ippolito, 1972], taking into account the frequency difference (20 GHz and 15.3 GHz).

By combined solution of the relationships in Fig. 2 and equation (9), we determine the maximum losses L_{m2} .

The noise-to-signal ratio at the earth station receiver input in clear weather conditions may be defined by the formula:

$$\left(\frac{P_{noise}}{P_{signal}} \right)_{o.e.} = \left(\frac{P_{noise}}{P_{signal}} \right)_{m.e.} \frac{T_{o.e.}}{T_{m.e.} L_{m2}} \quad (10)$$

where,

$T_{m.e.}$: maximum equivalent noise temperature of the earth station receiver.

In the example considered, the values obtained had to be corrected to complete (5).

The following result was obtained:

$$(e.i.r.p.)_s \times \frac{G}{T} \approx 80.1 \text{ dB(W/K)}$$

where,

$(e.i.r.p.)_s$: equivalent isotropically radiated power of satellite transmitter

G/T : figure of merit of earth receiving station in clear weather conditions.

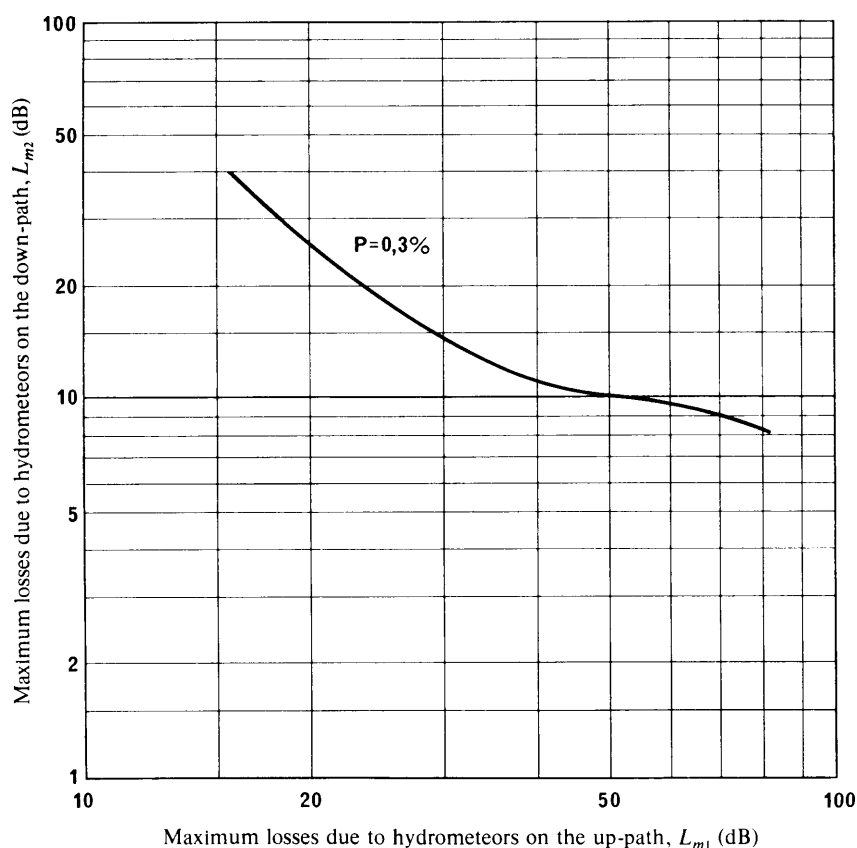


FIGURE 2 — Relationship between the maximum losses due to hydrometeors on the up path and the down path

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ANNEX IV

FACTORS RELATING TO THE CHOICE OF SIGNAL TRANSMISSION METHODS IN BANDS ABOVE 10 GHz

The main criterion in selecting the type of modulation and multiple access to be used, is the system capacity in telephone channels at a given power level on the down-path.

For operation in frequency bands above 10 GHz, variations in signal-to-noise ratio at the satellite link output caused by hydrometeors may substantially exceed the difference between the working and the threshold levels [Kaplunov, 1971]. As is noted in Annex III, the working level (10 000 pW0p with FDM-FM) must be maintained not only in clear weather conditions but also with precipitation of varying intensity. This calls for an additional increase in the link power level or, for a given power level on the down-path; system capacity will be reduced accordingly.

Furthermore, having regard to the fact that the differences between the working and threshold levels of analogue and digital transmission methods may diverge considerably, operation in frequency bands above 10 GHz may be expected to cause a considerable variation in the comparative characteristics of the transmission modes indicated, compared with operation in the frequency bands 6/4 GHz.

A comparison between the possible capacities of FDM-FM-FDMA and PCM-PSK-TDMA systems may be taken as an example.

With FDM-FM transmission, the working and threshold values and the probability that they will be exceeded are covered by Recommendation 353-3. The relationships given in Annex III are used to calculate the FDM-FM-FDMA system.

The technical characteristics of PCM systems are at present under consideration by the appropriate CCITT Study Groups; however, the CCIR has prepared Recommendation 522 for application with those types of systems which have not been taken into account in this Annex.

As noted in Report 708, in PCM-PSK systems, an error rate of 10^{-4} corresponds to a noise power of approximately 50 000 pW0p in the telephone channel.

Nominal operating involves an error rate of 10^{-6} in current PCM-PSK systems. The difference in signal-to-noise levels at the PSK demodulator input for these error rates is approximately 3 dB.

Therefore, by analogy with (5) and (6) for FDM-FM-FDMA in Annex III, for PCM-PSK-TDMA transmission we can write the following equations:

$$\text{— nominal level:} \quad \left(\frac{P_{noise}}{P_{signal}} \right)_{nom} = \frac{\Delta f_{noise}}{R E/N_0} \quad (11)$$

$$\text{— threshold level:} \quad \left(\frac{P_{noise}}{P_{signal}} \right)_{threshold} = 2 \frac{\Delta f_{noise}}{R E/N_0} \quad (12)$$

where the left-hand symbols have the same meanings as those of equations (5) and (6) in Annex III, and

Δf_{noise} : equivalent noise bandwidth of repeater,

R : bit rate, bit/s,

E : energy per bit, Ws,

N_0 : spectral noise power density, W/Hz.

For PCM-PSK-TDMA [Dalglish and Reed, 1969]

- efficiency of use of frame time, 95%,
- power ratio of down-path to up-path thermal noise, 10 : 1,
- threshold E/N_0 (error rate 10^{-4}) for practical two-phase modems = 11 dB,
- occupied bandwidth, $B = 1.25 \times R$,
- losses resulting from interference noise from other sources and system distortions, 0.5 dB,
- bit rate per telephone channel, $R_c = 64$ kbit/s.

For multi-phase PSK the increases in E/N_0 and B are given in Table II.

On the basis of the data given for FDM-FM-FDMA (cf. Annex III) and PCM-PSK-TDMA and applying the relations contained in Annex III, the capacity of a repeater band $\Delta f = 36$ MHz for 8 accesses and of FDM-FM transmission with one access were calculated for various $(e.i.r.p.)_S \times G/T$; $((e.i.r.p.)_S = \text{satellite transmitter e.i.r.p.})$.

TABLE II

No. of PSK phases	$\Delta (E/N_0)$ (dB)	ΔB (dB)
4	0	-3.0
8	+4.0	-4.8
16	+8.8	-6.0

A comparison of the results contained in Fig. 3 with similar results in [Dalglish and Reed, 1969] and Report 708 for the frequency bands 6/4 GHz shows that for the data relating to the example considered, the advantages of PCM-PSK-TDMA over FDM-FM-FDMA may be decreased. Further study should be carried out to identify those parameters necessary to ensure optimum system design for each mode of operation.

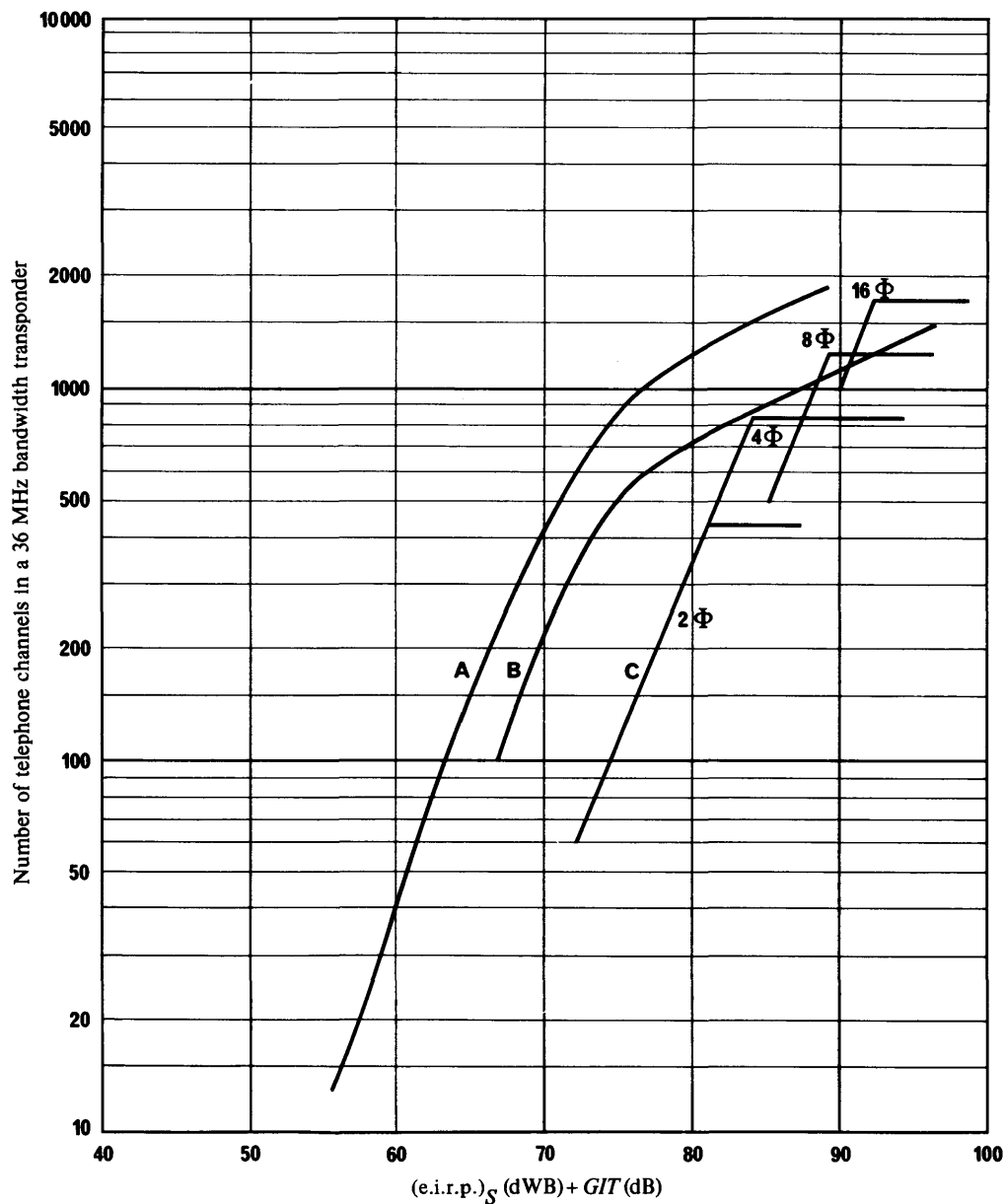


FIGURE 3 — Transponder channel capacities for different modulation schemes

Curves A: FDM-FM Single access
 B: FDM-FM-FDMA 8-carrier
 C: PCM-PSK-TDMA 8-access

REFERENCES

- DALGLEISH, D. J. and REED, A. G. [1969] Some comparisons of the traffic-carrying capacity of communication-satellites using digital techniques with the capacity of satellites using frequency modulation. INTELSAT/IEEE International Conference on Digital Satellite Communication.
- KAPLUNOV, M. B. [1971] Rasprostraneniye millimetrovyykh voln v atmosfere i sputnikovaya svyaz (Atmospheric propagation of EHF radio waves in satellite communications). *Obzornaya informatsiya o zarabeyhnoi tekhnike svyazi* (Review of Foreign Telecommunication Technology), Ministry of Telecommunications of the U.S.S.R., 5, 24 and 25.

ANNEX V

AN EXAMPLE OF EARTH STATION CHARACTERISTICS
FOR OPERATION IN THE 14/11 GHz BAND

1. Introduction

In this Annex some of the basic system characteristics affecting 14/11 GHz earth station design for FDM/FM/FDMA operation are discussed. The possible noise allocations to various segments of the satellite link are examined and their impact on the station design considered. Where site diversity is considered desirable (or necessary) to meet overall system performance the requirements of the interconnect link are discussed.

2. Noise performance

System noise performance requirements are given in CCIR Recommendation 353-3. However, in this Annex a performance requirement of 50 000 pW0p for 0.1% of any month or 0.01% of any year is assumed. This is more severe than the requirement of Recommendation 353-3 and is used for illustration only. It is also important to ensure that FM threshold is exceeded for at least the same period.

Since the propagation attenuation characteristics differ between 14 and 11 GHz from location to location and the effect on C/N is different for up-link compared to down-link, some logical approach should be developed to establish noise time budgets for both sides of a channel. The following summarizes briefly some of the most pertinent aspects of allocating the noise budget between the various link elements.

2.1 Up-link – 14 GHz

The most important aspect of 14 GHz up-link attenuation is that when the satellite transponder operates well below saturation there exists a direct dB for dB relationship to the total C/N . This implies that any attenuation margin deficiency would need to be made up by using power control, diversity switching or a combination of the two. Although power control should not be difficult to implement, some maximum range must be assumed since the control will be increasingly expensive to implement as a greater range is required. Where cross-strapped channels (i.e. 14 to 4 GHz) are used, the up-link effects are the same as the 14 to 11 GHz channels in the dB for dB, effects on the C/N ratio. On the direct 14 to 11 GHz links, it is reasonable to assign half of the 0.01% allotment to each link, whereas in the cross-strapped channels the entire 0.01% allotment can be applied to the 14 GHz up-link since essentially no fading will occur at 4 GHz.

2.2 Down-link – 11 GHz

The effects of 11 GHz attenuation on system performance are different from those at 14 GHz. The direct effect is only on the down-link C/N , but is greater than the attenuation alone since a noise temperature increase is experienced at the same time. The net effect on overall C/N is related to the ratio of total noise to down-link noise.

Fig. 4 shows an example of how the total down-link degradation varies as a function of rain attenuation for different receiving system noise temperatures T_S . For the example shown, a rain attenuation of 9.5 dB results in a total down-link degradation of approximately 11.5 dB for $T_S = 230$ K. This would rise to almost 14 dB down-link degradation for $T_S = 90$ K.

2.3 Power control considerations

The need for power control is established by the difference between the tolerable fade level and the total rain attenuation for the appropriate percentage of time. The amount of power control is determined by the requirement of the link with the least margin above FM threshold or the 50 000 pW0p limit.

3. Diversity interconnect link

A factor which must be considered is that the CCIR hypothetical reference circuit contained in Recommendation 352-3 includes the Diversity Interconnection Links (DIL) to the diversity switching point and any additional modulation/demodulation equipment required. This would mean that system noise budgets must include all the effects of the DIL.

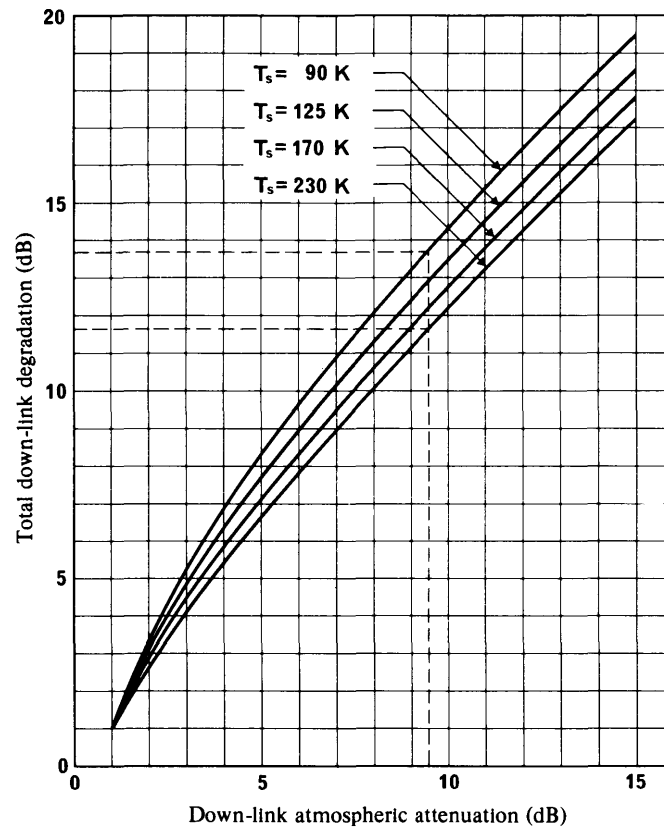


FIGURE 4 – Total down-link degradation versus VS down-link attenuation

T_S = total receive system temperature (K)

3.1 Basic configuration

3.1.1 Physical aspects

There are a number of different specific configurations which can be considered and it is assumed that reasons can be developed for preferring one of these. Two of these are identified and described in this Annex as (see Fig. 5):

- a main site which contains the diversity switch and the terrestrial interface. The diversity site is connected by a two-hop microwave DIL using either an active, or passive, repeater. (A repeater site is assumed, since the likelihood of mutual visibility of the diversity sites is small.)
- dual diversity sites and a separate control site with the interface and diversity switch; single microwave hops for each site to the control site.

It may also be possible to employ cable or waveguide links for the DIL.

3.1.2 Modulation requirements

Because the satellite link modulation and baseband configurations are usually different from those conventionally used for terrestrial systems, re-modulation will be required. Assuming that both systems use FM/FDM, the main difference is associated with the channel packaging. The terrestrial system will usually combine the channels in one or more basebands in each direction and will use a relatively low modulation index. The earth station will break these basebands down into multiple, multi-destination, transmit basebands; different from those on the terrestrial system and using a different modulation index. The receive basebands are even more numerous and may only consist of a few channels and these must be re-combined into the terrestrial basebands. This process requires modulation/demodulation equipment at the main earth station site and at the diversity site where conventional design of the DIL is used. All configurations can be implemented using the remodulation technique at the expense of providing duplicate equipment at the diversity site.

An alternative technique is to use the same modulation arrangements on the terrestrial system as used on the satellite system. Such a technique would appear to be technically feasible although not conventional. The incentive is to save the cost of remodulation equipment at perhaps some added cost to the terrestrial system, although savings may also result for this element as well.

The use of such a technique is only applicable to the second configuration of Fig. 5.

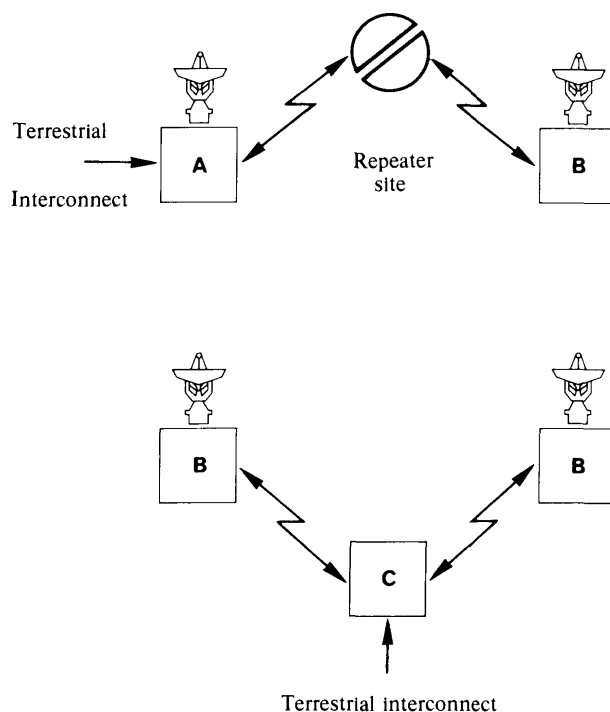


FIGURE 5 — Diversity configurations

A: Main site
 B: Diversity sites
 C: Control site

3.2 Technical factors

3.2.1 Frequency selection

Frequency selection for a microwave DIL requires careful study to ensure that the required overall performance is obtained. Information on terrestrial microwave propagation is shown in CCIR Reports 338-3 and 720.

3.2.2 Bandwidth requirements

The bandwidth required to implement the DIL can be related to the earth station bandwidth by a factor which may be unity or less, depending upon whether re-modulation is used or not. If only frequency translation is used then bandwidth requirements must be MHz for MHz. By re-modulating, a greater channel density can be achieved by using smaller FM modulation indices at the expense of a substantial multiplex interface.

3.2.3 Rain attenuation

A further factor is related to rain attenuation and site diversity characteristics as related to rainfall phenomenon. A dry climate is preferred. Diversity action is a function of the site spacing. It is expected that about 16 kms spacing is the nominal required. The best orientation of a line connecting the sites may be assumed to be perpendicular to the direction of predominant weather patterns since the most severe attenuation condition would not be expected to affect both sites simultaneously and maximum diversity action would be obtained, [Gray, 1973, Hall and Allnut, 1975, Davis and Croom, 1974]. The weather effects on the microwave DIL must be accounted for if the higher frequencies are used for these links, although this should be a secondary consideration.

3.2.4 Variations in transmission delay due to diversity switching

Another element of importance is associated with the differential transmission delay between the diversity signals as they arrive at the switching point. Variations in transmission delay due to diversity switching are considered in Report 383-3.

3.3 General considerations

To particular aspects of the DIL are important:

- the contribution to the overall system noise budgets, and
- the contribution to system outage.

These subjects are studied here to develop the effects of the important parameters and the interrelationship with the satellite link parts of the system.

The diversity link design can be made on two bases. If a re-modulation system is selected, then conventional radio-relay designs can be used. If a translation system is selected, then the design can follow a different pattern and will be very similar to the satellite system transmission design. Fading margins and noise contributions must be accounted for in overall performance. In the special case where the same frequencies are used for the DIL as for the satellite system, then interference noise allowances must also be made.

3.3.1 Noise budgets

The contributions of the DIL to the overall noise of the hypothetical reference circuit have to be made reasonably small in order to maintain the system performance in accordance with Recommendation 353-3 of the CCIR.

It seems reasonable to assume that the DIL noise contribution would be considered as part of the earth station budget (usually 1500 pW0p), as the DIL actually provides part of the normal earth station function. It only needs to be determined that such a contribution can be kept sufficiently small so that the total of 1500 pW0p is not exceeded. The fading of the DIL will contribute to the overall short term noise budget of the link.

The noise contribution from the DIL would have a number of components depending upon the implementation configuration and the frequency bands used. The components are:

(a) Thermal noise

Conventional CCIR designs for radio-relay are 1 to 3 pW0p per km or less, and can be held to 10 pW0p or less, for a single hop. Special designs also achieve small contributions. The time varying components due to multipath fading and rain attenuation are relatively large, but for short hops can be controlled to reasonable values. The thermal noise is dB for dB related to the fading from either mechanism.

(b) Basic intrinsic noise

This is baseband noise and is applicable only to re-modulating configurations. Noise levels of 50 to 100 pW0p are usual for back-to-back basebands. The normal earth station noise budget provides for one such contribution while a re-modulation configuration would add a second contribution.

(c) Interference

A very small interference contribution would be present from other microwave systems operating in the same frequency bands in some cases. This contribution can be considered to be negligible. For the special case of using the same frequency reuse design, up-link and down-link contributions of interference at the earth station can be expected. Values of the order of 10 to 100 pW0p are estimated for normal operation. In addition, certain fading situations may be accompanied by increases in this noise for very short time periods along with the thermal noise. This configuration does not require re-modulation, so all extra noise associated with item (b) is eliminated.

(d) Intermodulation

A re-modulating design will have an extra mod-demod pair plus IF amplifiers, while the translation design is all conventional earth station equipment and therefore contributes very little IM noise.

The following table illustrates a possible noise budget:

TABLE III

Sample budgets – Free space conditions				
	Remodulation (2 hops)		Frequency translation (1 hop)	
	<i>Low</i> (pW0p)	<i>High</i> (pW0p)	<i>Low</i> (pW0p)	<i>High</i> (pW0p)
Thermal	2	20	1	10
Baseband intermodulation	50	100	—	—
Interference	—	—	10	100
Intermodulation (RF)	100	200	20	50
Total (pW0p)	152	320	31	160

3.3.2 Frequency considerations

The fading characteristics as a function of frequency, climate and path length for rainfall can be derived from conventional microwave designs. Rain attenuation and multipath fading are independent events — in fact they are almost mutually exclusive.

Since the expected spacing of a diversity pair of earth stations is of the order of 16 to 24 km and since it is also expected that either a repeater or a common site will be needed, the individual path lengths of the DIL will probably not exceed 16 km. The margins for such a path length can normally be made sufficiently high to accommodate short term outages as low as 0.001% of the time.

4. Conclusions

The basic design of a 14/11 GHz earth station has been examined with particular application to the impact that system performance objectives have on its development. The concepts of site diversity interconnection have been considered and a determination made of those factors affecting its design.

The following points should be noted:

- Without site diversity some form of transmit power control may be required in order that a system meets its performance objectives. The amount of power control required will depend to some extent on how the noise allocation is made in the system.
- when using a diversity interconnection link it appears desirable from an economic standpoint to avoid re-modulation. A reasonable straight forward design appears feasible and should be the subject of further study.
- Diversity combining schemes should be explored.

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- GRAY, D. A. [22-24 August, 1973] Earth to space path diversity; dependence of baseline orientation. IEEE GAP International Symposium.
- HALL, J. E. and ALLNUT, J. E. [7-10 April, 1975] Results of site diversity tests applicable to 12 GHz satellite communications. IEE Conference Publication 126.
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SECTION 4C: BASEBAND CHARACTERISTICS

Recommendation and Reports

RECOMMENDATION 352-3

HYPOTHETICAL REFERENCE CIRCUITS FOR TELEPHONY
AND TELEVISION IN THE FIXED SATELLITE SERVICE

(Question 2-3/4)

(1963 – 1970 – 1974)

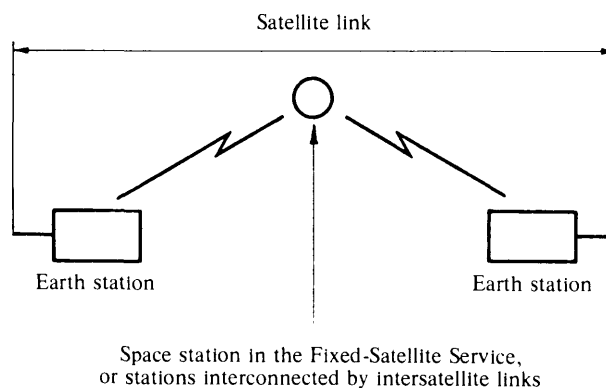
The CCIR,

CONSIDERING

- (a) that it is desirable to establish a hypothetical reference circuit for active fixed satellite systems to afford guidance to designers of equipment and systems for use in telephone and television networks;
- (b) that only high-altitude satellites are being used or planned;
- (c) that with such satellites it will become possible for most connections to be made with one satellite link, with occasional need for two links in tandem, particularly for television;
- (d) that the overall performance of each satellite link depends only to a small extent on the great circle distance between the earth stations;
- (e) that, to overcome fading, earth stations may operate in site diversity configurations, requiring terrestrial interconnection links between pairs of antennae;
- (f) that systems in the Fixed Satellite Service may include intersatellite links,

UNANIMOUSLY RECOMMENDS

1. that a hypothetical reference circuit for systems in the Fixed Satellite Service should consist of one Earth-space-Earth link in which the space portion may contain one or more satellite-to-satellite paths.
2. that for earth stations not connected in site diversity this circuit should include one pair of modulation and demodulation equipment for translation from the baseband to the radio-frequency carrier, and from the radio-frequency carrier to the baseband, respectively;
3. that links between these earth stations and their associated switching centres should not be included in this hypothetical reference circuit;
4. that, for site diversity earth stations, the hypothetical reference circuit shall also include the necessary terrestrial links and where appropriate additional modulation and/or demodulation equipment; the terrestrial/satellite system interface should then be assumed to be situated at the baseband, after the diversity switching point;
5. that terrestrial links between the site diversity switching points of such earth stations and the associated switching centres, should not be included in the hypothetical reference circuit.

FIGURE 1 — *Hypothetical reference circuit*

RECOMMENDATION 353-3

**ALLOWABLE NOISE POWER IN THE HYPOTHETICAL REFERENCE CIRCUIT
FOR FREQUENCY-DIVISION MULTIPLEX TELEPHONY
IN THE FIXED SATELLITE SERVICE**

(Question 2-3/4)

(1963 - 1966 - 1970 - 1978)

The CCIR,

CONSIDERING

- (a) that the hypothetical reference circuit is intended as a guide to the design and construction of actual systems;
- (b) that the cost of establishing and maintaining systems in the fixed satellite service are critically dependent on the overall signal-to-noise performance requirements;
- (c) that the total noise power in the hypothetical reference circuit should not be such, as would affect appreciably conversation in most telephone calls or the transmission of telephone signalling;
- (d) that the extent of fading cannot be determined fully until more experimental data are available, but is not expected to be appreciable in active systems in the Fixed Satellite Service;
- (e) that there may be other sources of noise of short duration,

UNANIMOUSLY RECOMMENDS

1. that the noise power, at a point of zero relative level in any telephone channel in the hypothetical reference circuit as defined in Recommendation 352-3 should not exceed the provisional values given below:
 - 1.1 10 000 pW0p psophometrically-weighted one-minute mean power for more than 20% of any month;
 - 1.2 50 000 pW0p psophometrically-weighted one-minute mean power for more than 0.3% of any month;
 - 1.3 1 000 000 pW0 unweighted (with an integrating time of 5 ms), for more than 0.01% of any year;
2. that the following Notes should be regarded as part of the Recommendation:

Note 1. — Noise in the multiplex equipment is excluded from the above. For frequency-division multiplex telephony, noise additional to the above values is introduced by the equipment necessary to translate the satellite baseband to and from the multiplex level required for interconnection to a terrestrial link. In considering the performance of an overall connection, the noise introduced by such equipment should be added to the values given in RECOMMENDS 1, § 1. The noise allowed by CCITT for multiplex equipment is given in CCITT Recommendation G.222, § (d).

Note 2. — It is assumed that noise surges and clicks from power supply systems and from switching apparatus (including switching from satellite to satellite) are reduced to negligible proportions and therefore will not be taken into account when calculating the noise power.

Note 3. — Some Administrations are continuing to use the objective that the noise power should not exceed the value of 1 000 000 pW0 unweighted (with an integrating time of 5 ms) for more than 0.03% of any month.

Note 4. — In applying the hypothetical reference circuit and the allowable circuit noise to the design of satellite and earth-station equipment for a given overall signal-to-noise performance, the system characteristics preferred by the CCIR, as found in its Recommendations, should be used where appropriate; where more than one value is recommended, the designer should indicate the value chosen; in the absence of preferred values, the designer should indicate the assumptions used.

Note 5. — For frequency-division multiplex telephony, it will be assumed that, during the busy hour, the baseband signal can be represented by a uniform-spectrum signal, the mean absolute power-level of which, at a point of zero relative level is equal to $(-15 + 10 \log N)$ dBm for 240 channels or more, and $(-1 + 4 \log N)$ dBm * for numbers of channels between 12 and 240, N being the number of channels. These formulae apply only to baseband signals without pre-emphasis and using independent amplifiers or repeaters for the two directions of transmission. Further information on the conventional load, in particular in the case of a repeater which is common to both directions of transmission, is given in CCITT Recommendation G.223 (*Orange Book*, Vol. III-1, Geneva, 1976).

Note 6. — It is not yet possible to make firm recommendations regarding requirements to be met, if VF telegraphy and data transmission are required over telephone channels in a system in the Fixed Satellite Service.

* It is considered that these formulae give a good approximation in calculating intermodulation noise when $N \geq 60$. For small numbers of channels, however, tests with uniform-spectrum random noise are less realistic, due to the wide difference in the nature of actual and test signals.

Note 7. — The noise power indicated in § 1 above should include interference noise (see Recommendations 356-4 and 466-2) and noise resulting from atmospheric absorption and increased noise temperature due to rain. In certain cases, however, additional noise may cause the limits fixed in the general objectives to be slightly exceeded. This should not cause serious concern, provided that the provisions of CCITT Recommendation G.222, § (b) 6, are met.

Note 8. — The value given in § 1.3 may on occasions be exceeded due to solar interference in the beam of the antenna but, because of the predictability of such interference, this is excluded from this Recommendation. Detailed information is given in Annex II of Report 390-3.

Note 9. — The objectives set out in this Recommendation are performance objectives, as distinct from availability objectives.

Further study is required to determine whether these objectives are still applicable when the link is unavailable.

Note 10. — It may be necessary to make special provision regarding the performance of intersatellite links. The extent of this provision is a matter requiring further study.

Note 11. — Short interruptions (less than 10 seconds) shall be treated as equivalent to the case where noise power of a circuit is more than 10^6 pW0 unweighted.

Note 12. — It is desirable that systems be planned on the basis of propagation data covering a period of at least four years. The performance recommended to be met in 'any year' should be based on the cumulative propagation statistics for all the complete years for which reliable data are available. The performance recommended to be met for 'any month' should be based on the propagation data corresponding to the median 'worst month of the year taken from the monthly statistics for all the years for which reliable data are available'.

Note 13. — In 1977 Joint Study Group CMBD suggested to the CCIR that it should add to clauses 1.1 and 1.2 an intermediate clause referring to 20 000 pW0p and 3% of any month. Administrations are therefore requested to study the advisability of introducing such a clause during the next study period.

RECOMMENDATION 354-2

VIDEO BANDWIDTH AND PERMISSIBLE NOISE LEVEL IN THE HYPOTHETICAL REFERENCE CIRCUIT FOR THE FIXED SATELLITE SERVICE *

(Question 2-3/4)

(1963 - 1970 - 1974)

The CCIR,

CONSIDERING

- (a) that the hypothetical reference circuit is intended as a guide to designers and constructors of actual systems;
- (b) that the costs of establishing and maintaining systems in the Fixed Satellite Service are critically dependent on the video bandwidth and the overall signal-to-noise ratio to be provided and these should, therefore, not be greater than is strictly necessary for acceptable transmission;
- (c) that it is desirable for the noise level in satellite transmission not to exceed the permissible level for international terrestrial transmissions (see Recommendation 567);
- (d) that it is desirable for international television programmes via space stations in the Fixed Satellite Service to be transmitted according to the television standards and system of origin, so as to ensure the best quality of service in conformity with Opinion 38,

UNANIMOUSLY RECOMMENDS

1. that, in the hypothetical reference circuit for systems in the Fixed Satellite Service, as defined in Recommendation 352-3, the nominal upper limit of the video bandwidth should be compatible with the necessary bandwidth for the television system or systems to be transmitted (see Recommendation 567);

* These requirements are provisional. In Question 13/CMTT and Study Programme 13D/CMTT, the CMTT invites Administrations to study the characteristics of a hypothetical reference circuit for the transmission of television by satellite.

2. that the signal-to-weighted noise ratios for continuous random noise at the end of the hypothetical reference circuit, defined in Recommendation 352-3, should provisionally be equal to the ratios recommended for the 2500 km terrestrial reference circuit in Recommendation 567 for the appropriate television standard.

Note 1. — The CMTT intends to study the definitions and characteristics of auxiliary circuits to be associated with picture and sound programme circuits (see Study Programme 17C/CMTT).

Note 2. — In the application of RECOMMENDS 2 of this Recommendation, special note should be taken of Note 2* of § 1.2 of Recommendation 421-3 (Geneva, 1974) with regard to noise in the hypothetical reference circuit.

Note 3. — The noise specified above should include the interference noise in Recommendation 483-1.

REPORT 208-4

FORM OF THE HYPOTHETICAL REFERENCE CIRCUIT AND ALLOWABLE NOISE STANDARD; VIDEO BANDWIDTH AND SOUND CHANNEL FOR TELEVISION FOR FREQUENCY-DIVISION MULTIPLEX TELEPHONY AND TELEVISION IN THE FIXED SATELLITE SERVICE

(Question 2-3/4)

(1963 – 1966 – 1970 – 1974 – 1978)

1. Form of the hypothetical reference circuit

As an aid to designers of systems in the Fixed Satellite Service a hypothetical reference circuit, analogous to that adopted for long-haul terrestrial systems, has been established in Recommendation 352-3. It facilitates specifying, designing and maintaining system performance and characteristics at the point of use or at the interface with other systems.

The hypothetical reference circuit for systems in the Fixed Satellite Service encompasses a single geostationary space link. In addition to telephony, the hypothetical reference circuit is applicable to other types of signals such as television and data when these are used in the fixed satellite service.

With respect to television, the definition and characteristics of reference chains comprising one or more hypothetical reference circuits and corresponding to different services, have been studied by the CMTT and are reflected in Recommendations 354-2 and 567.

Developments in the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, introduced new factors which should be considered when developing hypothetical reference circuits. The first in this regard is the introduction of the intersatellite service which may provide links between satellites in the Fixed Satellite Service. While systems utilizing intersatellite links have not yet been designed, it is clear that they will add both time delay and noise to the system.

The second factor is the new allocations to the fixed satellite service of frequencies 11, 14, 18 and 30 GHz where preliminary studies indicate a need for site diversity at earth stations suffering severe rain attenuation problems. There will have to be terrestrial interconnections provided for such facilities. The interface with other systems will include a terrestrial contribution to noise. Recommendation 352-3 refers.

2. Allowable noise standards

2.1 General considerations

Allowable noise standards in the hypothetical reference circuit for the Fixed Satellite Service should be commensurate with those adopted for other long-haul systems; the principles established by the Joint CCITT/CCIR Special Study Group CMBD on circuit noise for telephony, and by the CMTT for long-distance television transmission are relevant.

The criteria for short-term maximum allowable noise power in Recommendations 353-3 and 356-4 were derived from those applicable to terrestrial circuits. However, when the thermal noise alone is considered, for the 4 and 6 GHz frequency bands, the percentage of time for which 50 000 pW0p is exceeded may be considerably less than the 0.3% allowed by Recommendation 353-3. Experience gained from systems operating in these bands has tended to confirm this fact.

* *Note by the Secretariat:* this Note has been deleted in Recommendation 567 which replaces Recommendation 421-3.

These conclusions, however, may not apply to systems operating in higher frequency bands as they suffer both from increased rain attenuation as well as a significant increase in system noise temperatures. The receiving system noise temperature of an earth station in the absence of rain is given by:

$$T_0 = T_r + \left(\frac{w-1}{w} \right) T_w + \frac{T_s + T_g}{w} \quad \text{K} \quad (1)$$

and in the presence of rain by:

$$T_p = T_r + \left(\frac{w-1}{w} \right) T_w + \frac{T_g}{w} + \frac{T_s}{aw} + \left(\frac{a-1}{aw} \right) T_{rain} \quad \text{K} \quad (2)$$

where:

- T_r : noise temperature of receiver and following stages, K,
- w : waveguide loss factor,
- T_w : waveguide temperature, K,
- T_s : sky contribution to antenna noise temperature, K,
- T_g : ground contribution to antenna noise temperature, K,
- a : rain absorption factor,
- T_{rain} : effective temperature of the rain, K.

Fig. 1 shows an example of how the down-link degradation at 11 GHz will vary as a function of the earth station system noise temperature and rain attenuation.

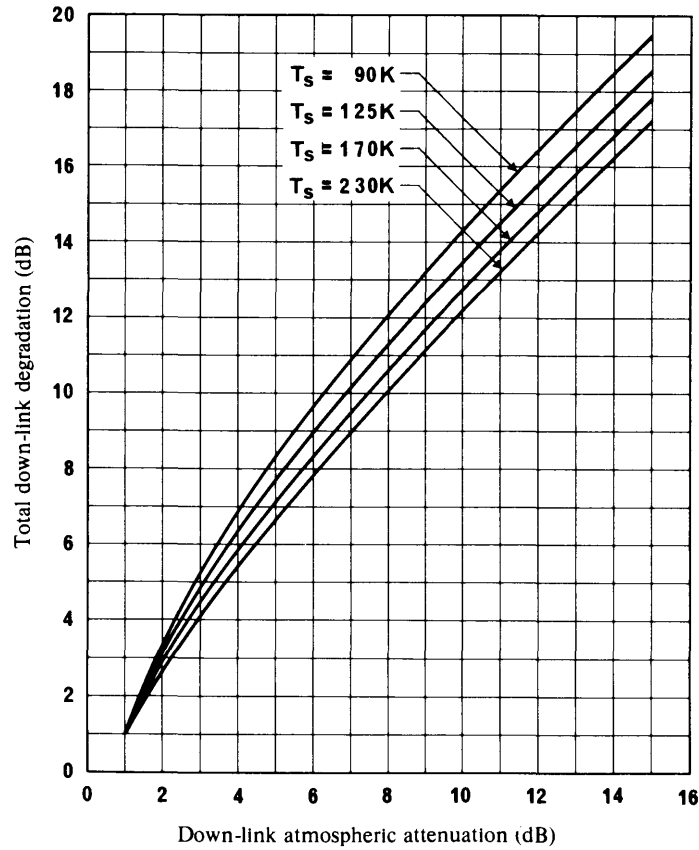


FIGURE 1 – Total down-link degradation versus or “vs” down-link attenuation

T_s : total receive system temperature (K)

Information needed to derive the path attenuations in different regions and for different frequency bands is given in the texts of Study Group 5, in the Radiometeorology and the Space Telecommunications Sections.

Further study of the short-term noise criteria for satellite systems is desirable in the light of the actual transmission behaviour of such systems, but bearing in mind the relevant principles established by the Joint CCITT/CCIR Special Study Group CMBD and by the CMTT and the behaviour of systems using frequency bands other than 4 and 6 GHz. Further study is also required to take into account fading mechanisms other than hydrometeors, in view of recent observations that ionospheric and tropospheric scintillation may affect signals at some earth stations.

2.2 *Allowable noise in the hypothetical reference circuit: frequency-division multiplex telephony*

In addition to the general considerations mentioned above, Recommendation 353-3 was prepared giving objectives in the light of the advice of the Joint CCITT/CCIR Special Study Group CMBD. The maximum value of 10 000 pW_{0p} (psophometrically weighted) for the mean noise in any hour in any telephone circuit of the hypothetical reference circuit, would correspond to 1.3 pW/km on a 7500 km great-circle distance. This objective is commensurate with those for other long-distance transmission media, as are also the objectives for the other integrating periods, i.e. 1 min and 5 ms. However, the two factors referred to in § 1 should also be considered to impact on this Recommendation.

For certain classes of circuits for direct connection over long distances but whose purpose is not to form part of an international connection, it may be desirable to allow higher values for the mean noise in the hypothetical reference circuit. The reasons for considering such higher allowable noise levels are discussed briefly in Annex I of this Report to facilitate further study by interested Administrations.

2.3 *Allowable noise in the hypothetical reference circuit: television*

The majority of international television connections are likely to contain only one satellite link, although two such links will be needed for the longest world-wide connections. Under these conditions, an entirely adequate performance for the continuous random noise at the end of the hypothetical reference circuit would be one which provisionally equals that for the terrestrial 2500 km hypothetical reference circuit — the precise values depending on the television standards involved (see Recommendation 567).

3. Video bandwidth in the hypothetical reference circuit

The following points have been taken into account in preparing Recommendation 354-2 on the nominal upper limit of the video-frequency band in a fixed satellite system for television:

- the video bandwidth should be adequate for acceptable transmission of television signals up to and including 625-line standards;
- the need, for economic reasons, to provide a video bandwidth no wider than is strictly necessary;
- the desirability that the width of the baseband for television should be compatible with that for high-capacity frequency-division multiplex telephony.

Taking these factors into account, it is recommended that the video bandwidth in the hypothetical reference circuit for television should be compatible with the necessary band for the television system or systems in question.

4. Simultaneous transmission of a sound channel and a television picture

To avoid excessive differences in transmission delay between a television picture signal and the corresponding sound signal, there are advantages in transmitting both over the same satellite link. In this event, a wider baseband may be needed to accommodate the sound signal (e.g., on a separate sub-carrier in the baseband). Alternatively, the sound signal might be transmitted by time-division multiplex with the video signal, e.g., using the synchronizing pulses or the blanking intervals, without the need for a wider baseband. Also, the sound may be transmitted by radio channel on the same satellite.

ANNEX I

NOISE PERFORMANCE OBJECTIVES FOR SATELLITE TELEPHONE CIRCUITS — RELATED TO USER PREFERENCES

1. Introduction

In terrestrial telephone circuits and channels, noise is substantially dependent on the circuit length, and this has led to an approach of specifying noise in terrestrial circuits as a function of the distance spanned by the circuit plus a constant noise contribution that is independent of distance due to those equipment and interference characteristics that are not distance-dependent.

However, if one examines the philosophy underlying the method of arriving at terrestrial circuit noise standards the most important feature is the quality of service given to telephone users under average and extreme conditions within the network.

Whilst distances impose a major constraint on transmission performance in terrestrial circuits, satellite circuit noise and attenuation (or loss) are largely independent of distance. Therefore it would seem more appropriate to determine a value, or range of values, that will provide satisfactory connections irrespective of the distances spanned by the satellite circuits. In the light of these considerations it may be desirable to examine the feasibility of departing from the noise levels allowed by Recommendation 353-3, and the effects of such a departure on the quality of telephone connections via satellite networks for a national service.

2. Possible practical solutions in providing satellite circuits

An analysis and discussion submitted by Australia during the period 1974-1978 demonstrates that for certain classes of circuits used in a national traffic situation, the standards applied generally to international telephone circuits via satellite can be modified to gain economic advantage yet provide an adequate service within a country. It will not be possible to take advantage of this for all connections and some special arrangements may be necessary to ensure conformity with international requirements when these "national standard" satellite circuits are to be connected to an international circuit.

There are, of course, national traffic situations where standards exceeding those in Recommendation 353-3 may have to be applied.

The analysis considered three types of link:

- (a) conforming with Recommendation 353-3 (10 000 pW0p circuits),
- (b) relaxation of 3 dB (20 000 pW0p circuits),
- (c) relaxation of 6 dB (40 000 pW0p circuits).

It would be feasible to provide separate transponders for separate types or a mixed arrangement within one transponder. The possible changes in system capacities by departing from the 10 000 pW0p value depends on the system configuration considered, but can offer as much as 100% increase in the total number of channels per transponder in return for 6 dB relaxation from Recommendation 353-3, [Feder, 1976].

It may also be desirable to provide some links with a very low noise contribution to enable very long terrestrial extensions to be permanently associated with them. Such links could perhaps conform to the Recommendation 353-3 standard. These could then be extended with about 6500 km of terrestrial transit circuits.

Another possible arrangement is when all traffic to or from international sources is restricted to terrestrial trunks where possible, thus allowing the provision of only type (c) circuits with very few of the other types being necessary. This arrangement would have the advantage of simplifying the special international switching arrangements that would be necessary to avoid excessive tandem satellite connections.

Finally, if it is acceptable to use, say, 40 000 pW0p or 20 000 pW0p circuits, rather than the 10 000 pW0p circuit standard, then it will be desirable to re-examine both the total allowance of non-thermal noise (assumed to be constant at 6000 pW0p) and also, the interference component of this non-thermal noise (assumed at 2000 pW0p). Clearly, if the interference and hence the non-thermal noise contribution could be increased at the expense of thermal noise, some economic benefits might occur in terms of relaxed co-ordination requirements of the satellite system.

3. Conclusion

Noise objectives in the terrestrial network must recognize the worst and average conditions that may be encountered and which generally are due to the distance factor. Within the constraints of the overall noise standards currently recommended by the CCITT, standards for satellite circuits can be chosen that should provide equivalent or somewhat better performance than comparable long distance terrestrial connections. Essentially it is envisaged that the noise allowance for a satellite circuit should correspond to the noise allowance of the terrestrial systems it notionally replaces. Where special conditions require better circuits a special arrangement could be made to meet the requirements. It has been shown that this method of establishing the satellite circuit objectives rather than the simple application of the Recommendation 353-3 standard, leads to a possible increase in a given system's capacity, leading to a reduction in cost per channel for a given system, or reduction in system costs for a given channel requirement.

REFERENCE

- FEDER, A. [1976] Transmission performance objectives for national satellite telephone circuits. *Australian Telecommunication Research*, Vol. 10, 2, 59-74.

RECOMMENDATION 521

HYPOTHETICAL REFERENCE CIRCUIT FOR SYSTEMS USING DIGITAL TRANSMISSION
IN THE FIXED SATELLITE SERVICE

(Study Programme 2N/4)

(1978)

The CCIR,

CONSIDERING

- (a) that it is desirable to establish a hypothetical reference circuit for active fixed satellite systems to afford guidance to designers of equipment and systems for use in networks employing digital transmission techniques;
- (b) that it will become possible for most connections to be made with one satellite link, with occasional need for two links in tandem;
- (c) that inter-satellite links may be used in the Fixed Satellite Service;
- (d) that satellite links using digital transmission should form part of the recommended plesiochronous international digital network;
- (e) that only geostationary satellites are being planned for use in such networks;
- (f) that the transmission delay variation introduced by satellite movement relative to the Earth is of particular significance in a plesiochronous network;
- (g) that a number of new techniques such as TDMA (time division multiple access) and DSI (digital speech interpolation) are being developed for use in digital satellite links;
- (h) that primary or higher order digital multiplex signals may be transmitted on digital satellite links;
- (j) that the problems raised by the use of digital satellite links in an international plesiochronous network are still under study in the CCITT,

UNANIMOUSLY RECOMMENDS

1. that the hypothetical reference circuit for systems using digital transmission in the Fixed Satellite Service should consist of one Earth-space-Earth link, including inter-satellite link(s), if used;
2. that this hypothetical reference circuit should include the equipment indicated in Fig. 1, which is required to interface with the terrestrial network at the primary multiplex levels recommended by the CCITT (Recommendations G.732, G.733);

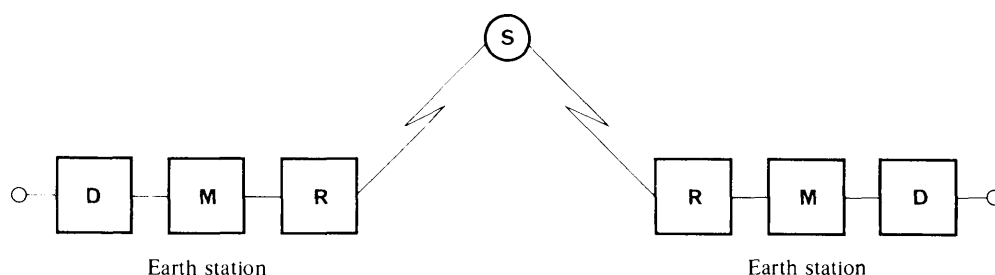


FIGURE 1 — Hypothetical reference circuit

S : Space stations in the Fixed-Satellite Service, or space station in the Fixed-Satellite Service interconnected by satellite links
 D : Direct digital interface equipment (DDIE)
 M : Modem equipment (including TDMA equipment if used)
 R : IF/RF equipment

3. that the direct digital interface equipment should include any equipment required for the purpose of compensating for the effects of satellite link transmission time variation;
4. that links between these earth stations and their associated digital switching centres should not be included in this hypothetical reference circuit;
5. that for site diversity earth stations the hypothetical reference circuit should also include the terrestrial links and any associated equipment necessary for connecting the diversity earth stations to the diversity switching point;

Note 1. — Single-channel-per carrier digital systems are not considered for the purposes of this Recommendation.

Note 2. — In the case when part of the direct digital interface equipment is located at the transit centre (TC), further study is required as to whether its functions are to be included in this hypothetical reference circuit.

Note 3. — The concept of "hypothetical reference circuit" as used in this Recommendation is analogous to that of "digital hypothetical reference path" used in Recommendation 556 of Study Group 9 and in CCITT Recommendation G.721 (see definition 9003 in CCITT Recommendation G.702, Volume III of the *Orange Book*). It is desirable that a standard terminology should be considered by the CCIR and CCITT Study Groups concerned, with the aim of developing terms which take due account of the problems of the various Study Groups.

RECOMMENDATION 522

ALLOWABLE BIT ERROR RATES AT THE OUTPUT OF THE HYPOTHETICAL REFERENCE CIRCUIT FOR SYSTEMS IN THE FIXED SATELLITE SERVICE USING PULSE-CODE MODULATION FOR TELEPHONY

(1978)

The CCIR,

CONSIDERING

- (a) that the hypothetical reference circuit is intended as a guide to the design and construction of actual systems;
- (b) that the costs of establishing and maintaining digital communication-satellite systems are critically dependent on the overall bit error rate performance;
- (c) that the bit error rate in the hypothetical reference circuit should not be such as to appreciably affect conversation in most telephone calls, or the transmission of telephone signalling;
- (d) that the bit error rate may vary with time due to the effect of varying propagation conditions;
- (e) that high bit error rates may occur for short periods due to other sources of noise, such as interference,

UNANIMOUSLY RECOMMENDS

1. that the bit error rate at the output of the hypothetical reference circuit, as defined in Recommendation 521, should not exceed the provisional values given below:

- 1.1 one part in 10^6 , 10-minute mean value for more than 20% of any month;
- 1.2 one part in 10^4 , 1-minute mean value for more than 0.3% of any month;
- 1.3 one part in 10^3 , 1-second mean value for more than 0.01% of any year;

2. that the following Notes should be regarded as part of the Recommendation:

Note 1. — Only the effects of random bit-errors are considered in this Recommendation. The Recommendation may be taken at present to apply also to bursts of errors, but further study of requirements for bursts of errors is needed.

Note 2. — It is assumed that the errors caused by noise surges and transients from power supply systems and from switching apparatus (including switching from satellite to satellite) are reduced to negligible proportions and therefore need not be taken into account when making the calculations.

Note 3. — The performance of a digital satellite system is generally much more sensitive to a variation in performance in the radio-frequency part of the network than is the case with analogue systems. It is therefore particularly important for designers to allow adequate margins for degradations which may occur during the life of the system if the recommended performance is to be maintained;

Note 4. — The objectives for bit error probability indicated in RECOMMENDS 1. above, include the effects due to interference noise, and noise due to atmospheric absorption and rain;

Note 5. — It is assumed that no framing information other than that required for the adequate operation of the satellite system, would be transmitted over the satellite. If PCM multiplex framing information is to be transferred unmodified via the satellite link, note should be taken of the possible effect of the higher error rates in RECOMMENDS 1.2 and 1.3 on the alarm indication system of the terrestrial systems.

Note 6. — The objectives for bit error probability indicated in RECOMMENDS 1. above apply only to the transmission of PCM-telephony (see CCITT Recommendation G.711). Different objectives may be required for the transmission of data.

Note 7. — The objectives set out in this Recommendation are performance objectives, as distinct from availability objectives. Further study is required to determine whether these objectives are still applicable when the link is unavailable.

Note 8. — It may be necessary to make special provision regarding the performance of inter-satellite links. The extent of this provision is a matter requiring further study.

Note 9. — Short interruptions (less than 10 seconds) shall be treated as equivalent to the case in which the bit error rate of a circuit is more than one part in 10^3 .

Note 10. — It is desirable that systems be planned on the basis of propagation data covering a period of at least four years. The performance recommended to be met in "any year" should be based on the cumulative propagation statistics for all the complete years for which reliable data are available.

The performance recommended to be met for "any month" should be based on the propagation data corresponding to the median "worst month of the year" taken from the monthly statistics of all the years for which reliable data are available.

RECOMMENDATION 446-2

CARRIER ENERGY DISPERSAL FOR SYSTEMS EMPLOYING ANGLE MODULATION BY ANALOGUE SIGNALS OR DIGITAL MODULATION IN THE FIXED SATELLITE SERVICE

(Study Programme 2D-1/4)

(1966 - 1974 - 1978)

The CCIR,

CONSIDERING

- (a) that use of carrier energy dispersal techniques in systems in the Fixed Satellite Service can result in a substantial reduction of interference to stations of a terrestrial service operating in the same frequency bands;
- (b) that in many cases the use of such techniques can result in a moderate to substantial reduction in the level of interference between systems in the Fixed Satellite Service operating in the same frequency bands, although in other cases the use of such techniques may not reduce the level of interference between such systems;
- (c) that such techniques are being regularly and successfully employed in systems in the Fixed Satellite Service without noticeable deterioration of the quality of operation;
- (d) that a Recommendation, (Spa2 - 11), relating to carrier energy dispersal in systems in the Fixed Satellite Service, was adopted by the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971,

UNANIMOUSLY RECOMMENDS

- 1. that systems in the Fixed Satellite Service should use carrier energy dispersal techniques, as far as is practicable and in a manner consistent with satisfactory operation of the systems (see Report 384-3, §§ 2 and 3), with a view to spreading energy such that the interference to stations of a terrestrial service operating in the same frequency bands is maintained within specified tolerable limits at all times;
 - 2. that the capability for carrier energy dispersal up to the maximum degree practicable (see Report 384-3) should be included in the design of satellite systems to be available for implementation when necessary to maintain a reduced level of interference between systems in the Fixed Satellite Service operating in the same frequency bands.
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REPORT 384-3

ENERGY DISPERSAL IN THE FIXED SATELLITE SERVICE

(Study Programme 2D-1/4)

(1966 - 1970 - 1974 - 1978)

1. Introduction

It is clear from studies of frequency sharing between the Fixed Satellite Service and terrestrial radio-relay systems and between different fixed satellite networks that, to ensure that mutual interference between the systems is kept to a tolerable level, it will be essential in most cases to use energy dispersal techniques to reduce the spectral energy density of the transmissions of the Fixed Satellite Service during periods of light loading. The reduction of the maximum energy density will also facilitate:

- efficient use of the geostationary satellite orbit by minimizing the orbital separation needed between satellites using the same frequency band;
- and
- multiple-carrier operation of broadband transponders.

The amount of energy dispersal required obviously depends on the characteristics of the systems in each particular case and this question is appropriate to studies of frequency sharing under Study Programmes 2D-1/4 and 2J-2/4. It is clear, however, that it is desirable that the maximum energy density under light loading conditions should be kept as close as possible to the value corresponding to the conditions of busy hour loading.

In this Report, the results of some theoretical and experimental studies of energy dispersal techniques, separately applicable to analogue frequency-modulation and to digital radiocommunication-satellite systems, are reported.

It is concluded that substantial energy dispersal can be obtained in most circumstances. However, there are some possible limitations on the efficiency of the dispersal and these are mentioned in the Report.

2. Energy dispersal for analogue FM systems

2.1 *Multi-channel telephony systems*

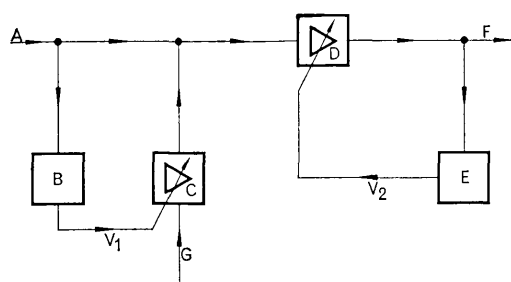
Annex I examines a number of methods of maintaining a high degree of carrier energy dispersal in telephony systems, with particular reference to the dependence of the obtainable dispersal on the complexity of the means of dispersal and the attendant increase in occupied radio-frequency bandwidth as a function of distortion. The methods fall into one or other of two general cases; one which adds a dispersal waveform not necessarily of constant magnitude to the input signal and the second which, in addition, effectively controls the deviation sensitivity of the frequency modulator. Various arrangements of these two methods are discussed in Annex I and illustrated in Fig. 1.

Method 1(a) is the simplest; consisting of the addition of a dispersal waveform of fixed magnitude. The relative effectiveness of this method (i.e. the ratio of the maximum dispersed power per 4 kHz to the maximum power per 4 kHz under full load conditions), using each of four low-frequency dispersal waveforms is shown in Fig. 2 for an assumed 10% increase in occupied radio-frequency bandwidth. The four waveforms are considered in greater detail in Annex I.

It is evident from Fig. 2, that the low-frequency triangular waveform (Curve D) is the most effective of these waveforms, but it suffers from the disadvantage of producing a higher level of interference into some single-channel-per-carrier (SCPC) systems due to the long dwell time of the dispersed unwanted signal within the bandwidth of the wanted signal. (Other methods of dispersal which cause less interference to SCPC transmissions are mentioned in § 4.) Apart from this, the only one that appears to offer possibilities for general application is that of low-frequency noise (Curve C). Dispersal by low-frequency noise has the advantage that the frequency band can be readily altered to suit whatever sub-baseband range is available, and that it does not depend for its effectiveness on a precisely specified waveform. However, it has been found in practice that it can be difficult to generate and apply.

On the other hand, for the triangular waveform, careful attention has to be paid to the linearity of the waveform since departures from linearity will cause variations in the spectral density with consequent deterioration in the dispersal efficiency. Removal of the high order harmonics of the triangular waveform by means of a filter will cause non-linearity in the form of rounding of the peaks which will again reduce the effectiveness of the dispersal. This reduction will be less serious however, if there are some pilot tones during light-loading conditions. The decision on whether or not to employ such a filter in any particular case will need to take account of the conflicting requirements to minimize interference with the low-frequency baseband channels on the one hand and the loss in dispersal efficiency on the other.

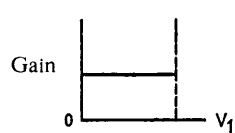
It would be useful to study the possibility of using, instead of noise, a known pseudo-random signal with uniform spectrum in the low-frequency band. This would make it possible to suppress the signal at the receiver, thus avoiding certain disadvantages of this method.



A: Baseband signal input
 B: R.m.s. detector
 C: Amplifier 1
 D: Amplifier 2
 E: R.m.s. detector
 F: Output to frequency-modulator
 G: Dispersal waveform

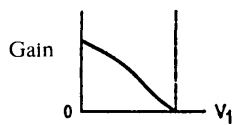
Method

1(a)



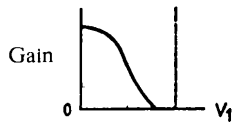
No control

1(b)



No control

2(a)

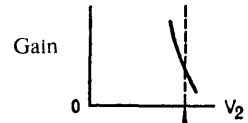
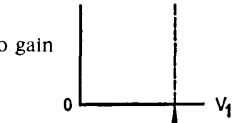


2(b)



2(c)

Zero gain



Full load

Full load

FIGURE 1 — Simplified block diagram
 (Possible filters, buffer-amplifiers and gain-regulating pilots omitted)

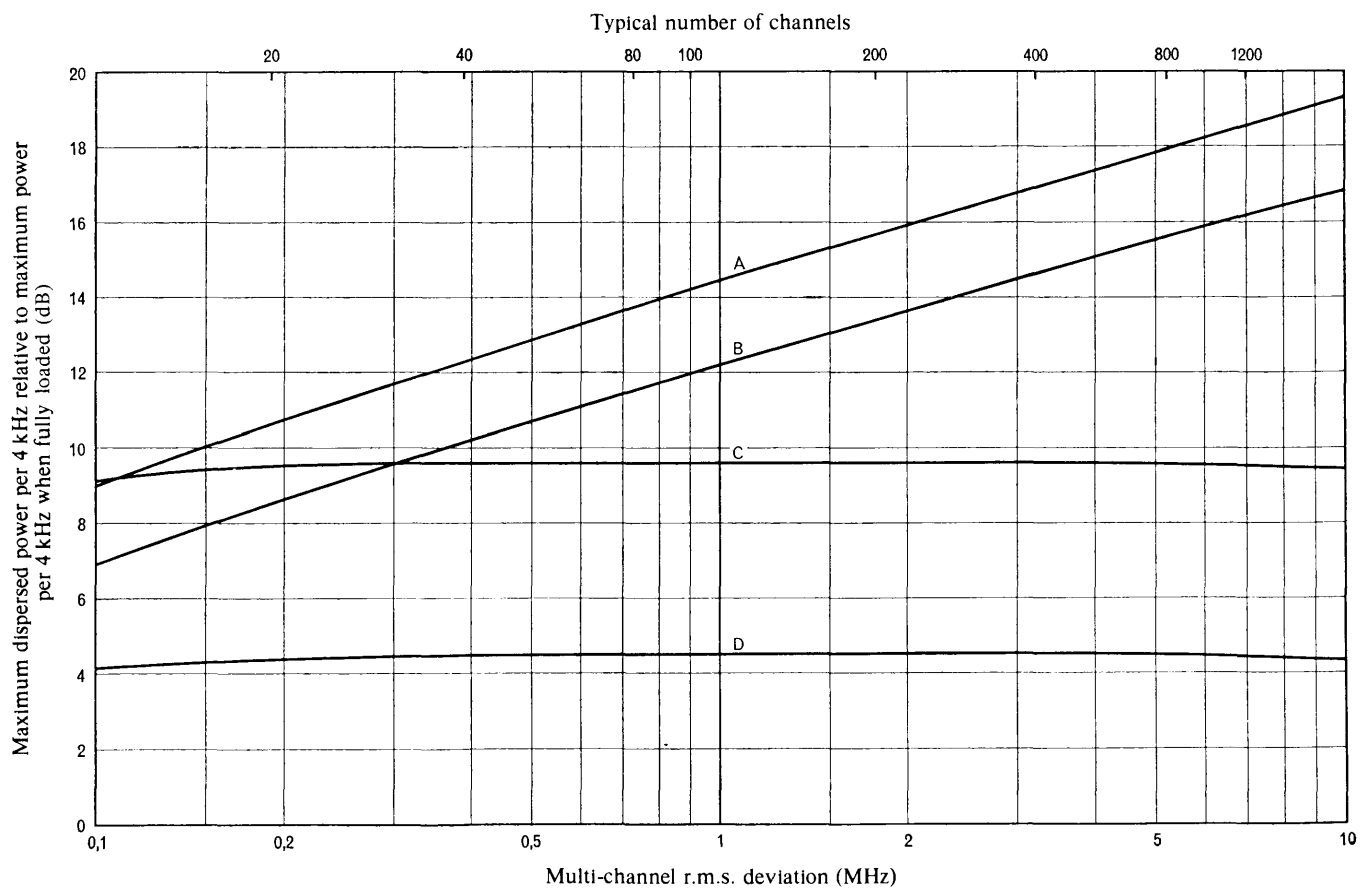


FIGURE 2

Considering now the methods of application of the dispersal waveform, the use of Method 1(a) would result in an undue increase in the occupied bandwidth if it were desired to approach the busy-hour loading conditions. Hence, Method 1(b), which incorporates automatic means of adjusting the degree of dispersal applied according to the state of the loading of the system, offers a much more attractive arrangement.

Method 2 is more complicated than Method 1, but turns to advantage the need to provide energy dispersal by improving system noise performance when the deviation sensitivity is increased under light loading conditions. The obvious disadvantage of this method is the need to provide overall gain regulation, while the extent of the advantage which would accrue under conditions of light loading is dependent on traffic loading outside the busy periods of the day. Of the variants of Method 2 discussed in Annex I, Method 2(a) would seem to be the most suitable for general application.

With any method which requires the amount of added dispersal to be changed abruptly as the loading varies, careful attention must be paid to the choice of delay time between the change in loading and the time of switching the dispersal.

In considering the amount of dispersal which can be achieved in practice, it has to be borne in mind that the fully loaded condition will not necessarily provide the degree of dispersal postulated by the Gaussian distribution as in Annex I, § 1 (see Report 792). It would be unwise to assume that, in practice, this ideal condition is attained, until there is some convincing support for such an assumption. It has been shown by practical measurements using white noise loading that systems which apply a triangular dispersal waveform can maintain the dispersal of carrier energy to within 2 dB of the dispersal under simulated fully busy-hour loading conditions. It is not yet known how closely this condition will be approached with actual traffic loading but it seems unwise to assume that the energy will be dispersed to within less than 3 dB of that applying with busy-hour load conditions, without some increase in radio-frequency bandwidth.

2.2 Television systems

Annex II considers the general problem of energy-dispersal techniques for television systems and gives the results of an experimental study, to determine the subjective effects of the addition of various low-frequency waveforms to 625-line/50 fields-per-second television signals. The results show that a "symmetrical" triangular waveform is preferable to other waveforms considered and that the subjective effect of adding this waveform, (of peak-to-peak amplitude up to 50% of the peak-to-peak amplitude of the video signal before pre-emphasis), is negligible, provided that:

- the dispersal waveform is locked in both phase and frequency to the field frequency;
- suitable simple means of removing the added waveform are used at the receiving earth station;
- the transmission system does not introduce intermodulation between the dispersal waveform and the vision signal.

By a "symmetrical" triangular waveform is meant a wave in the form of an isosceles triangle (i.e. with equal rise and fall times). Sawtooth waveforms, with either rise or fall times approaching zero were also considered (see Annex II).

If only the television aspects of the problem are taken into consideration, there is little to choose between the 12.5 and 25 Hz "symmetrical" sawtooth waveforms. There is a slight instrumental advantage to be gained by using the latter and it is considered, therefore, that, for the energy dispersal of 625-line/50 fields-per-second television signals, a synchronized 25 Hz "symmetrical" triangular waveform should be used and it is not expected that significantly different results would be obtained by using a synchronized 30 Hz "symmetrical" triangular waveform with 60 fields-per-second television systems.

To determine the dispersal effect produced by this method, it will be assumed, for the purpose of example, that the overall system performance restricts the permissible peak-to-peak amplitude of the dispersal waveform to 30% of the peak-to-peak amplitude of the video signal. Considering a 625-line system employing the normal pre-emphasis network (Recommendation 405-1), this peak-to-peak deviation of the dispersal waveform will be 9.4% of the peak-to-peak deviation of the video signal without pre-emphasis. Using the symbol ΔF in MHz for the peak-to-peak deviation of the video signal, the dispersal obtained is approximately:

$$10 \log \left(\frac{\text{maximum energy per 4 kHz}}{\text{total energy}} \right) = 10 \log \frac{0.004}{0.094 \Delta F} = -(14 + 10 \log \Delta F) \quad \text{dB}$$

For comparison, the theoretical dispersal obtained in the telephony case, (assuming a Gaussian spectral distribution and a peak-to-r.m.s. ratio of 12 dB as in Annex I), is:

$$-\left(28 + 10 \log \frac{\Delta F}{8} \right) = -(19 + 10 \log \Delta F) \quad \text{dB}$$

which means that the television case is likely to be only some 5 dB below optimum for some 10% increase in radio-frequency bandwidth.

In the interests of bandwidth economy, it would be desirable to be able to control the deviation on the lines of Method 1(b) of Annex I. It is not obvious that any simple method is possible as it would presumably be necessary to monitor the energy concentration in the radio-frequency spectrum.

In addition to the methods of energy dispersal discussed above, two other systems are described in §§ 5 and 6 of Annex II. The first describes dispersal by video transformation, the second describes dispersal techniques used to improve protection to SCPC telephony transmissions for which the dispersal signal has the frequency of the television line frequency.

Finally, it should be noted that the use of any of the above mentioned methods of energy dispersal for colour television would demand an even higher degree of system linearity than that required for monochrome transmission.

3. Energy dispersal for digital modulation systems

Annex III examines the need for energy dispersal in systems using digital modulation and outlines two methods of baseband code conversion which ensure that the transmitted RF spectrum is maintained in a condition approximating the ideal which would be achieved if the information bit stream was completely random.

Dispersal of the spectra of transmissions in the Fixed Satellite Service employing digital modulation methods is likely to be necessary in many cases. The use of a pseudo-random number sequence to randomize the digital information at the transmitter, followed by its removal at the receiver, provides a simple method of achieving a high degree of dispersal.

It will not normally be necessary for bit rates of a few tens of megabits per second and above, to apply the dispersal signal to the preamble of a TDMA system, since the spectral density due to this part of the transmission will usually be comparable with that obtained with ideal dispersal.

The length of the pseudo-random number sequence chosen will depend on the degree of dispersal required. However, it will not generally be necessary to use a sequence which is longer than the frame duration in single access systems, or greater than the burst duration in TDMA systems, and frequently sequences of shorter lengths than these will be adequate.

4. Conclusions

It appears that the most promising methods of energy-dispersal are as follows:

- for frequency-modulation telephony systems: the addition of a signal below the baseband, controlled according to the loading as in Method 1(b) of Fig. 1. The controlled signal may be noise or a “symmetrical” triangular waveform but the actual implementation is generally easier with the latter;
- for frequency modulation television systems: the addition of a “symmetrical” triangular waveform, synchronized to the picture frequency as in Method 1(a) of Fig. 1;
- for digital modulation systems: code conversion by which the message bit stream is multiplied by a pseudo-random pulse train, using methods similar to those outlined in Annex III.

Currently triangular dispersal waveforms are applied to frequency modulated carriers in most fixed satellite networks. The extent to which the theoretical advantage of triangular dispersal waveforms is approached in practice depends on the linearity of the waveform used. The use of these methods could provide energy dispersal as great as that provided under full-load conditions, however, the excess of the dispersal power per 4 kHz over that achieved under full-loading conditions (assuming a Gaussian spectrum), is unlikely in practice to be less than 3 dB for telephony and 5 dB for television. With this level of energy dispersal the addition to the radio-frequency bandwidth occupied, has not presented any difficulties.

The energy dispersal currently being obtained from triangular dispersal waveforms is proving satisfactory in practice except when the wanted signal is a single-channel-per-carrier system. With the use of low frequency (≤ 1 kHz) triangular dispersal waveform on multi-channel systems, a wanted single-channel-per-carrier system can be exposed to nearly the full power of an interfering carrier for short periods. This problem might be overcome in frequency modulated television systems, by using video signal transformation for dispersal, or by using a triangular dispersal waveform at the television line frequency.

ANNEX I

ENERGY DISPERSAL TECHNIQUES FOR USE WITH ANALOGUE FREQUENCY MODULATION TELEPHONY SIGNALS

1. General

In studying ways of achieving high degrees of carrier energy dispersal, it is useful to know what is the dispersing effect of the fully-loaded baseband signal, to have some reference value with which to compare what can be obtained artificially. It is legitimate, for the general class of wide-deviation frequency-modulation systems

under consideration, i.e. those in which the multi-channel r.m.s. deviation (δF) exceeds the highest baseband frequency, which in turn greatly exceeds the lowest baseband frequency; to assume that the mean power spectrum under the conventional busy-hour loading conditions is of Gaussian form. Hence, the dispersing effect obtained under these conditions is:

$$10 \log \left(\frac{\text{maximum energy per 4 kHz}}{\text{total energy}} \right) = 10 \log \frac{0.004}{\sqrt{2\pi} \delta F} = -(28 + 10 \log \delta F) \quad \text{dB}$$

(δF is expressed in MHz).

The dispersing effect when δF is less than the highest baseband frequency can be calculated using the information contained in Report 792.

Possible arrangements for maintaining a high degree of carrier energy under conditions of reduced loading, by the methods discussed in this Annex, are shown diagrammatically in Fig. 1.

2. Dispersal by added waveforms

2.1 Method 1(a)

The simplest way of bringing about some degree of carrier energy dispersal is to add to the baseband signal, a suitable low-frequency dispersing waveform of fixed magnitude, as in Method 1(a) of Fig. 1. Of a variety of dispersal waveforms that have been proposed, the following are examined in this Report:

- a sinusoidal signal (Curve A of Fig. 2),
- a sinusoidal signal plus 30% third harmonic added in suitable phase (Curve B of Fig. 2),
- a band of low-frequency noise (Curve C of Fig. 2),
- a low-frequency triangular waveform (Curve D of Fig. 2).

To provide some basis for comparing the efficiencies of these waveforms, the maximum energy spectral density, which they produce when applied to an unmodulated carrier, has been calculated for an assumed 10% increase in occupied radio-frequency bandwidth. The results are plotted in Fig. 2, relative to that which would occur under the conditions of busy-hour loading; the curves of Fig. 2 have been designated A-D as described above. Some approximation occurs here, because difficult questions of the relation between signal distortion and radio-frequency bandwidth limitation have been avoided by assuming:

- Carson bandwidth occupancy (with peak-to-r.m.s. ratio of 12 dB) throughout;
- that this bandwidth formula may also be applied to the sum of the signal and dispersed r.m.s. deviation when the dispersal is by noise band;
- in other cases, that the occupied radio-frequency bandwidth is increased by the peak-to-peak dispersal deviation.

The errors so incurred are not thought to be large, and in any case should be in the same sense for all waveforms. As a further approximation, each type of dispersing waveform is represented in Fig. 2 by a single curve. The relation between the typical channel capacities and r.m.s. deviations implied by the two abscissae scales is based on the information given in the Annex to Report 708.

2.1.1 Sinusoidal dispersal

It is evident from Curve A of Fig. 2 that carrier energy dispersal by a sinusoidal signal is rather inefficient, while Curve B shows that a sinusoidal signal with 30% of third harmonic is only about 2 dB better. For a typical 20-channel transmission, the maximum power density in either case, exceeds that which occurs under full-loading conditions by about 10 dB. It is a feature of both these types of dispersal, that the amount by which the dispersed power-density exceeds that at full loading increases, with the r.m.s. multi-channel deviation, and hence, with channel capacity. For example, the excess for 1200 channels is about 18 dB.

2.1.2 Triangular dispersal

The most effective way, for a given increase in occupied bandwidth, of dispersing the energy present in a single spectral line is, at least theoretically, by the application of a triangular waveform. The dispersed power-density is inversely proportional to the permitted percentage increase in radio-frequency bandwidth and Curve D of Fig. 2 shows that, if a 10% increase in occupied bandwidth is permitted, the dispersed power per 4 kHz exceeds that under full-loading conditions by only about 4.5 dB for most numbers of channels.

With the use of low-frequency (≤ 1 kHz) triangular dispersal waveform on multi-channel systems a wanted single channel-per-carrier system can be exposed to nearly the full power of an interfering carrier for significant periods of time.

The triangular waveform evidently offers a simple and efficient means of dispersing the energy present in isolated spectral lines of telephony transmissions. It must be remembered, however, that its effectiveness depends upon faithful preservation of the shape of the wave until it appears as frequency-modulation, particularly when a high degree of dispersal is required. If 32 dB of dispersal were required for a 1200-channel transmission, for example, flattening of the extremities of the wave by only 0.25% might lead to a local doubling of spectral energy density.

The triangular signal may have to be filtered before being applied, to prevent the harmonics of the fundamental from disturbing the lower channels of the telephone multiplex. For triangular waveform frequencies of up to 150 Hz and for a low frequency multi-channel baseband of 4 kHz, filtering causes deformation at the angles of the signal waveform and thus at the energy density peaks at the extremities of the modulation spectrum under light-loading conditions.

Table I below, shows measured values for the increase in energy density at the extremities of the spectrum in relation to the density at the centre frequency of the spectrum, for a 132-channel multiplex, as a function of the frequency of the triangular waveform. Discontinuous single step regulation was used for this system.

TABLE I

Frequency of triangular waveform (Hz)	Increase in energy density (dB)
20	3
80	5
150	7

The low-pass filter used was a 7-pole Chebitchev-type filter with a cut-off frequency of 2.7 kHz and an attenuation at 4 kHz equal to 34 dB.

It is, however, possible to take account of the presence of the continuity pilot at the modulator input provided it is generated independently of the telephone multiplex. Under the same measurement conditions as indicated earlier, the application of a pilot at a level of -20 dBm0 makes it possible to reduce the energy density peaks at the extremities of the band from 7 to 3 dB.

2.1.3 Dispersal by a band of low-frequency noise

A form of carrier energy dispersal that is not critical in its application and shares with triangular dispersal the property of yielding a maximum energy spectral-density, inversely proportional to the amplitude of the waveform, may be accomplished by adding a band of low-frequency noise to the multi-channel baseband. Curve C of Fig. 2 shows that, for a 10% increase in occupied bandwidth, the maximum dispersed power per 4 kHz exceeds that under full-loading conditions by about 9.5 dB for all numbers of channels.

Note. — When the level of the dispersal signal is not fixed, the required amount of dispersion can be attained by the methods given in [CCIR, 1970-74].

2.2 Method 1(b)

An obvious variant of Method 1(a), would incorporate automatic means for adjusting the degree of artificial energy dispersal, applied according to the state of loading of the system, as shown in Method 1(b) of Fig. 1. It might, in fact, be possible in this way, using say, noiseband dispersal, to maintain the maximum energy spectral-density of a transmission quite close to its full-loading value without any increase in occupied radio-frequency bandwidth. The performance that could be achieved in practice, would depend on the distortion produced by the interaction (via radio-frequency bandwidth limitation and other transmission characteristics) of the dispersal waveform and isolated tones and active telephone channels under light-loading conditions. It is probable that the matter can only be settled experimentally, since there is as yet no generally accepted way of calculating the distortion that frequency-modulation signals undergo during transmission, even for the simplest case of white-noise loading.

A particular method which has been proposed for applying the variable degree of dispersal to which the present sub-section relates, relies on filling a suitable proportion of unoccupied telephone channels with simulated speech (i.e. band-limited noise). Although full dispersal could in this way be maintained without increase of bandwidth, the complexity of the apparatus likely to be required for the method is a serious disadvantage, as is the probable necessity for applying it at the audio switchboards from which the baseband originates.

3. Dispersal by automatic deviation control

3.1 General

It would clearly be possible to adjust the signal level entering the system frequency modulator so as to maintain the r.m.s. (or peak) frequency deviation at some constant value. The desired level could be obtained merely by subjecting whatever the baseband content happens to be, to sufficient amplification, or by so amplifying after the addition of some fixed or variable amount of artificial dispersal. The overall baseband transmission loss of the system would be kept sensibly constant by a compensating adjustment of the post-demodulation gain through the medium of a system pilot tone. The possibilities are discussed in the following paragraphs.

3.2 Method 2(a)

The most general method of carrier energy dispersal considered in this Report, of which the others are in a sense degenerate forms, is Method 2(a) in Fig. 1. This consists in adding to the baseband, before the application of automatic deviation control, a source of artificial energy dispersal whose amplitude is made to depend upon the loading conditions. The use of this method might add little or nothing to the occupied radio-frequency bandwidth. Furthermore, if the application of artificial dispersal were delayed until the approach of light-loading conditions, a valuable decrease in the sensitivity of the system to thermal noise, distortion and interference might result. The magnitude of this decrease would depend upon what fraction of the fully-loaded baseband power was attributable to speech signals. As for Method 1(b), some determination of the baseband distortion associated with this method is desirable, although, other things being equal, such distortion would be less than in the earlier method, because the increased deviation-per-channel under light-loading conditions would render the system less sensitive to the radio-frequency distortion components produced.

With regard to the choice of a means of artificial dispersal to be added to the baseband, this might consist of any of the low-frequency dispersal waveforms considered in § 2. The noise-band waveform resembling one or more perpetually active telephone channels is perhaps to be preferred, because it is moderately efficient and because it has the same dispersing effect for a given r.m.s. deviation as the baseband signal, it permits accurate deviation control by a simple r.m.s. detector and presents no difficulties of application at large amplitudes.

3.3 Method 2(b)

As a trivial simplification of the foregoing method, the amplitude of the added dispersing waveform might be set at some fixed value. There would be some increase in occupied radio-frequency bandwidth, although not so much as in Method 1(a) for the same degree of dispersal.

3.4 Method 2(c)

The complete omission of artificial dispersing waveforms from the modulating signal would reduce dispersal by automatic deviation control to its simplest form. The effectiveness of the method would seem to depend on the baseband spectrum retaining some moderate degree of complexity even under light-loading conditions. Unfortunately, it may not be possible to count upon this; in the complete absence of telephone channel activity, the system loading would degenerate to a number of pilot tones, carrier leaks and the like. There might be enough of these in a large system to yield some semblance of evenly distributed baseband power, but this is unlikely to be true of low-capacity systems. In such systems, particularly if many of the carrier leaks were at an unusually low level, the lowest levels of loading might derive from a very small number of prominent pilots.

It can readily be shown that, if the loading of a system results from only one or two prominent tones in the baseband, the radio-frequency spectral-densities may exceed those obtained under full-load conditions by many decibels. It would, therefore, be unwise to rely upon the presence of a few tones to bring about, by application of automatic deviation control alone, a similar degree of energy dispersal to that which results from full-loading.

REFERENCE

CCIR Document

[1970-74]: Doc. 4/273 (U.S.S.R.).

ANNEX II

ENERGY DISPERSAL TECHNIQUES FOR USE WITH ANALOGUE FREQUENCY MODULATION TELEVISION SIGNALS

1. Introduction

In a television transmission system using frequency-modulation a large proportion of the radiated power may be concentrated on or near the radio carrier-frequency under certain modulation conditions, e.g. when a television picture with large areas of the same brightness is being transmitted. Energy dispersal can be achieved by adding a suitable low-frequency waveform to the video signal before modulation.

To obtain information on the degree of degradation which would be introduced when this type of energy dispersal technique is used, an experimental study has been made to determine the subjective effects, on 625-line monochrome television signals, of adding and removing, by several methods, various low-frequency waveforms which are suitable for energy dispersal purposes.

2. Dispersal waveform

The amplitude and shape of the dispersal waveform which is added to the video signal before modulation, must produce the required amount of carrier energy dispersal without introducing a significant degradation in the transmission performance of the system. This latter requirement also depends upon the efficiency of the method used to remove the added waveform and on the overall linearity of the transmission system. Two forms of triangular waveform (the "symmetrical" triangular and the "sawtooth" waveform), having repetition frequencies centred around 50, 25 and 12.5 Hz, have been considered in some detail to determine which waveform is to be preferred.

It was thought that the most favourable result would be obtained by synchronizing the dispersal waveform to the field-frequency of the television signal and also, that the relative phasing of the synchronized signals might, in some cases, give variations in picture impairment. These effects were examined by using both synchronized and unsynchronized dispersal waveforms and, as far as impairment to the received picture is concerned, the tests showed that there is a considerable advantage to be gained by using a synchronized, rather than an unsynchronized waveform. As the generation of waveforms synchronized to the television field-frequency presents no practical problems, the remaining experiments were confined to synchronized waveforms.

The process of synchronization should normally ensure correct phasing of the waveform with respect to the television field information. With the 50, 25 and 12.5 Hz "sawtooth" and the 25 and 12.5 Hz "symmetrical" waveforms, all points of inflection will occur during the field-blanking interval and the discontinuities in the slope of the waveform will not appear as an impairment to the picture. With the 50 Hz symmetrical waveform, only alternate points of inflection can coincide with the field-blanking interval and the remaining points occur at the mid-point in each television field (i.e. across the middle of the picture).

It was thought likely that the peak-to-peak level of waveform which would be required for energy dispersal purposes, was between 10 and 50% of the peak-to-peak amplitude of the video signal before pre-emphasis, and the tests were confined to this range of levels.

A method of increasing the level of dispersal without, at the same time, increasing the peak frequency deviation is described by [Kumysh, 1970] and [Shavdiya and Ignatkin, 1974]. In this method it is proposed that the spikes formed at the edges of the video signal pulse as a result of the normal pre-emphasis network, be subjected to non-linear processing prior to modulation. This process decreases the peak-to-peak amplitude of the video signal, thereby providing the possibility of increased dispersal within the original bandwidth of the system.

A further factor to be taken into account in the design of dispersal systems is the likely presence of "natural" dispersal resulting from imperfections of system components. For example, systems involving up converters may introduce a significant level of dispersal as a result of "jitter" within the oscillators included in these units. Further study is required to determine what contribution "natural" dispersal may make to the problem of co-ordination, without at the same time introducing unacceptable reduction in system performance of the dispersed system.

3. Linearity of the transmission channel

When there are non-linearities in the transmission channel, intermodulation phenomena may appear between the dispersal waveform and the video signal. In such cases, there may be serious defects in the television picture, especially in colour pictures. For example, tests made with the PAL system and a symmetrical triangular dispersal waveform at 50 Hz (synchronized in the field scan) and about 0.5 V peak-to-peak amplitude, measured before pre-emphasis at a point where the video signal is at the nominal reference level (see Recommendation 270-2), showed that the subjective quality index of the picture was equal to 3 in the six-grade quality scale (Note 2 in Report 405-3) under the following conditions:

— differential phase	8°
— differential gain	10%
— short-term non-linearity	10%

It would seem advisable to continue the study of this subject, so as to determine the permissible limit of non-linearity for various television systems, in a satellite television link using energy dispersal.

4. Removal of dispersal waveform

At the receiving earth station, the dispersal waveform must be removed from the baseband signal, and the following methods have been proposed:

4.1 Waveform cancellation

The dispersal waveform can be removed from the baseband signal by "cancelling" it with a locally generated dispersal waveform which is added in anti-phase. It may be useful to transmit the dispersal waveform in a subsidiary channel as an alternative to regenerating the waveform locally.

Two methods of cancellation are possible. In the first method the dispersal waveform may be added in anti-phase, after demodulation. In the second method the local oscillator in the earth-station receiver is frequency modulated by the anti-phase dispersal waveform. This has the advantage that, since the energy dispersal is cancelled before demodulation of the frequency-modulation signal, no increase in the IF bandwidth is necessary. Recent experiments indicate that waveform cancellation followed by clamping (as described in § 4.2) is an effective method, and removes the dispersal waveform more completely than one or two stages of clamping alone.

4.2 *Black-level clamping*

The effects of the dispersal waveform may be removed from the baseband signal by using a well established television technique known as "black-level clamping". The "clamp" is a device which is normally used to remove low-frequency distortion from a television signal by means of a sampling and error correcting process [Savage, 1962; Doba and Rieke, 1950].

The amount by which a low-frequency error-signal may be reduced by "clamping" is a function of the frequency of the error signal and of the level of random noise present on the video signal. As initial satellite systems may have to handle video signals having a poor signal-to-noise ratio, the characteristics of the clamps used in these experiments were adjusted to be consistent with the optimum performance which can be obtained with 625-line systems operating under conditions of poor signal-to-noise ratio. A typical characteristic for sinusoidal error-signals is given in Table II.

TABLE II

Error-signal frequency (Hz) (sine-wave)	50	25	12.5
$\frac{\text{Peak-to-peak error-signal output}}{\text{Peak-to-peak error-signal input}}$ (dB)	-15	-21	-27

(It should be noted that as the frequency of the error signal decreases, both the efficiency of the clamp and the visibility of flicker on a picture increase; on a subjective impairment basis, therefore, these two effects tend to cancel each other out.)

The effect of clamping an error signal having a triangular shape, produces a result which is similar to that which would be obtained if the error waveform were differentiated and with the levels which may be necessary in a practical energy-dispersal system, a single clamp of the type described does not reduce to an acceptable level the impairments introduced by any of the various waveforms under consideration.

At this point a major difference between the "sawtooth" and "symmetrical" waveforms should be mentioned. Because the slope of the "sawtooth" waveform is constant during the "active" part of each television field, the only impairment which may be observed on a picture monitor after the video signal has been clamped, is a slight, and probably insignificant shading across the picture. However, the very high slope of the dispersal waveform during the field-blanking interval causes a serious distortion of the waveform during this period, the magnitude of which is dependent upon the level of dispersal waveform being used. In practice, this distortion is most undesirable, as it can interfere with both synchronizing and vertical interval test signals which occur during the field-blanking interval. It is also extremely difficult to remove this form of distortion once it has been introduced into the video waveform.

With the "symmetrical" waveform, the residual impairment left after a single clamping operation can be observed as a picture impairment. With the 50 Hz waveform, the impairment appears as a disturbance across the middle of the picture. For the 25 and 12.5 Hz waveforms, a picture "flicker" can be observed. This effect is also dependent on the level of dispersal waveform being used, but the application of a further clamp will reduce the flicker effect to a level where it is imperceptible, even with a dispersal waveform amplitude of 50% of the peak-to-peak amplitude of the video waveform.

Although the characteristics of the waveform distortion left after twice clamping the signal are somewhat different in character, the magnitude of the residual distortion when a "symmetrical" dispersal waveform is used is some 10 to 20 dB less than when a "sawtooth" waveform is used.

4.3 *Frequency feedback*

The dispersal signal may be removed by the use of narrowband frequency feedback techniques applied to the IF stage of the receiver. This method has the advantage that it allows the effective receiver bandwidth to be reduced thereby improving the noise threshold of the receiver.

In a particular application of the above mentioned principle, a dispersal signal of 2.5 Hz was selected. At the receiver the dispersal signal is removed by means of a negative feedback circuit containing a low frequency filter with a cut-off frequency lower than the lowest frequency of the video signal. The frequency deviation caused by the dispersal signal is thereby reduced by a value dependent on the degree of feedback employed, and a reduction of 15 dB is readily achievable; the amplitude of the video signal being unaffected.

5. Dispersal by video signal transformation

With angular modulation of the television signal, carrier energy dispersal can be provided by reversing the polarity of the video signal line by line and replacing line and frame synchronizing pulses by bursts of sinusoidal oscillations. The period of each burst is equal to that of the corresponding synchronizing pulse, and the peak-to-peak amplitude of the sinusoidal oscillation is equal to that of a video signal.

The test results obtained by this carrier dispersal method are given in [Mustafidi and Finogeev, 1976].

6. Line frequency energy dispersal waveform

The conventional television energy dispersal waveform, a triangular wave at one-half the field frequency, is ineffective in providing protection for single-channel-per-carrier (SCPC) transmissions. This is because, with the resulting frequency sweep rate of about 1 MHz per 1/50 s, the time spent by the television carrier within the SCPC receive passband is much greater than the response time of the receiver IF filter. As a result the demodulator in the SCPC receiver is periodically exposed to the full television carrier power.

In order to protect the SCPC receiver, it is desirable to use a much higher frequency for the energy dispersal waveform; however, the frequency must be chosen so that the waveform can be easily removed from the video signal at the receiving end of the satellite link, and so that any unavoidable residue tends not to be noticed by the television viewer.

A waveform that meets these requirements is a triangular wave at the line frequency, whose phase is reversed after each line. The reversals occurring simultaneously with the horizontal sync pulses [Weinberger, 1977]. In a test using this waveform, interference to SCPC transmissions using FM with syllabic companding was undetectable at a carrier-to-interference (C/I) ratio of -4 dB. With the conventional waveform, on the other hand, interference could be detected at a C/I ratio of 25 dB.

Other tests have confirmed that the above described dispersal waveform is not readily discernable by the viewer. It also does not appear to interfere with synchronization in home receivers when the signal-to-noise ratio is high.

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ANNEX III

ENERGY DISPERSAL TECHNIQUES FOR USE WITH DIGITAL SIGNALS

1. General

When the information pulse train has a random pattern, the energy of the RF carrier is sufficiently dispersed to reduce the peaks of the power flux-density at the surface of the Earth produced by emission from the space station. If, however, the information pulse train includes a fixed pattern having a periodic repetition rate, some line components appear in the spectrum of the RF carrier, and it follows that some of the peaks of the power flux-density at the surface of the Earth may exceed the level recommended by the CCIR.

The purpose of the energy dispersal techniques described here is to reduce the peaks of the spectrum by producing a transmission pulse train similar to a random pattern, irrespective of any patterns in the information pulse train. Two methods of energy dispersal techniques are described in § 3.

2. Spectra of PSK digital signals

The power spectrum of a carrier modulated by ideal phase reversals consists of "lines" which for a pseudo-random sequence of N symbols of t seconds per symbol are separated by $1/Nt$ Hz. The power spectrum of these lines is given approximately by the following equation:

$$W(f) \approx \frac{1}{N} \left\{ \frac{\sin \pi (f - f_c)t}{\pi (f - f_c)t} \right\}^2 \delta \left(f - f_c - \frac{n}{Nt} \right) \quad (1)$$

where:

- N : length of the pseudo-random sequence (symbols)
- t : symbol duration (seconds)
- n : integer

f_c : RF carrier frequency (Hz)

δ : delta function.

The largest line is at $n = 1$.

As the sequence length approaches infinity, $N \rightarrow \infty$ then $Nt \rightarrow \infty$, and the "line" separation $\rightarrow 0$. In this case the power spectrum becomes continuous and thus:

$$W(f) = t \left\{ \frac{\sin \pi (f - f_c) t}{\pi (f - f_c) t} \right\}^2 \text{ per Hz} \quad (2)$$

In this case, it is seen that the maximum spectral-density occurs at the carrier frequency.

Equation (2) shows the mean value of the power spectrum with the idealized situation of a random pulse train. The actual modulating signal may be far from random. For example, in the case of PCM telephony employing 8 bits per sample, there is likely to be considerable periodicity at one-eighth of the bit rate, and during periods of light traffic loading the situation could arise that the transmitted signal consists almost entirely of zeros. Under these conditions the PSK spectrum will have much of its power concentrated into one, or a few, spectral lines and the dispersal factor could approach 0 dB.

In addition to the non-randomness in the information part of the signal there will also be repetitive patterns in the preambles of time division multiple access (TDMA) transmissions.

Also, in a practical system, the spectrum will be modified by pulse phasing and/or post-modulator filtering. However, this will have greatest effect towards the edges of the spectrum and the maximum spectral-density will not be greatly affected.

To ensure a desired degree of dispersal a pseudo-random sequence of Nt duration can be modulo-2 added to the information bit or symbol stream, as shown in Fig. 3.

For a reference bandwidth of 4 kHz, an energy dispersal factor (D) may be defined as:

$$D = 10 \log \frac{\text{total power}}{\text{maximum power per 4 kHz}} \quad (3)$$

When a pseudo-random sequence is utilized for energy-dispersal the degree of dispersal can be estimated by equations (1) and (3) when $1/Nt \geq 4$ kHz and by equations (2) and (3) when $1/Nt < 4$ kHz.

As it is indicated by the preceding equations, the degree of dispersal is proportional to N as long as the sequence duration is less than the reciprocal of the reference bandwidth. There is little additional dispersal to be gained after the sequence duration reaches 250 μ s (4 kHz reference bandwidth).

3. Energy dispersal techniques

3.1 Method 1: Pseudo-random scrambler

This method consists of maintaining the transmission pulse train in a state similar to that which it would have for a random pattern, irrespective of channel occupancy, by synthesizing a pseudo-random sequence from the information pulse train generated in a pseudo-random code generator using an exclusive OR circuit (Modulo-2 Adder). A schematic diagram of an energy dispersal circuit of the transmitting unit is shown in Fig. 3a. In a receiving unit a pseudo-random code generator, generating the same code pattern as that in the transmitting unit, recovers the original information by synthesizing the pseudo-random code sequence, generated by the pseudo-random code generator, with the transmission pulse train in an exclusive OR circuit. Fig. 3b shows a schematic diagram of such a receiving unit.

One of the merits of this technique is that the energy-dispersal can be achieved without any degradation of the quality of the information pulse train. On the other hand, a disadvantage of this technique is that it necessitates the synchronization of the pseudo-random code generator in the receiving unit with the pseudo-random code generator in the transmitting unit. However, in the case of TDMA systems, the synchronization between both pseudo-random code generators can be effected by utilizing the burst synchronization signal already provided by the receiving unit, hence no additional device will be needed for synchronization.

It should be noted that the symbol (or "chip") rate of the pseudo-random sequence need not necessarily be equal to that of the information pulse train.

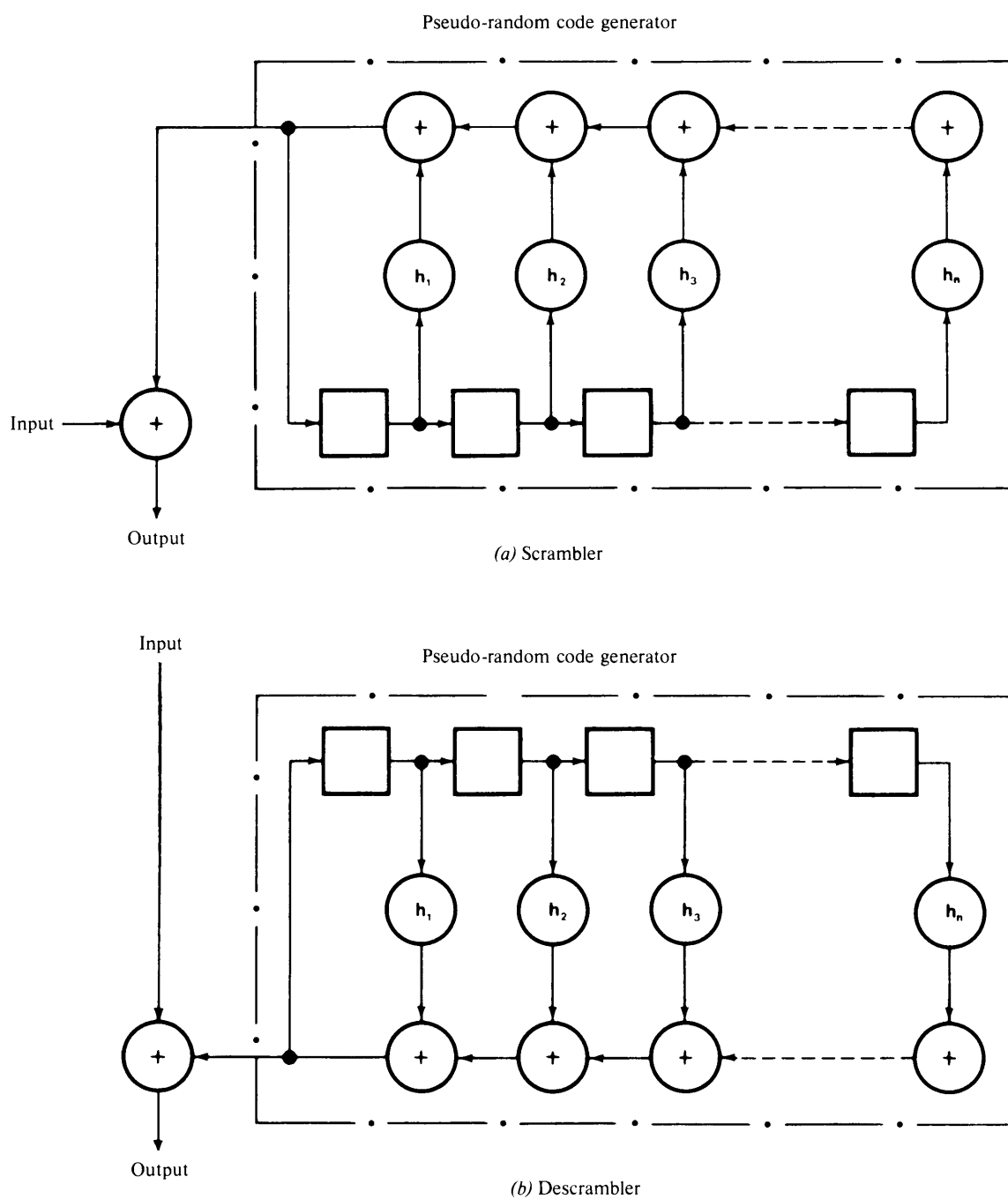


FIGURE 3 — An example of energy-dispersal circuits using method 1

Note. — $h_1, h_2, \dots, h_n$ represent the shift register internal connections which determine the code sequence.

3.2 Method 2: Self scrambler

In this energy dispersal technique, shift registers having a feedback loop and a feedforward loop are installed in the transmitting and receiving units, respectively. In the transmitting unit a code conversion is performed for each bit of the information pulse train. At the receiver, each bit of the transmission pulse train is reconverted to recover the original information pulse train. Typical circuit arrangements of such scramblers and descramblers are shown in Fig. 4a and b respectively.

One of the merits of this energy dispersal method is that no synchronization is needed between the scrambler and the descrambler. On the other hand, there is a disadvantage in that, if r is the number of the stages of the shift register, the initial state of this register affects the first r bits of the transmission pulse train and consequently a single bit error in the RF transmission channel affects the r bits immediately following the error bit. This method, however, can be used together with error detection and correction; and it may represent a suitable energy dispersal method for use in PCM data transmission systems, especially those operating in the continuous mode as distinguished from the TDMA mode.

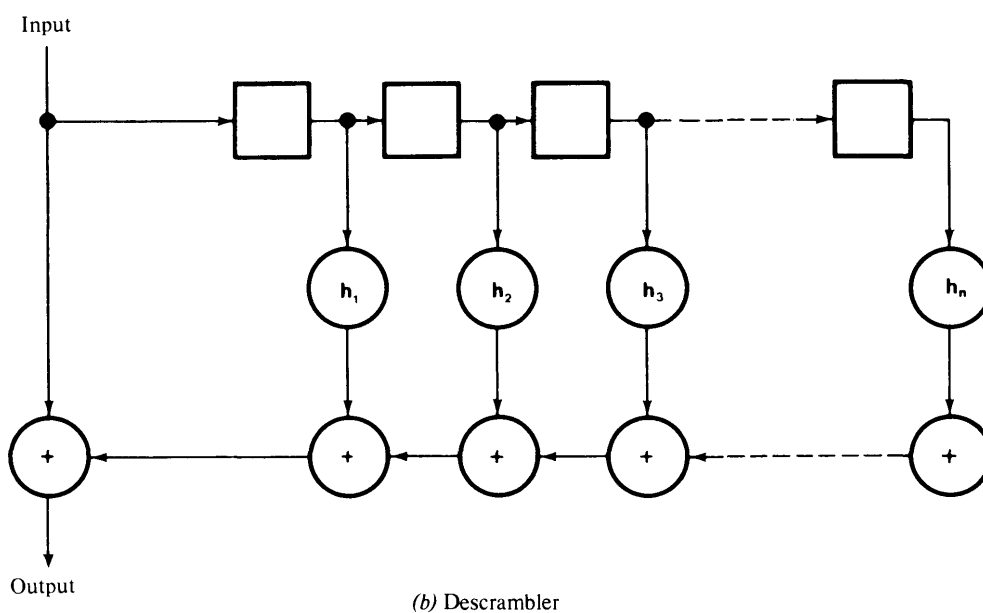
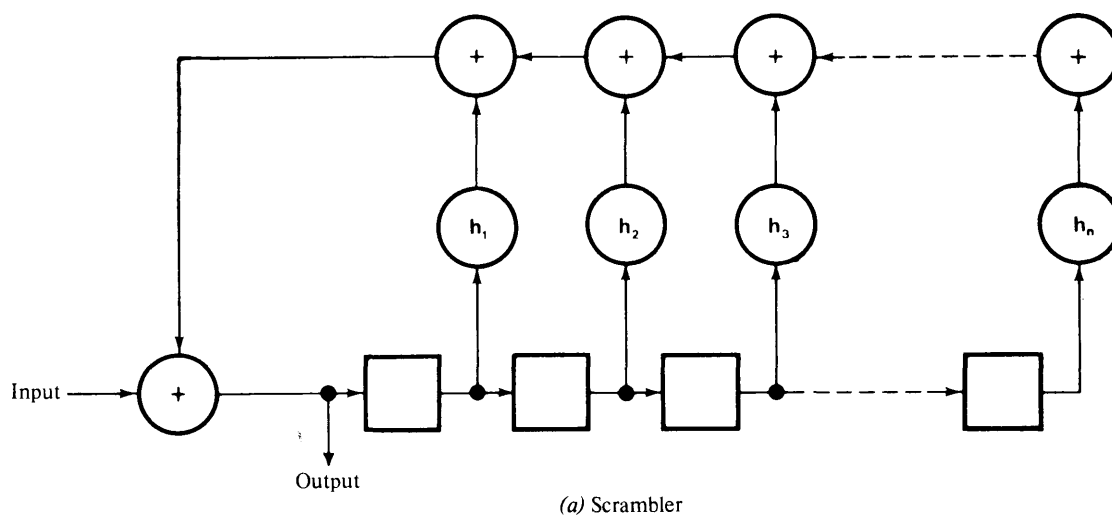


FIGURE 4 — An example of energy-dispersal circuits using method 2

Note. — $h_1, h_2 \dots h_n$ represent the shift register internal connections which determine the code sequence.

4. Energy dispersal factor for TDMA systems

The degree of dispersal obtained by Method 1 is directly proportional to the length of the pseudo-random sequence. However, there is no point in using a sequence which is greater than 250 μ s in duration since the spectral lines in the dispersed spectrum would then be at less than 4 kHz separation. In a TDMA system the pseudo-random signal generated at the receiver can be most readily synchronized with that at the transmitter, if the sequence starts again from the beginning in every TDMA burst. This means that sequence lengths will usually be less than 250 μ s and that the ideal dispersal will not be achieved.

The energy-dispersal effects for a TDMA signal depend on the length of the pseudo-random sequence, the frame length, the number of the bursts, the length of each burst, the scrambler methods and so on. If it is assumed for the sake of simplicity, that the length of each burst is equal to, or less than, 250 μ s, and that each burst is scrambled by the same pattern of the pseudo-random sequence in every frame, the energy dispersal factor (D) can be given approximately by the following equations:

$$D = 10 \log N + 10 \log B - K, \text{ when } N < M \quad (4)$$

$$D = 10 \log M + 10 \log B - K, \text{ when } N > M \quad (5)$$

where:

N : length of the pseudo-random sequence (symbols),

M : length of the information sequence (symbols),

B : number of the bursts in one frame,

K : margin for the energy-dispersal effect.

In the above equations, K is the statistical variation term indicating the decreasing degree of the energy dispersal effects caused by:

- the effect of the partial coincidence between an information sequence and a pseudo-random sequence;
- the effect of the difference between the length of the information sequence and that of the pseudo-random sequence;
- the effect of the carrier phase coherency between the bursts.

Among these effects, the first can be evaluated as follows: when the information sequence has weak frame correlation, the margin due to partial coincidence depends on the observation period of the power spectrum. On the other hand, when the information sequence has strong frame correlation, almost the same sequence pattern would be generated in every frame, so that its margin can be estimated by regarding the frame period as the observation period mentioned above.

The second effect could be made negligibly small by properly choosing the degree and the initial value of the pseudo-random sequence, if the length of the pseudo-random sequence is less than several times that of the information sequence.

The third effect is also negligibly small, since the carrier frequency of each burst is usually different by more than several hundred Hz from the adjacent bursts.

Clearly, the complexity of the system is greatly reduced if the pseudo-random sequence is applied only to the information part of the signal and not to the preamble of a TDMA burst. Generally the preamble will consist, at least in part, of a simple repetitive pattern. In some cases, it may even contain a period of unmodulated carrier. The results presented in Table III, below, show that for a repeated 0011 preamble pattern in a 4-phase PSK system, the preamble will not contribute significantly to the maximum spectral-density except perhaps for low bit rate systems. Other preamble patterns having the same duration as that assumed for Table III would be no more than 3 dB worse.

To illustrate what dispersal factors might be achieved in practice, Table III shows the values for a TDMA system in which the preamble is not dispersed. Certain assumptions were made as follows:

- frame length, 125 μ s;
- modulation, 4-phase PSK;
- preamble signal, 40 bits of alternating 0011;
- carrier frequencies of all stations are within 4 kHz of each other, but the symbol timing of different stations is not necessarily in phase;
- pseudo-random sequence generators are reset after every burst.

Statistical variation of the power spectrum is such that 1% of the spectral lines will exceed the r.m.s. envelope by 6.5 dB.

5. An example of energy dispersal applied to an experimental TDMA system

Method 1 energy-dispersal techniques were utilized in the TTT system, an experimental, 50 Mbits/s TDMA system developed in Japan for use in satellite radiocommunications systems. In this system, only the information bits are scrambled, yet it is found that the peak value of the power spectrum is suppressed by about 20 dB.

It is noted that when energy dispersal using a pseudo-random sequence is applied to a TDMA system, the probability of false detection of a given "unique word" may increase to an extent depending on the manner in which the burst is synchronized.

False detection of the unique word can be avoided by changing the initial state of the pseudo-random sequence for every frame.

TABLE III — Illustrative energy-dispersal factors for a range of pseudo-random sequence lengths

	Single access			10 equal station access						Resultant dispersal factors (dB)		
				Maximum power in a 4 kHz band (dB relative to total steady power)								
				(a) due to preambles			(b) due to information					
Bit rate (Mbit/s)	10	50	250	10	50	250	10	50	250	10	50	250
Random modulating signal	31	38	45							31	38	45
127 bit pseudo-random sequence	12	12	12	-23	-37	-51	-20	-22	-22	20	22	22
511 bit pseudo-random sequence	18	18	18	-23	-37	-51	-20	-28	-28	20	28	28
2 047 bit pseudo-random sequence	24	24	24	-23	-37	-51	—	-29	-34	—	29	34
32 767 bit pseudo-random sequence	25	32	36	-23	-37	-51	—	—	-36	—	—	36
Typical fully loaded FM system occupying same bandwidth as the digital system (based on Gaussian spectrum and a ratio of RF bandwidth to baseband width equal to 15)	27	34	41									

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RECOMMENDATION 464

**PRE-EMPHASIS CHARACTERISTICS FOR FREQUENCY-MODULATION SYSTEMS
FOR FREQUENCY-DIVISION MULTIPLEX TELEPHONY
IN THE FIXED SATELLITE SERVICE**

(Study Programme 2D-1/4)

(1970)

The CCIR,

CONSIDERING

- (a) that the pre-emphasis characteristic should preferably be such that the r.m.s. deviation due to the frequency-division multiplex telephony signal is the same with and without pre-emphasis;
- (b) that in a frequency-modulation system for frequency-division multiplex telephony operating well above threshold the thermal noise is highest in the top channel and decreases with decreasing baseband frequency;
- (c) that in a phase-modulation system, or in a frequency-modulation system with pre-emphasis at 20 dB per decade, operating well above threshold the thermal noise is constant over the whole baseband;
- (d) that the thermal noise in the highest channel of a phase-modulation system is approximately 4.8 dB lower than the corresponding channel of a frequency-modulation system, assuming that both systems operate well above threshold and are adjusted to have the same multi-channel r.m.s. frequency deviation;
- (e) that the reduction in frequency deviation with decreasing baseband frequency in a phase-modulation system makes such a system more sensitive to low frequency noise, especially that arising in threshold extension demodulators operating near to threshold;
- (f) that for earth stations normally operated above threshold the efficiency of use of satellite transmitter power is practically unaffected by changes in the range of pre-emphasis characteristic from below 6 dB to about 8 dB, but the efficiency of use of radio-frequency bandwidth increases slightly with an increase in pre-emphasis range;
- (g) that there is insufficient information at the present time to assess the optimum pre-emphasis characteristic for systems using radio-frequency carriers with capacities of less than 12 telephone channels,

UNANIMOUSLY RECOMMENDS

1. that in systems in the Fixed Satellite Service employing frequency modulation, radio-frequency carriers with capacities of 12 or more telephone channels should be used with pre-emphasis and should use the same normalized pre-emphasis characteristic;
2. that the pre-emphasis characteristic for numbers of telephone channels less than 12 should be the subject of further study;
3. that the preferred pre-emphasis characteristic is given by the expression:

$$\begin{array}{l} \text{Relative frequency} \\ \text{deviation of the test tone} \\ \text{at the frequency } f \end{array} = 5 - 10 \log_{10} \left[1 + \frac{6.90}{1 + \frac{5.25}{\left(\frac{f_r}{f} - \frac{f}{f_r}\right)^2}} \right] \quad \text{dB}$$

where $f_r = 1.25 f_{max}$ is the resonant frequency of the network, f_{max} is the highest telephone channel baseband frequency of the system and f is the baseband frequency. The variation of deviation with frequency is shown in Fig. 1;

4. that the tolerance on the frequency response of the pre-emphasis characteristic, and also on the de-emphasis characteristic should be such that, within the nominal upper and lower limits of the baseband, the departure of the characteristic of a practical network from the theoretical characteristic should be confined within a variation of $\pm (0.1 + 0.05f/f_{max})$ dB, f being the baseband frequency and f_{max} the nominal maximum frequency of baseband. This corresponds to component tolerances of about $\pm 1\%$ for resistors and about $\pm 0.5\%$ for capacitors and inductors. Further, the magnitude of the departure should exhibit no rapid variations within this frequency range.

Note 1. — It is recognized that it may be desirable to achieve the pre-emphasis characteristic by inserting a network at different places in various types of equipment. An example of pre-emphasis and de-emphasis network, to work between a constant-voltage source and an open-circuit load, is shown in Figs. 2a and 2b, respectively. An example to work between matched resistive input and output impedances is shown in Figs. 3a and b, respectively.

Note 2. — In the expression for the relative deviation as indicated in § 2, it should be noted that the frequency at which the deviation with pre-emphasis corresponds to that without pre-emphasis is $0.608 f_{max}$. It may be convenient to adopt this frequency for testing the loss between baseband terminal points of systems when these are not in service.

Note 3. — It is recognized that it may sometimes be desirable to use a different pre-emphasis characteristic by agreement between the Administrations concerned.

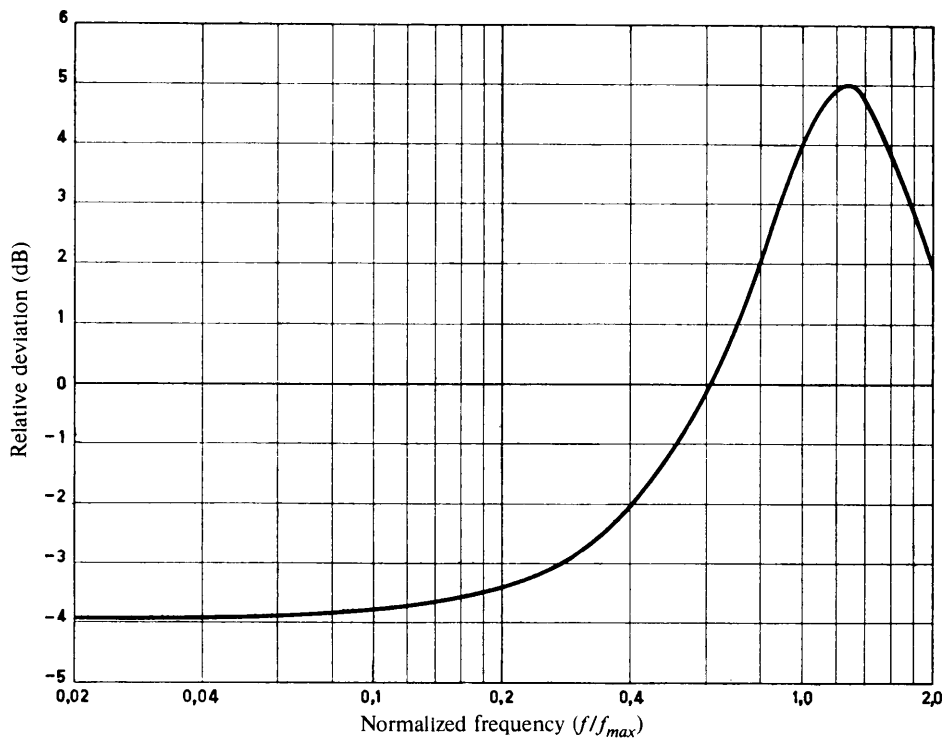


FIGURE 1 — Pre-emphasis characteristic for telephony

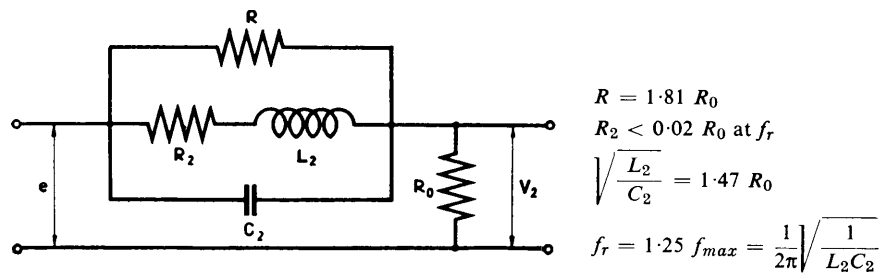
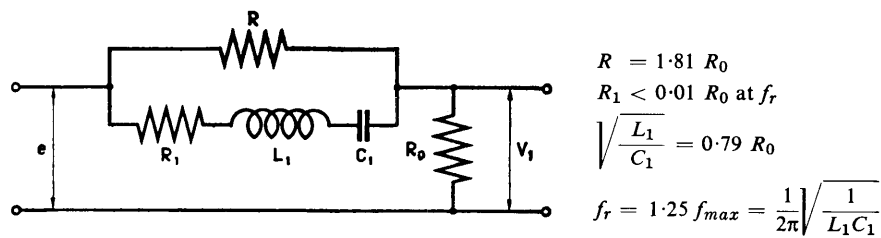
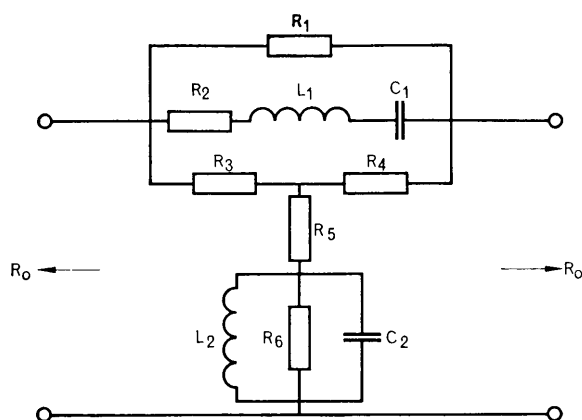


FIGURE 2 — Pre-emphasis and de-emphasis networks to work between a constant-voltage source and an open-circuited load



(a) Pre-emphasis network

$$R_1 = 1.81 R_0$$

$$R_2 < 0.01 R_0$$

$$R_3 = R_4 = R_0$$

$$R_5 = \frac{R_0}{1.81}$$

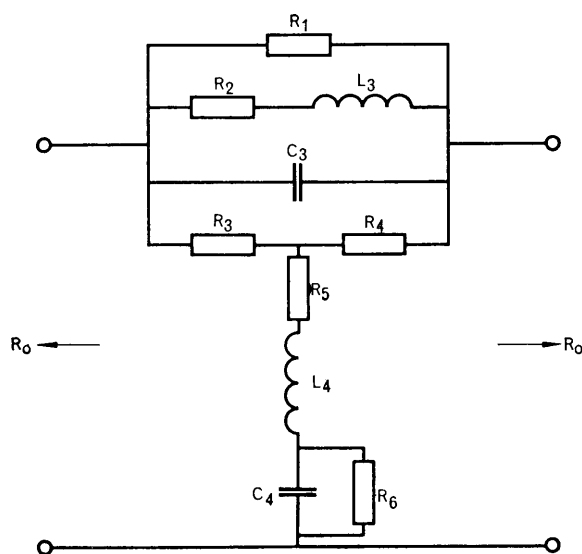
$$R_6 > 100 R_0$$

$$f_r = 1.25 f_{max} = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1}}$$

$$= \frac{1}{2\pi} \sqrt{\frac{1}{L_2 C_2}}$$

$$\sqrt{\frac{L_1}{C_1}} = 0.79 R_0$$

$$\sqrt{\frac{L_2}{C_2}} = \frac{R_0}{0.79}$$



(b) De-emphasis network

$$R_1 = 1.81 R_0$$

$$R_2 < 0.01 R_0$$

$$R_3 = R_4 = R_0$$

$$R_5 = \frac{R_0}{1.81}$$

$$R_6 > 100 R_0$$

$$f_r = 1.25 f_{max} = \frac{1}{2\pi} \sqrt{\frac{1}{L_3 C_3}}$$

$$= \frac{1}{2\pi} \sqrt{\frac{1}{L_4 C_4}}$$

$$\sqrt{\frac{L_3}{C_3}} = 1.47 R_0$$

$$\sqrt{\frac{L_4}{C_4}} = \frac{R_0}{1.47}$$

FIGURE 3 — Pre-emphasis and de-emphasis networks to work between matched resistive input and output impedances

REPORT 212-3

**USE OF PRE-EMPHASIS IN FREQUENCY-MODULATION SYSTEMS
FOR FREQUENCY DIVISION MULTIPLEX TELEPHONY
AND TELEVISION IN THE FIXED SATELLITE SERVICE**

(Question 2-3/4)

(1963 - 1966 - 1970 - 1974)

1. Introduction

The use of pre-emphasis in systems in the Fixed Satellite Service for frequency-division multiplex telephony using frequency modulation results in a useful improvement in the signal-to-noise ratio in the higher frequency channels of the system and thus enables the space-station transmitter power and bandwidth requirements to be reduced.

The use of pre-emphasis for television modifies the energy distribution in the radio-frequency emission of systems in the Fixed Satellite Service, in such a way as to reduce, substantially in some circumstances, the possibility of interference within and between systems in the Fixed Satellite Service and between systems in the Fixed Satellite Service and radio-relay systems using the same frequency bands.

The use of pre-emphasis for television may also enable the effective frequency deviation of the system in the Fixed Satellite Service to be increased, thereby improving the signal-to-noise ratio; however, too large an increase in deviation could offset the reduction of interference potential.

The deviation and pre-emphasis used to obtain the best possible transmission of some television signal standards may differ appreciably from those recommended for telephony.

The use by different Administrations of the facilities offered by active systems in the Fixed Satellite Service, including the shared use of space-station repeaters, would be facilitated by the use of agreed pre-emphasis characteristics for such systems employing frequency-modulation.

At the present time it has not been found possible to recommend a preferred pre-emphasis characteristic for systems in the Fixed Satellite Service used for television. This matter is a subject for further study, but some information which may be of assistance in these studies is given in § 3 of this Report.

2. Telephony

The effect of pre-emphasis will be to improve the signal-to-noise ratio in the high frequency channels and to reduce it in the low frequency channels. This may in turn affect the carrier-to-noise ratio at which the noise in the worst channel reaches 50 000 pWp at a point of zero relative level. Each of these effects will have repercussions on the satellite power and bandwidth required to meet the noise objectives of Recommendation 353-3. Furthermore the optimum characteristic for a system operated at or below threshold for a considerable proportion of the time may not be the same as that for systems which normally operate above threshold.

The threshold margin of present satellite systems is generally sufficient to prevent them from operating below threshold for all but very small proportions of the time and the same is expected to be true for future systems. For general use, therefore, a pre-emphasis characteristic with a relatively wide range of attenuation will be optimum.

Measurements of signal-to-noise ratios in an operational system have confirmed that the network described in Recommendation 464 which has an 8 dB range of attenuation, gives satisfactory results in practice.

However, for systems operating nearer to threshold, a narrower range of attenuation may be found to be optimum.

3. Television

In the transmission of colour television signals, special attention must be paid to:

- noise in the video bandwidth;
- distortion, especially that which may affect the chrominance channel video frequencies (around 4.4 MHz for 625-line systems);
- subjective threshold of the receiver.

The insertion of a pre-emphasis network has the goal of:

- improving the signal-to-weighted noise ratio;
- reducing distortion.

These goals must be attained with minimum impairment of the receiver subjective threshold.

For a given system bandwidth, the signal-to-weighted noise ratio can be improved by modifying the shape of the video noise spectrum, i.e., by modifying the deviation that the various components of the video signal produce on the radio-frequency carrier.

The criteria which influence the design of an optimum emphasis characteristic may differ in different colour television systems. In the following sections the results of studies made by some Administrations on the PAL and SECAM systems are given.

The optimization of the pre-emphasis characteristic for colour television is closely dependent upon the form of the weighting curve adopted for noise measurement. Although this is specified for 625-line system I in Recommendation 567, it has not been universally adopted and thus it will be difficult to agree on a single new pre-emphasis characteristic. The work reported here indicates a possible approach to the problem.

3.1 625-line PAL systems B, G and H

Theoretical calculations have shown [CCIR, 1966-69a] that, for a given signal-to-unweighted noise ratio, the maximum signal-to-weighted noise ratio is obtained when the de-emphasis characteristic produces a spectrum of noise which is uniform with frequency across the video band (0-5 MHz). Applying this principle to a particular noise weighting curve [CCIR, 1966-69b] a new pre-emphasis curve shown in Fig. 1 has been derived which can be shown to improve the signal-to-noise ratio by about 2 dB (assuming a triangular noise distribution). This compares with an improvement of about 1 dB using the pre-emphasis curve of Recommendation 405-1 (with the same noise weighting curve).

Experiments made to investigate the influence of a limitation in the radio-frequency band using the new pre-emphasis curve have shown that the differential distortions in the presence of emphasis were reduced by a factor of between 5 and 15 depending on the form of the modulating signal, compared with distortions measured without emphasis. On the other hand, the luminance-to-chrominance ratio was slightly increased. The overall picture quality measured subjectively was essentially unchanged. Other experiments made with a receiver operating close to threshold, showed that in general the use of pre-emphasis raised the level of threshold assessed subjectively, for example, by 1.5 to 2 dB for the emphasis of Fig. 1 of this Report, or Fig. 1 curve B of Recommendation 405-1 or certain other pre-emphasis curves.

Other studies [Lari and Tomati, 1972] also show that by a suitable selection of a pre-emphasis curve, it is possible to achieve some saving, either in satellite transmitter power or in the bandwidth required, for the same values of signal-to-weighted noise ratio and margin above subjective threshold.

3.2 625-line SECAM system

In the SECAM colour television system, in which the colour information is transmitted by frequency modulation of a sub-carrier at 4.43 MHz, the demodulation of the sub-carrier is subject to the well-known behaviour of frequency demodulators at threshold. Thus, when the noise in the chrominance channel becomes significant, the picture deteriorates rapidly. It becomes necessary to determine the limits of noise in both the luminance and chrominance channels.

These limits have been derived from subjective tests of pictures degraded by thermal noise [CCIR, 1970-74a]. For the degradation of the chrominance signal N_2 , to be equal to the degradation of the luminance signal N_1 , the following relationship should be satisfied:

$$8.5 \text{ dB} < 10 \log_{10} \frac{N_2}{N_1} < 9.5 \text{ dB} \quad (1)$$

where N_1 is the power of the weighted noise in the luminance signal measured at the output of the network as described in Recommendation 567 and N_2 is the power of the filtered noise in chrominance signal measured at the output of the band-pass filter as described in Recommendation 567.

The pre-emphasis network designed for black and white 625-line television systems, described in Recommendation 405-1, is now used for colour television. When so used, it produces the non-optimum value of 12 dB as shown in equation (2):

$$10 \log_{10} \frac{N_2}{N_1} \approx 12 \text{ dB} \quad (2)$$

Therefore, a new pre-emphasis network for SECAM colour television seems desirable. The network and its transfer function are similar to the one described in Recommendation 405-1:

$$-\frac{1}{y} \times \frac{1 + j\omega\tau_p}{1 + j\omega\frac{\tau_p}{y}} \quad (3)$$

where $20 \log y$ is the maximum attenuation of the network in dB, and τ_p is the time-constant of the network in ns.

Values proposed for this transfer function are:

$$\begin{aligned} y &= 8 \quad (\text{instead of } y = 5 \text{ as in Recommendation 405-1;} \\ \tau_p &= 227 \text{ ns (instead of } \tau_p = 508 \text{ ns as in Recommendation 405-1.} \end{aligned}$$

These values are in conformity with the limits given in relation (1).

Fig. 2 shows this characteristic in relation to the one given by Recommendation 405-1 for 625-line television systems at equal overall image impairment. It is clear that the new curve is below the former one in the greater part of the video band; therefore, the radio-frequency spectrum congestion will be less with a network of this type than with the network presently recommended, and the non-linear video distortions due to the bandwidth limitation will be reduced.

Further studies are necessary to ensure that satellite links using the new characteristic will conform in all respects with the specification of Recommendation 567 concerning the hypothetical reference circuit.

3.3 625-line PAL system I

A study has been carried out [CCIR, 1970-74b] to check the validity of the pre-emphasis characteristics shown in Figs. 1 and 2 for the case of 625-line PAL system I. The subjective effect of signal/noise degradation has been evaluated using the method of "impairment units" (imps) [Lewis and Allnatt, 1968] and using the noise weighting networks specified in Recommendation 567.

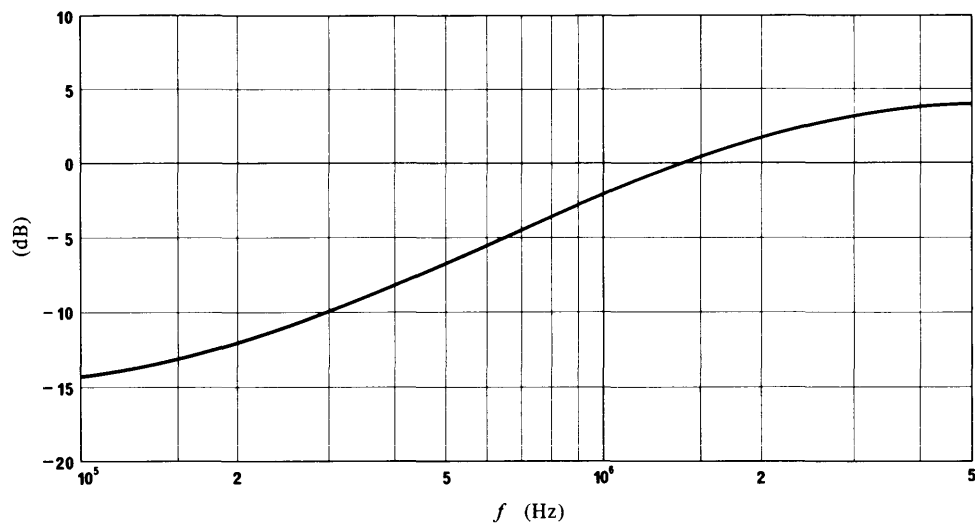


FIGURE 1 — *Experimental pre-emphasis characteristics for the PAL system*

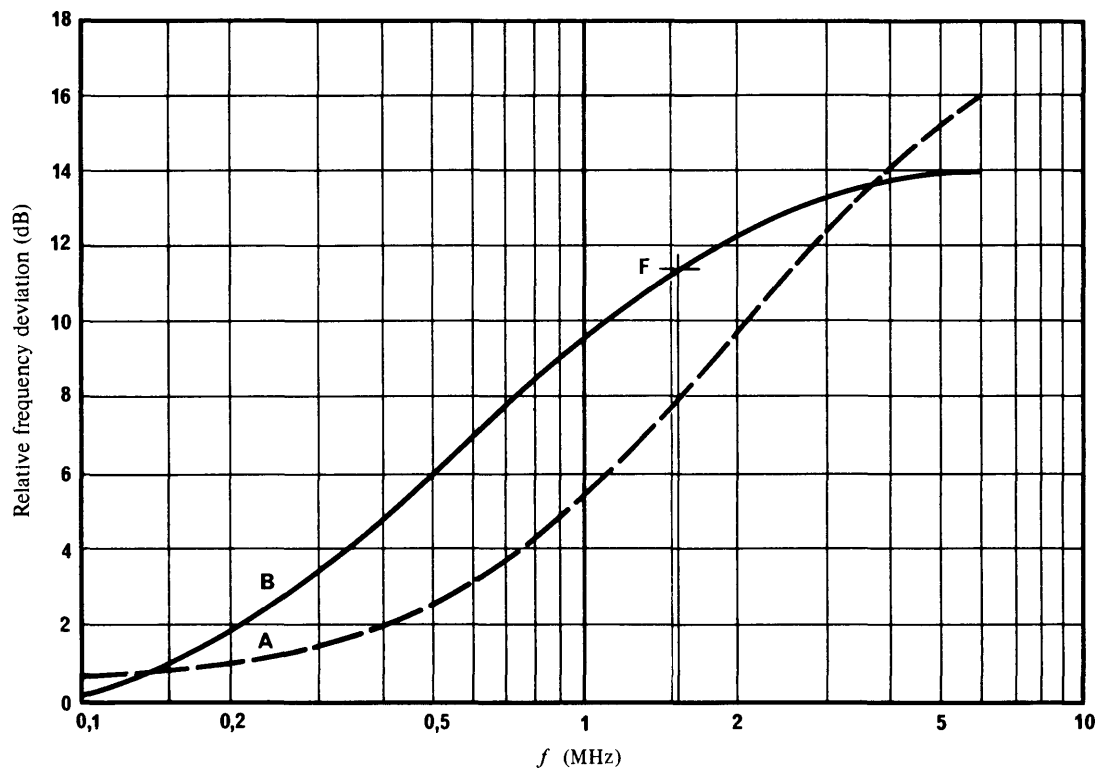


FIGURE 2

A: Calculated pre-emphasis curve proposed for the SECAM system
 B: Pre-emphasis curve recommended in Recommendation 405-1
 F: Reference frequency

The noise was assumed to have a substantially triangular characteristic as will normally be the case when the system is operating near the threshold. The results of this evaluation indicated that, for PAL system I, the network of Recommendation 405-1 gives better results than the other two networks. This may well be due to the fact that the latter have been derived for other television systems using either a different video bandwidth or different chrominance sub-carrier modulation and for different noise weighting networks. Whilst it may eventually be possible to find a new pre-emphasis characteristic which will show some improvement over that of Recommendation 405-1, there seems to be no justification for a change at present. Further study is required which should include the effect on various distortions in addition to signal/noise ratio.

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RECOMMENDATION 481-1

MEASUREMENT OF NOISE IN ACTUAL TRAFFIC FOR SYSTEMS IN THE FIXED SATELLITE SERVICE FOR TELEPHONY USING FREQUENCY-DIVISION MULTIPLEX

(Question 20-1/4)

(1974 – 1978)

The CCIR,

CONSIDERING

- (a) that measurements by means of a generator producing white noise (Recommendation 482-1) are only possible when the radio-frequency channel is not carrying traffic;
- (b) that systems carrying multi-channel telephony cannot be withdrawn from service for measurement at will;
- (c) that protection channels, similar to those used in terrestrial radio-relay systems, are not available for maintenance purposes;
- (d) that maintenance measurements of the total noise (thermal and intermodulation noise) are useful for determining the quality of a system and must be made while the system is carrying traffic;
- (e) that it is convenient to place the channels used for this kind of measurement outside the total bandwidth of the multiplex signal;
- (f) that, when these measuring channels are located outside the total multiplex signal band, they should be positioned as near the limits of the total signal band as possible, to measure the intermodulation products due to the non-linearity of the system;
- (g) that, on the other hand, to facilitate and to minimize the cost of filter construction, the measuring channels should not be positioned too near these limits;
- (h) that measurements in channels about 10% above the upper limit of the total multiplex signal band are generally sensitive to changes of thermal and intermodulation noise in the radio-frequency and intermediate-frequency circuits of the equipment;

(j) that it is usually necessary to use band-stop filters at the input of the system to minimize noise on the incoming circuit in the bands occupied by the measuring channels, and that it will be necessary to specify the minimum performance of these filters, both in the stopband of these filters and at the edges of the total multiplex signal band,

UNANIMOUSLY RECOMMENDS

1. that noise occurring in links in the fixed satellite service while actual traffic is being carried should be measured at the output of the system in relatively narrow bands situated above the total multiplex signal band;
2. that the centre frequencies of these measuring bands should be those listed in Table I;
3. that the attenuation of the band-stop filters at the input of the system should exceed 50 dB over a minimum frequency band of $\pm (0.005 f + 2)$ kHz (f being the centre frequency in kHz of the measuring channel). The additional attenuation caused by the insertion of the band-stop filters at the upper edge of the total multiplex signal band shall not exceed 0.3 dB referred to the additional attenuation caused in the centre of the multiplex signal band;
4. that the effective bandwidth of the bandpass filters in the receiving equipment should be small enough for use with the input band-stop filter mentioned above;
5. that, in all cases where different frequency bands are used, or where there are differences between the measurement techniques, special agreements should be made between the Administrations which use the same space systems of the Fixed Satellite Service.

TABLE I

System capacity (number of channels)	Limits of band occupied by telephone channels (kHz)	Centre frequencies, f of noise-measuring channels (kHz)
12	12- 60	66
24	12- 108	116
36	12- 156	172
48	12- 204	224
60	12- 252	277
72	12- 300	331
96	12- 408	448
132	12- 552	607
192	12- 804	884
252	12-1052	1157
312	12-1300	1499
432	12-1796	1976
612	12-2540	2794
792	12-3284	3612
972	12-4028	4430
1092	12-4892	5381
1332	12-5884	6300
1872	12-8120	8932

RECOMMENDATION 482-1

MEASUREMENT OF PERFORMANCE BY MEANS OF A SIGNAL OF A UNIFORM SPECTRUM FOR SYSTEMS USING FREQUENCY-DIVISION MULTIPLEX TELEPHONY IN THE FIXED SATELLITE SERVICE

(Question 20-1/4)

(1974 - 1978)

The CCIR,

CONSIDERING

- (a) that it is desirable to measure the performance of satellite links in the fixed satellite service for frequency-division multiplex telephony under conditions closely approaching those of actual operation;
- (b) that a signal with a continuous uniform spectrum (white noise) has statistical properties similar to those of a multiplex signal when the number of channels is not too small;

- (c) that the use of a signal with a continuous uniform spectrum to measure the performance of such links is already widespread;
- (d) that it is necessary to standardize the frequencies and bandwidths of the measuring channels to be used for such measurements;
- (e) that for reasons of international compatibility it is necessary to standardize the minimum attenuation and the bandwidth of the stop filters which may have to be used in the white-noise generator;
- (f) that the CCITT has indicated, for the planning of telephone circuits, a mean value of speech power in the baseband of a multiplex telephone system to be taken into consideration during the busy hour (CCITT Recommendation G.223, *Orange Book*, Vol. III-1),

UNANIMOUSLY RECOMMENDS

1. that the performance of frequency-division multiplex satellite links in the fixed satellite service should be measured by means of a signal with a continuous uniform spectrum in the frequency band used for the telephone channels;
2. that the nominal power level of the uniform spectrum test signal should be in accordance with the conventional load, specified in CCITT Recommendation G.223, *Orange Book*, Vol. III-1 *;
- 2.1 that the sending equipment should be capable of providing, at the output of an inserted band-stop filter, a loading level of at least up to +10 dB, relative to the nominal power level defined above;
- 2.2 that, within the bandwidth corresponding to the baseband of the system under test, the r.m.s. voltage of the white noise spectrum measured in a band of about 2 kHz should not vary by more than ± 0.5 dB. This degree of spectrum uniformity should be met in the level range of up to +6 dB, relative to the nominal power level;
- 2.3 that the white noise test signal should be available at the output of the sending equipment with a peak factor of about 12 dB with respect to the r.m.s. value;
3. that the nominal effective cut-off frequencies (the cut-off frequencies of hypothetical filters having ideal square cut-off characteristics and transmitting the same power as the real filters) and tolerances, for the band-limiting filters proposed for the various bandwidths of systems to be tested, should be as specified in Table I. (To reduce the number of filters required, compromises have been made between the nominal effective cut-off frequency and the system bandwidth-limiting frequency in some cases. The tolerances ensure that consequent calibration errors do not exceed ± 0.1 dB and errors in measurement of intermodulation noise do not exceed ± 0.2 dB assuming system pre-emphasis conforming to Recommendation 464);

TABLE I

Capacity (channels)	Limits of band occupied by telephone channels (kHz)	Effective cut-off frequencies of band-limiting filters (kHz)		Frequencies of recommended measuring channels ⁽¹⁾ (kHz)
		High pass	Low pass	
12	12- 60	12 ± 0.5	60 ± 0.5	16 56
24	12- 108	12 ± 0.5	108 ± 1.0	16 98
36	12- 156	12 ± 0.5	156 ± 1.0	16 140
48	12- 204	12 ± 0.5	204 ± 1.5	16 185
60	12- 252	12 ± 0.5	252 ± 2.0	16 240
72	12- 300	12 ± 0.5	300 ± 2.0	16 270
96	12- 408	12 ± 0.5	408 ± 3.0	16 240 394
132	12- 552	12 ± 0.5	552 ± 4.0	16 240 534
192	12- 804	12 ± 0.5	804 ± 6.0	16 394 770
252	12-1052	12 ± 0.5	1052 ± 8.0	16 534 1002
312	12-1300	12 ± 0.5	1296 ± 8.0	16 534 1248
432	12-1796	12 ± 0.5	1796 ± 12	16 534 1002 1730
612	12-2540	12 ± 0.5	2600 ± 20	16 770 1730 2438
792	12-3284	12 ± 0.5	3284 ± 25	16 1002 2438 3150
972	12-4028	12 ± 0.5	4100 ± 30	16 1002 2438 3886
1092	12-4892	12 ± 0.5	4892 ± 40	70 1002 2438 4650
1332	12-5884	12 ± 0.5	5884 ± 50	70 1002 3150 4650 5340
1872	12-8120	12 ± 0.5	8160 ± 75	70 1002 3150 5340 7600

⁽¹⁾ See also Recommends 6.1 of this Recommendation.

* The level of the conventional load in dBm0 is given by:

- 1 + 4 log N , for $N < 240$ channels
- 15 + 10 log N , for $N \geq 240$ channels.

3.1 that the discrimination of a low-pass filter should be at least 20 dB at a frequency of more than 10% above nominal cut-off and at least 25 dB at frequencies of more than 20% above nominal cut-off. The discrimination of a high-pass filter should be at least 25 dB at frequencies of more than 20% below nominal cut-off;

3.2 that to limit discrimination against measuring channels, the spread of losses introduced by any pair of high-pass and low-pass filters should not exceed 0.2 dB over a range of frequencies which includes the upper and lower measuring channels;

4. that values of the characteristics for the discrimination in each stopband at the output of a sending equipment are given in Table II. The passband of each band-stop filter shall be designed to cover at least the largest baseband frequency range with which it is to be used, as indicated in the column entitled "Limits of band ..." in Table I. These characteristics are intended to apply over a temperature range from 10° to 40 °C;

5. that, when the receiving equipment is connected directly to a sending equipment provided with band-stop filters which only just meet the requirements of item 4, the ratio of the noise power indicated by the receiving equipment when the band-stop filter is by-passed, to that indicated when the filter is in circuit, should be a minimum of 67 dB; this requirement applies when a conventional load is applied. The minimum effective bandwidth of the receiver should be 1.7 kHz. The maximum reading of absolute noise power arising from leakage given by a receiver of 1.74 kHz effective bandwidth and which just meets the foregoing leakage requirement is -85.6 dBm0p;

6. that additional measuring channels may be provided by agreement between the Administrations concerned;

6.1 that for the selection and technical characteristics of any new measuring or band-limiting filters the technical details indicated in the Annex to Report 553-1 should be taken into account.

Note. — An overall accuracy of ± 2 dB and better, is assumed for systems in operation in the Fixed Satellite Service. Attention is also drawn to CCITT Recommendation G.228, Annex 1 and Annex 2 which discuss the method of measurement and the measuring accuracy.

TABLE II

Centre frequency f_c (kHz)	Bandwidth (kHz) in relation to f_c over which the discrimination should be at least: ⁽¹⁾				Bandwidth (kHz) in relation to f_c outside of which the discrimination should not exceed:	
	70 dB	55 dB	30 dB	3 dB ⁽²⁾	3 dB	0,5 dB
16	± 1.5	± 2.1	± 2.7	—	± 5	± 7
56	± 1.5	± 1.8 ⁽³⁾	± 2.1 ⁽³⁾	—	± 5	± 10
70	± 1.5	± 2.2	± 3.5	—	± 12	± 18
70 ⁽⁴⁾	± 1.5	± 1.7	± 2.0	—	± 5	± 10
98	± 1.5	± 1.8	± 2.1	—	± 4	± 9
140	± 1.5	± 1.8	± 2.2	—	± 5	± 14
185	± 1.5	± 1.8	± 2.2	—	± 5	± 17
240	± 1.5	± 1.8	± 2.2	—	± 5	± 21
270	± 1.5	± 2.3	± 2.9	—	± 8	± 24
394	± 1.5	± 3.0	± 4.5	—	± 11	± 35
534	± 1.5	± 3.5	± 7.0	—	± 15	± 48
770	± 1.5	± 3.8	± 8.0	—	± 21	± 70
1002	± 1.5	± 4.0	± 9.0	—	± 27	± 90
1248	± 1.5	± 4.0	± 11.0	—	± 35	± 110
1730	± 1.5	± 4.2	± 14.0	—	± 48	± 155
2438	± 1.5	± 4.5	± 19.0	—	± 60	± 220
3150	± 1.5	± 9.0	± 22.0	—	± 85	± 285
3886 ⁽⁵⁾	± 1.5	± 15.0	± 30.0	—	± 110	± 350
		± 1.8	± 3.5	± 8.0	± 12	± 100
4650	± 1.5	± 2.0	± 3.8	± 8.5	± 13	± 120
5340	± 1.5	± 2.2	± 4.0	± 8.5	± 14	± 150
7600	± 1.5	± 2.4	± 4.6	± 9.5	± 16	± 200

(1) The discrimination values quoted are relative referred to the minimum attenuation of band-stop filters within the baseband frequency range defined by high-pass and low-pass filters in Table I.

(2) New 3 dB-column from CCITT Recommendation G. 228.

(3) The values accepted at the Final Meeting of Study Group 4 were: ± 2.0 (55 dB) and ± 2.5 (30 dB).

(4) New band-stop filter from CCITT Recommendation G. 230.

(5) The characteristics recommended for the filters 16 kHz to 3150 kHz inclusive are based on inductor-capacitor type filters. Those characteristics recommended for the filters at 4650 kHz and above are based on crystal-type filters. Optional characteristics are recommended for the 3886 kHz filter to permit a choice of design between a coil-capacitor type (upper line in table) or crystal-type filter (lower line in table).

The design of the receiver selectivity of 3886 kHz should be matched to the characteristic of the crystal-type band-stop filter. It is suggested that in the range from 3150 kHz to 7600 kHz the receiver selectivity should be related to the characteristics of crystal-type band-stop filters.

REPORT 706

AVAILABILITY OF CIRCUITS IN THE FIXED SATELLITE SERVICE

(Question 24/4)

(1978)

1. Introduction

This Report discusses various parts of Question 24/4 on how the concept of availability could be applied to the hypothetical reference circuit (Recommendation 352-3) in the Fixed Satellite Service for telephony and television. It suggests a philosophy which could be applied, and some of the parameters which could be specified, in deriving meaningful availability criteria for telephony and television circuits in the Fixed Satellite Service.

The concepts of reliability and availability in respect to radio-relay systems for television and telephony as discussed in Report 445-2 have been noted with the objective of achieving consistency, insofar as is possible, between corresponding considerations for radio-relay systems and for the Fixed Satellite Service.

The Report also presents the results of practical experience in different countries.

2. Definition of circuit availability

2.1 *Application of the concept of availability to the Fixed Satellite Service*

Circuit availability should be defined between both ends of the hypothetical reference circuit (Recommendation 352-3).

Availability of circuits in the Fixed Satellite Service can be derived from the duration of interruptions. The definition should be defined without regard to any particular system or equipment arrangements, such as the use of spare satellites, earth station antennae or other redundant equipment.

2.2 *Definition*

Circuit availability can be defined as:

$$A = \frac{(\text{Scheduled operating time}) - (\text{down time})}{(\text{Scheduled operating time})} \times 100 \quad (\%) \quad (1)$$

where scheduled operating time, is the time during which the circuit of interest is expected to perform its intended function, and down time, is the cumulative time of circuit interruptions within the scheduled operating time.

In the case of a full-time circuit the scheduled operating time is the same as the calendar time.

3. Interruptions

The availability of a telephone or television circuit in the Fixed Satellite Service is determined by interruptions. An interruption is a period in which there is complete or partial loss of signal, excessive noise, or a discontinuity or severe distortion in the signal. Several aspects should be considered.

- a definition of that which constitutes an interruption;
- a description of the time aspects, such as the length of an interruption, the period between successive interruptions, etc.;
- a determination, for the purposes of specifying an availability objective, of whether all interruptions should be included within the objective, or if not, what specific types of interruption should be excluded.

In the case of telephony an interruption should be taken into account in the determination of availability if it would cause a call to be disconnected making it necessary to re-establish the connection.

3.1 *Characteristics of interruptions*

There may be a separate significance depending on whether the interruptions are unscheduled or scheduled.

The characteristics of unscheduled interruptions which may require definition are:

- mean time between interruptions. This is to ensure that interruptions of extended duration do not occur too frequently;
- total interruption over a long period. This would ensure a minimum value of availability for the system;
- mean duration of interruption. This would ensure that, if an interruption occurred, it would not be too long;
- the rate of occurrence (e.g. measured on an hourly basis);
- the total interruption time over a period (e.g. of any year);
- the statistically defined duration of interruptions. It may then be desirable to specify several points on a statistical distribution.

4. Causes of interruption

The main causes of interruption to a Fixed Satellite Service circuit are the following:

failure in the satellite

- temporary reduction in performance in periods of eclipse for example, or during positioning or stabilizing manœuvres;
- switching of redundant components in the event of failure in repeater sub-assemblies;
- abrupt cessation of emissions from the satellite and use of a standby;

failure in the earth stations

- failure or degradation of the radio equipment;
- failure of the standby switching equipment;
- failure of the power system;
- failure of the antenna equipment or the satellite pointing system;

influence of natural phenomena

- passage of the sun or the moon in the antenna beam of the down path earth station;
- excessive attenuation and increase of noise due to precipitation on the up- and down-paths;
- depolarization due to the troposphere;

influence of interference

- noise exceeding a certain level, caused by interference;

influence of natural disasters

- loss of pointing accuracy in the antenna and serious damage to earth station buildings in the case of an earthquake or exceptional disaster;

influence of human activity

- poor design of the logistics for maintenance and repair of the sub-assemblies;
- mistakes by the operational staff perhaps due to inadequate training.

5. Objectives for circuit availability

Provisional objectives for circuit availability given in Annex II are consistent with the data in Annex I. Additional studies are necessary to finalize these objectives. The requirements for further study are outlined in Study Programme 24A/4. In considering availability objectives, account should be taken of the more severe propagation effects that exist in frequency bands above 10 GHz.

6. Measurement of circuit availability

In establishing availability objectives both the user's requirements and the circuit availability now achieved in the Fixed Satellite Service have to be taken into account.

Examples of measured data of circuit availability between points defined in Recommendation 352-3 for the hypothetical reference circuit appear in Annex I. Further collection of data on circuit availability is desirable and a suggested procedure for obtaining these measurements is given below.

Both-way circuit availability

In practice, it is difficult to observe at any one earth station the precise time duration of an interruption for both directions of transmission (because data for the distant earth station are sometimes difficult to obtain).

Therefore, the following equation is suggested for the measurement of availability of a pre-assigned both-way circuit.

$$A_B = \frac{T_S - 2(TA_U + TA_D + TA_{COM}) - T_{SAT}}{T_S} \times 100 \quad (0/0) \quad (2)$$

where,

- T_S : scheduled operating time;
- TA_U, TA_D : cumulative time of circuit interruptions attributable to the factors on the up-link and down-link of the earth station (except those attributable to factors in the satellite and common portions to the up- and down-link);
- TA_{COM} : cumulative time of circuit interruptions attributable to the factors in the common portion of the up- and down-link of the earth station (except those caused by failures of satellite);
- T_{SAT} : cumulative time of circuit interruptions caused by failures of the satellite.

Formula (2) above, implies that the total time of circuit interruptions attributable to the factors on up- or down-links of earth stations at either end of the link are equal. It also implies that the factors applying to the common portions of both links are identical.

Note 1. — In the event of two or more items occurring simultaneously, only the duration for one item should be taken into account.

Using this formula, it will be possible to estimate the average and distribution of the value of circuit availability in a satellite network from values of A_B collected from many earth stations within the network.

Note 2. — For demand assignment systems the availability philosophy may require further study.

ANNEX I

Based on contributions submitted by Administrations as a partial answer to Question 24/4 (Decides 3), this Annex contains examples of circuit availability and shows possible ways of collecting data.

1. Examples of circuit availability

1.1 Example 1

Fig. 1 shows examples of circuit availability on a yearly basis, which were calculated using Formula (2) of § 6, from data obtained at an existing earth station for international satellite communication from 1971 to 1975. This Figure gives the average value of circuit availability with respect to eight both-way telephone circuits. Fig. 2 represents the percentage of time for the main causes of circuit interruptions on a yearly basis, which were observed at an existing earth station. Fig. 3 shows circuit availability in respect of the main causes of interruption.

It should be borne in mind that circuit availability does not suffer interruptions due to propagation effects.

For calculation of availability, the following assumptions were adopted:

- all circuits are for full-time service. Thus, the sum of operating time and down-time is equal to all calendar time (i.e. one year);
- circuit interruption is a state in which the signal-to-unweighted noise ratio is less than 30 dB for 10 seconds or more;

this earth station has a 1 : 1 redundancy except for the antenna unit.

The circuit interruption during the point-over to a spare satellite is categorized into "Unknown" rather than into "Satellite".

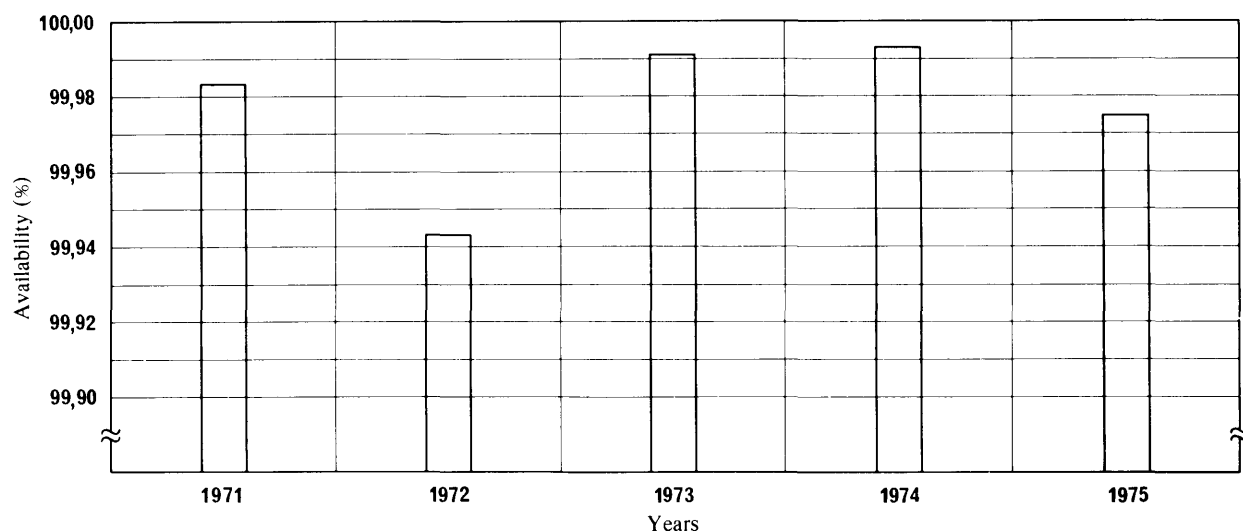


FIGURE 1 — Example of circuit availability

Note. — Earth station facilities were replaced by new facilities at the end of 1971.

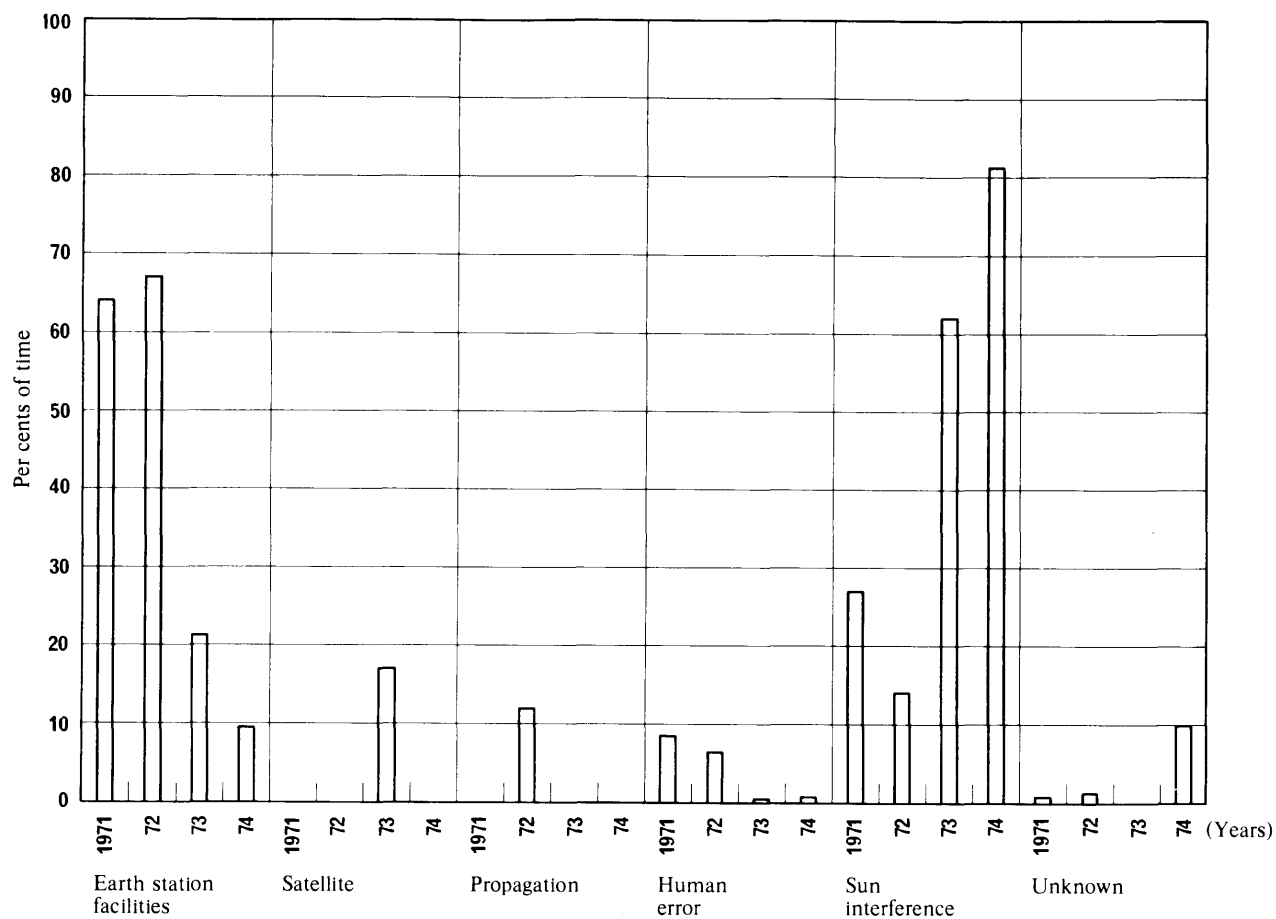


FIGURE 2 — Percentage of time of the main causes of circuit interruption (yearly basis)

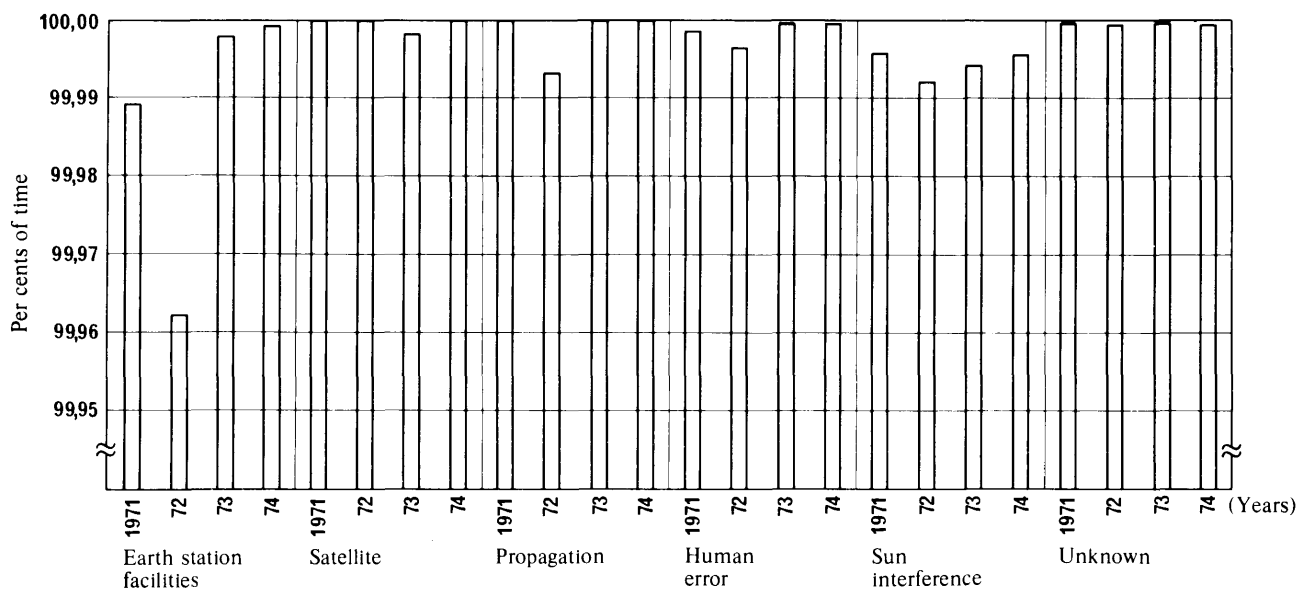


FIGURE 3 — Circuit availability in respect of main causes of interruption

1.2 Example 2

The values obtained since 1971 for the mean availability of station-satellite-station circuits in the INTELSAT system are as follows:

Year	Availability
1971	99.812%
1972	99.870%
1973	99.875%
1974	99.888%
1975	99.892%
1976	99.876%

Note. — These figures were derived by the use of a different formula from that shown in equation (2). In general, close correlation between the results derived from the two methods is usually expected.

2. Effects of earth station on circuit availability

Earth station facilities have considerable effect on circuit availability. As an example of this effect Table I gives results of the number and duration of interruptions due to equipment failures and sun interference at one earth station operating in a global satellite system, for a period of three years including the first year of operation.

TABLE I

Cause of interruption	Year	Duration of interruptions (minutes)	Availability (%)	Number of interruptions	Percentage of total duration of interruptions
A	1974	0	100	0	0
	1975	63.6	99.988	8	56.2
	1976	0	100	0	0
H	1974	7.5	99.999	3	3.4
	1975	10.5	99.998	3	9.3
	1976	8.5	99.998	5	26.2
P	1974	189	99.964	10	86.3
	1975	21	99.996	5	18.6
	1976	18	99.996	2	55.4
O	1974	0	100	0	0
	1975	1	99.999	1	0.9
	1976	0	100	0	0
U	1974	0.5	99.999	1	0.2
	1975	0	100	0	0
	1976	0	100	0	0
L	1974	6	99.999	1	2.8
	1975	0	100	0	0
	1976	0	100	0	0
S	1974	16	99.997	4	7.3
	1975	13	99.997	4	11.5
	1976	5	99.999	2	15.4
GCE	1974	0	100	0	0
	1975	4	99.999	1	3.5
	1976	1	99.999	1	3.0
Total	1974	219	99.958	19	100
	1975	113	99.978	22	100
	1976	32.5	99.994	10	100

A: Antenna tracking
H: High power amplifier
P: Power subsystem
O: Other

L: Low noise amplifier
S: Sun interference
GCE: Ground comm. subsystem
U: Unknown

The presentation of this data is consistent with the criteria contained in Annex II with the exception that instead of the 10^6 pW criterion, an unweighted noise power of 700 000 pW at a point of zero relative level, has been used to define an interruption.

Based on this data, circuit availability due to the effects of an earth station at one end of the hypothetical reference circuit has been calculated using the definition in § 2.2.

Table II contains earth station availability data for several earth stations operated in the INTELSAT system in the period 1972 to 1976, as well as average earth station availability in the whole INTELSAT system.

TABLE II

Year Earth station	1972	1973	1974	1975	1976
1	99.921	99.841	99.533	99.937	99.996
2	—	99.994	99.997	99.960	99.997
3	—	99.86	99.87	99.96	—
4	—	99.93	99.87	99.76	—
5	—	99.92	99.93	99.88	—
6	—	—	99.958	99.978	99.994
INTELSAT average	99.86	99.88	99.90	99.91	99.88 (1)

(1) Includes statistics up to October 1976 only.

Note. — Measurement periods for the various earth stations in Table II started in different months of the year.

ANNEX II

The following text could be used as a basis for the subsequent establishment of a Recommendation on the availability of a telephone transmission line in the Fixed Satellite Service. In addition to the criteria given below, it is appropriate to examine whether other parameters should also be taken into account, such as the maximum number of interruptions for a given period.

1. The availability of a circuit in the Fixed Satellite Service should be defined by the following formula:

$$A = \frac{(\text{Scheduled operating time}) - (\text{down time})}{(\text{Scheduled operating time})} \times 100 \quad (0/0)$$

2. That provisionally the availability of a circuit in the Fixed-Satellite Service should not be less than 99.8% of a year.

3. A link in the Fixed Satellite Service defined between the ends of the hypothetical reference circuit in Recommendation 352-3 and in Recommendation 521 should be considered unavailable if at least one of the following conditions exists at either of the receiving ends of the link for more than 10 consecutive seconds: *

- 3.1 the wanted signal entering the circuit is not received at the other end;
- 3.2 in analogue transmission of a telephone channel, the unweighted noise power at a point of zero relative level, with 5 ms integration time, is higher than 10^6 pW0 (Note 5);
- 3.3 in digital transmission, the bit error rate is higher than 10^{-3} (Note 5).

4. That the following notes should be regarded as part of this text:

Note 1. — The availability of multiplexing equipment is not taken into account in the foregoing.

Note 2. — The availability value is a planning objective for satellite systems; it should neither be included in system specifications nor used for acceptance tests.

* Values given in this section are provisional and are still under study.

Note 3 — The periods during which one of the conditions in Point 3 exists when caused by adverse propagation conditions may or may not need to be included in the performance calculations. This matter requires further study.

Note 4 — The planners should indicate their assumptions concerning mean time between failures, mean time for resumption of service, precautions taken against interruptions, fading and impairment of satellite performance (especially use of reserve channels and back-up systems), and the incidence of fading for more than 10 consecutive seconds.

Note 5 — The periods of less than 10 seconds during which conditions in Point 3 exist, are not taken into account in this text.

Note 6 — Circuits in the Fixed Satellite Service used for national networks only, may not comply with the present text.

REPORT 553-1

OPERATION AND MAINTENANCE OF EARTH STATIONS IN THE FIXED SATELLITE SERVICE

(Question 20-1/4)

(1974 – 1978)

1. Introduction

In addition to an appropriate organization responsible for the operation and maintenance of earth stations forming part of systems of the Fixed Satellite Service, some technical facilities are necessary for the line-up and maintenance of satellite radio links and communication equipment installed at earth stations.

To perform the necessary measurements over single or multiple destination satellite radio links, close co-operation is necessary between the earth stations. Comprehensive end-to-end measurements will have to be performed when the links are initially placed into service and also during the operation of the system.

The technical facilities referred to above consist of measuring- and test-instruments having performance characteristics which are based on the operational requirements and performance objectives specified for the system of the Fixed Satellite Service concerned.

For reasons of economy, it may be desirable to design earth stations to operate unattended by technical personnel for several hours each day or for several months at a time. Such earth stations are now in operation in regional networks.

2. Compatibility of equipment

In order to allow the measurements to be performed with the required accuracy and permit correct interruption and comparison, compatible test instruments are required at all earth stations of a common satellite system. Furthermore, under special circumstances, for example when a carrier cannot be received on a looped back basis from the satellite, a facility for an "automatic report back" of test results would be very helpful, and this also would require compatibility of methods and equipment.

To obtain such compatibility, the characteristics of test instruments have in some cases been included in CCIR and CCITT Recommendations (for example Recommendation 482-1). International agreement has also been obtained for other equipments, for example, microwave link analysers as used in the INTELSAT system.

It is important that technical documents should be furnished by Administrations so that the best possible specifications based on economic and technical considerations can be prepared, e.g. the Annex I sets forth the reasons for the specification of filters in Recommendation 482-1.

3. Equipment utilization

Procurement and storage of test instruments at earth stations should be simplified if it were possible to keep the number of necessary instruments to a minimum. Therefore, multi-purpose, multi-range instruments may be considered, taking into account the relevant reliability and availability aspects. As an example, when considering video test instruments for use in the intercontinental links in the fixed satellite service, it is desirable that these test instruments can be used for measurements on 525/60 and 625/50 black-and-white and 525/60 NTSC, 625/50 PAL or 625/50 SECAM colour television systems.

Optimum utilization of test instruments at earth stations would be achieved if these instruments were purchased in accordance with uniform specifications agreed upon at an international level. This will avoid high investments for test equipment which might become obsolete after a short time of use.

4. Automatic test equipment

With system growth it can be expected that the large number of measurements necessary to facilitate system operation will require test instruments which will:

- considerably shorten measuring times;
- diminish as much as possible, human errors during measurements;
- require a minimum of manual control.

Consequently, automatic test instruments will be of increasing importance at earth stations, because such instruments are normally suited for both automatic and manual operation.

It may be possible for attending technicians to transport and utilize such test equipment when performing normal maintenance functions in unattended earth stations.

5. List of equipment

As far as FDM/FM/FDMA modulation systems are concerned, typical lists of equipment have been prepared for specific systems [INTELSAT, 1971].

6. Design of unattended earth stations

One approach to the design of unattended earth stations is to:

- design the equipment from the outset to comply with the nominal characteristics during normal working, without a redundant chain of components kept on passive standby;
- ensure that a breakdown in any sub-system component would not result in the sub-assembly ceasing to function completely, but only in a deterioration in its characteristics;
- define parameters to guarantee continuity of service despite possible failures in certain sub-assemblies;
- reduce to a minimum the control and command equipment and to design them to offer a much higher degree of reliability than the routine components in the station.

The amount and type of control and monitor equipment to be incorporated into an unattended earth station should be determined by an analysis of the earth station availability and the grade of service required.

Reference [Plottin, 1975] briefly reviews methods which may be used to detect faults, to formulate commands and to ensure remote supervision of the essential transmission characteristics.

Reference [Guillarme and Penicaud, 1975; Lombard and Viana, 1972] is related to possible modifications of transmission parameters enabling the continuity of service under degraded equipment conditions.

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ANNEX I

CHOICE OF FILTER CHARACTERISTICS FOR PERFORMANCE MEASUREMENTS USING WHITE NOISE TEST SIGNALS

When considering specifications for filters used for white noise performance measurements, two main criteria have to be taken into account:

- centre frequency;
- bandwidth characteristics.

1. When choosing the centre frequency it should be ascertained whether a suitable frequency for the channel size in question has already come into widespread use.

For example, in the case of Recommendation 482-1, centre frequencies are derived from Annex I to CCITT/CCIR, CMBD Question 8/C, CCIR Recommendation 399-3 and various INTELSAT documents.

When centre frequencies have to be chosen which are not yet specified the preferred frequencies should be those which can be used for as many channel capacities as possible. If a new upper measuring frequency is needed and if there is no recommended frequency in the range between 0.9 and 0.965 of the effective cut-off frequency, a measuring frequency of approximately 0.95 of the effective cut-off frequency of the band-limiting low-pass filter should be chosen.

2. When specifying the bandwidth characteristics of new filters, a choice has to be made between coil-capacitor-type or crystal-type filters. For frequencies higher than 3886 kHz it seems desirable to use crystal-type filters.

Fig. 1 shows the bandwidth ($\pm$ kHz) of the various band-stop filters tabulated in Table II of Recommendation 482-1. These curves demonstrate that a set of generalized curves can connect the various values, and consequently any new filter specifications can be directly read off the diagram. As an example, dropping a vertical line from the 185 kHz centre frequency filter produces intercepts — at the following bandwidth points: ± 17 , ± 5 , ± 2.2 , ± 1.8 and ± 1.5 kHz. Reading from right to left on Table II these figures are noted.

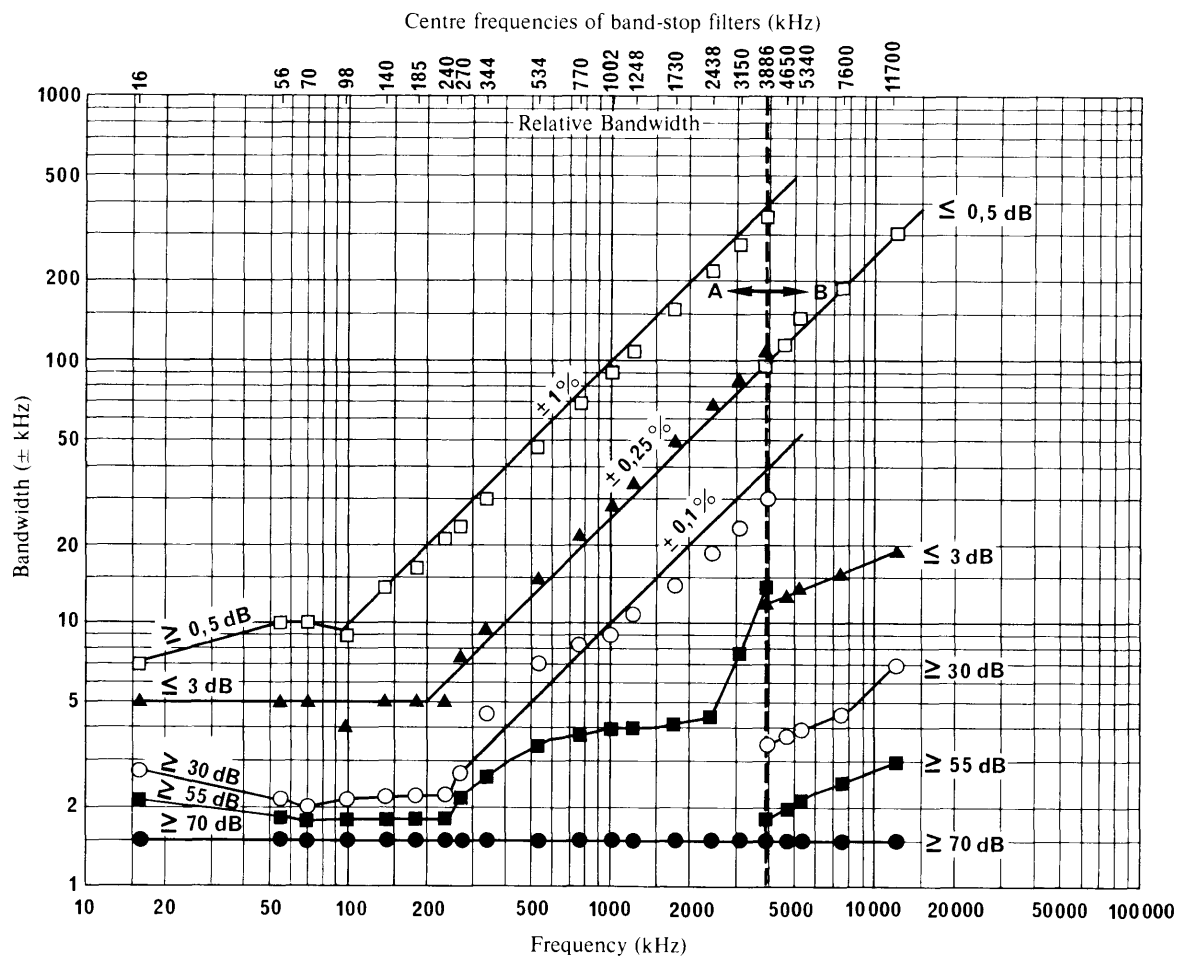


FIGURE 1 — Bandwidth (in $\pm$ kHz) of band-stop filters as contained in Table II of Recommendation 482-1

A: Coil-capacitor-type filters
B: Crystal-type filters

REPORT 707

DIGITAL INTERFACE CHARACTERISTICS BETWEEN SATELLITE
AND TERRESTRIAL NETWORKS

(Study Programme 2N/4)

(1978)

1. Introduction

This Report discusses aspects of Study Programme 2N/4 which concern problems of interfacing international digital links (direct digital interface equipment, DDIE) between countries having mixtures of analogue and digital terrestrial networks. Also considered are some aspects related to the transmission of the signalling and link monitoring of the PCM multiplex. A preferred plesiochronous interconnection is suggested but a solution involving justification of the satellite link is also included for those occasions when plesiochronous connection is considered undesirable.

2. Outline of problem

Digital transmission techniques are likely to spread throughout the networks of the Fixed Satellite Service in the next few years, since they lead to a much more efficient use of satellites than the present analogue systems. On the other hand, the introduction of digital satellite links is likely to create new problems of connection with terrestrial networks; since most of these are analogue systems, provision will have to be made for analogue-digital conversion. It does not seem to be advantageous to do this at the earth stations, in view of the need to add equipment for demultiplexing to channel level. Since the switching operations at the International Transit Centre (TC) are carried out at channel level, it would seem advisable to install the analogue-digital conversion there also. This clearly shows that it would be desirable in most cases to extend satellite digital links by using terrestrial digital links at least up to the international transit centres. This measure should also facilitate the integration of this link in the terrestrial network if this network is subsequently digitized.

This Report discusses various aspects of the connection of a digital satellite link with a terrestrial link and of the constraints that must be imposed on the two types of link to ensure compatibility at the interface.

2.1 *Types of international digital links*

Three types of digital transmission links appear to be candidates for probable use in the establishment of international digital communication networks:

- A digital transmission link based on single-channel-per-carrier PCM/PSK/FDMA transmission facilities. Typically this link would operate at a gross bit rate of 64 kbit/s, for telephony or data transmission. Rate 3/4 or rate 7/8 coding/decoding interfacing with the terrestrial network at a net bit rate of 48 kbit/s or 56 kbit/s could also be used if the error rate for data transmission were not good enough.
- A digital transmission link which basically utilizes multichannel PCM/TDM/PSK/FDMA transmission facilities; for example a primary or higher order multiplex employing PSK modulation. This type of transmission can handle a variety of signals; for example telephony with or without DSI or high speed data transmission.
- PCM/PSK/TDMA transmission links where the transmission rate within a burst might typically be about 60 to 120 Mbit/s although the information rate to any one destination would be less than this. For this type of transmission there will be a slight difference in rate between the transmitted and received signals due to satellite movement.

Because of the relatively greater technical complexity and resulting difficulty in the implementation of PCM/PSK/TDMA links, it is likely that the first two types of digital links may be utilized for the early establishment of international digital transmission via satellite.

2.2 *Types of networks*

There are three types of network which require international connection. They are considered in historical order.

2.2.1 *Analogue network*

These form the majority of existing networks and comprise mainly analogue links, but digital links are being increasingly used in these networks. However, it is assumed that in this class of network the International Transit Switching Centre (TC) remains analogue.

2.2.2 *Digital switching at TC, national networks non-synchronous*

This is the likely next phase in the introduction of digital techniques in international communications. It is probable that at this stage the TC will be connected to the earth station by digital links.

2.2.3 *Synchronous national networks interconnected by digital links*

This will also include national networks using high stability clocks which are plesiochronously connected. This is foreseen to be the ultimate network configuration envisaged by the CCITT.

It should be borne in mind that configurations comprising mixtures of these networks will have to co-exist.

2.3 *The interconnection of digital streams emanating from different clocks*

At the interface between two digital links, the clocks controlling the signals may have time differences which necessitate resetting one of them, so that information can pass from one link to the other. The two main causes of these time differences are, firstly, the plesiochronous operation of reference clocks (they have the same nominal frequency, but are independent, with a fixed frequency tolerance) and secondly, variations of propagation time on the link.

Ultimately an international digital satellite link will be required to interface between two independent synchronous terrestrial networks. Assuming that the clock frequency in each network is maintained within 2×10^{-11} or 1×10^{-11} of its nominal value, it is not important from the viewpoint of the satellite/terrestrial interface whether the two terrestrial networks have separate clocks or are synchronized to one another.

Two methods can be used to reset a clock in the case of plesiochronous working. The first is to apply frame slips (i.e., at intervals not to transmit a frame or to transmit one frame twice running) in order to offset the discrepancy between the transmission and reception rates. This process, generally used in asynchronous switched networks, provides satisfactory working in telephony, but these frame slips are liable to prove troublesome in other services, such as high-speed data transmission. The slip frequency must therefore be kept at a very low value, either by synchronizing the clocks to obtain a synchronous interface or by ensuring high clock stability.

The second solution lies in transmitting the digits via a link operating at a bit rate slightly higher than either of the two networks. The difference is compensated for by justifying the link which makes the link effectively transparent but does not eliminate slip between the networks so connected. Two methods of justifying primary multiplexes transferred via TDMA systems are discussed in Annex I but it should be borne in mind that the operation of multi-destination links and Digital Speech Interpolation (DSI) will be restricted if justification is used.

The one-way time delay of the transmission path via a geostationary satellite may have a daily peak-to-peak cyclic variation in the order of 0.15 to perhaps 1.5 ms due to orbital perturbations. Longitudinal drift of the satellite about its nominal position can cause additional longer term cyclic variations of about the same order of magnitude. These variations may be offset at earth stations, either on transmission or reception depending on the particular application involved, by means of elastic buffer stores. For conversion between two slightly different bit rates, the signals are stored at the reception rate and read at the transmission rate. If the transmission rate is greater than the reception rate, the store will tend to empty, and in the contrary case, to fill up. Since satellite movements are restricted, the two states will alternate and the mean in time will be zero. Conceivably, extreme bit rate variations can be absorbed without data loss or repetition by suitable dimensioning of the store capacity.

2.4 *Higher order multiplex transmissions*

Transmission of higher order multiplexes should be possible between countries using the same digital hierarchy when the satellite link is not TDMA and does not use DSI. If however TDMA is used the following disadvantages are incurred:

- No simple slip strategy can be implemented at the interface. This is because it would be necessary to discard (or repeat) one or more of the higher order multiplex frames without disturbing the integrity of the primary multiplex frames carried within them. Since the number of primary multiplex frames in a second order multiplex frame is not an integral number, either a very complicated slip strategy or another order of justification will need to be implemented.
- In a multi-destination TDMA system, the bit-interleaved nature of the higher order multiplex signal would also make the demultiplexing equipment associated with a multi-destination burst more complex. Each of the multiple destinations would have to process the entire sub-burst associated with the interface module at the transmitter in order to separate the fraction of the multiplex traffic associated with that particular receiving station. In this case the full efficiency of TDMA may not be realized.
- DSI is not so readily implemented at higher levels as the 8 bits associated with each speech channel are not easily identifiable due to the bit-interleaving inherent in the multiplexed signal.

3. Discussion of solutions

3.1 *Analogue switched national networks*

It is not considered desirable to provide the analogue to digital conversions at the earth stations because it will be necessary to include channel multiplexing equipment. Since further multiplexing will also be required at the international transit centre (TC) it would obviously be better if the TC to earth station link were also to be

digital. However because the terrestrial network is mainly analogue and therefore digital switching at the TC is not used, the clock rate of the digital link is not critical. For point-to-point PSK systems, it should therefore, be possible to control the digital transmission rate of the receive terrestrial part of the link from a clock derived at the earth station. This clock would originate from the clock at the transmit side of the remote TC coding equipment. In the case of TDMA systems the clock would be obtained from the frame reference clock generated by the reference station; the Doppler shift due to satellite movement is likely to be insignificant. However if slip is to be eliminated entirely, the clock variation due to Doppler shift will need to be absorbed by means of elastic buffers at the receive side of the link. With such a solution no loss of digital information will occur. The use in TDMA systems of DSI does not affect this solution.

In the case of interconnection between countries using different primary multiplex systems it is impractical to maintain the frame format between the different multiplexers. However, it will always be necessary to maintain the integrity of the channel time slots. In such cases the DDIE at the transmitting earth station will have to remove any additional bit(s) which may be used for signalling, framing, etc.

The DDIE at the receiving earth station will have to reassemble the primary multiplex that is used in that country. Even between countries using the same primary multiplex arrangement some alteration to the frame format may be necessary, or desirable, to make it match the TDMA system format.

3.2 *Digital switching at the TC, national networks non-synchronous*

In this situation there will generally be a small difference in rate between the clock controlling the switch at the TC and the digital signals coming into the TC. Thus, frame slips will have to be allowed. In this case there seems little point in avoiding frame slips again at the earth station interface. Assuming a clock in the TC accurate to 1 in 10^8 and a clock in the TDMA reference station accurate to 1 in 10^7 , then one 125 μ s PCM frame slip would occur no more frequently than every 19 minutes, if the satellite were in an ideal geostationary orbit; and every 12 minutes for a satellite having 3° orbit inclination and no elastic buffer to remove the transmission delay variations.

For these situations therefore, the DDIE needs to perform only the alignment and frame slipping function and to carry out any necessary modification to the frame format, (as stated in § 3.1). For satellites without orbit inclination control the DDIE may also need to include an elastic buffer to remove transmission delay variations.

3.3 *Digital switching with synchronous national networks*

It has been recommended by the CCITT that the interworking between national synchronous networks be plesiochronous. With the national networks controlled to an accuracy of 1 in 10^{11} this would result in a minimum of 70 days between frame slips.

When the international connection is by means of a TDMA satellite system having reference clock accuracy substantially worse than 1 in 10^{11} then either the rate of frame slip must be substantially greater than 1 in 70 days or a DDIE with justification may be used. However this complication is avoided if the TDMA system itself is timed to an accuracy comparable with that of the national networks, i.e. 1 in 10^{11} . In such a case the DDIE will need to perform the alignment function, carry out any necessary modification to the format and remove the transmission delay variations caused by satellite movement by using elastic buffers at the transmit and receive sides of the link. This is therefore the preferred solution for the interconnection of national synchronous networks.

In a practical TDMA system only a relatively small number of earth stations need to perform as reference stations. It should therefore not be difficult to ensure the required TDMA timing accuracy by letting those countries with synchronous digital networks serve as reference stations. It may be necessary initially, when there are only very few countries with synchronous networks, to accept a lower TDMA system timing accuracy and allow slips more frequently, perhaps once per day.

4. Aspects of signalling and monitoring

The CCITT has defined the characteristics needed for the digital PCM multiplex equipment used in telecommunication networks and has also defined the information on the fault conditions which should be transmitted to the end of a link to ensure effective monitoring (e.g., Recommendation G.734), but the studies which resulted in this definition were confined to point-to-point links. These conclusions are no longer necessarily valid for satellite systems in which multiple destination links are widely used, especially TDMA systems, and further studies are required. In particular, it may well be necessary to regard a TC — earth station — satellite — earth station — TC link as consisting of three independent sections as far as fault indications are concerned. In this case, earth stations would be regarded as multiplex terminals from the standpoint of alarms. However, from a switching point of view the link between TCs constitutes one section.

From the transmission angle, it does not seem necessary to transmit the alarms from one section to another. However, some signalling systems require information on faults in the transmission line. In these signalling systems the service alarm indication must therefore be transmitted forward.

Common channel signalling systems, such as CCITT No. 6, seem to present no difficulties at present. CCITT System No. 5 and both versions of CCITT System R-2 will also be used over digital satellite links (it should be noted that recent tests have shown that the call setup time from end of dialling on satellite links is appreciably shorter with CCITT System R-2 than with CCITT System No. 5). The requirements of these two systems are recapitulated below. The application of other systems will have to be studied in detail.

CCITT No. 5:

No alarm needs to be transmitted. The satellite multi-destination can be provided at the channel level.

Analogue CCITT R-2:

The alarm indications must be transmitted forward. A distinction will have to be drawn between faults that affect all the channels of the multiplex (e.g. loss of frame alignment) and those that affect only TS 16 (loss of multiframe signal).

The satellite multi-destination can only be provided at the primary multiplex level.

Digital CCITT R-2:

The alarm indications must be transmitted forward but this can be done at the channel level. If the alarms are transmitted individually in each channel no distinction needs to be made between the two types of fault.

The satellite multi-destination can be provided at the channel level.

One method of dealing with signalling and alarms is indicated in Annex II.

5. Conclusions

Either plesiochronous or justified satellite links can be used to interconnect digital networks but it is considered that plesiochronous operation raises fewer problems and is therefore recommended.

The periodic time delay variation introduced by geostationary satellites can be taken up by using the technique of buffer-storage and therefore no frame slip will occur due to satellite periodic variation.

There are several digital satellite link aspects involving signalling and alarm conditions that require further study. Some of these problems have been discussed and suggestions for the digital case have been presented. The relatively long transmission delay introduced by satellites does not present any special problem for plesiochronous operation. The effects of transmission delay on data networks are the subject of CCIR Study Programme 2Q/4.

ANNEX I

TWO EXAMPLES OF JUSTIFICATION TECHNIQUES FOR TDMA SYSTEMS

1. Features of TDMA systems

TDMA is a digital technique by which several earth stations use a given satellite transponder on time sharing basis. Each burst-mode carrier which is intermittently transmitted by different earth stations, does not overlap with bursts transmitted from other stations in the transponder.

The frame period in TDMA systems is currently designed as an integral multiple of 125 μ s, and the length of the burst can be varied according to the traffic volume. The preamble portion contains the frame synchronization signal to synchronize the burst, and the information portion includes the data for multiple destinations.

To summarize, the TDMA link is different from the conventional terrestrial digital path in the following respects:

- each burst has preamble bits for burst synchronization;
- it is a point-to-multipoint link;
- the terminal has buffer memories;
- the link capacity can be varied by changing the burst length.

2. Desirable Direct Digital Interface (DDI) frame for TDMA transmission

As mentioned above, the TDMA link has several different features compared with the terrestrial digital paths. Therefore, the frame structure of the TDMA burst should be formulated taking into consideration the features of the TDMA link as well as the simplicity of the interface equipment.

A possible frame structure for the transmission of PCM primary groups via TDMA link is discussed below:

- As the burst synchronization signal can be utilized for the detection of justification service digits and justification time slots, it is not necessary to include the frame alignment signal in each justification frame.
- It is not necessary to compose the higher order groups by bit interleaving, because the TDMA terminal has buffer memories. In addition, considering the fact that the TDMA link is a point-to-multipoint link and that the link capacity can be varied by changing the burst length, the adoption of tributary interleaving makes it easy to extract the desired data on the receiving side and gives flexibility to changing the link capacity. Fig. 1 shows the general concept of "tributary interleaving".

- In order to keep the justification error probability sufficiently small, 5 bits are required for each justification-frame as the justification service digits.
- It is desirable that the justified gross bit rate is selected in integral multiples of 64 kbit/s to simplify the TDMA terminal.

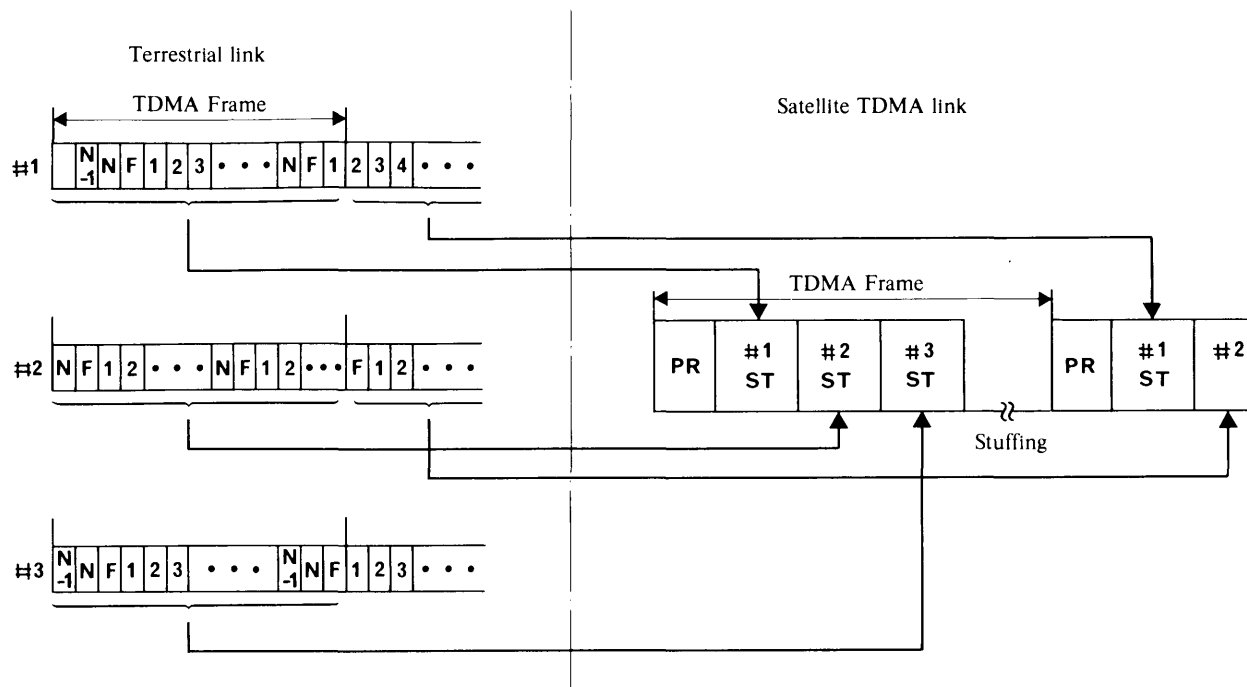


FIGURE 1 — General concept of proposed TDMA tributary interleaving

F: Framing bit
PR: Preamble

3. Examples of justification-frame structure

Table I shows the major parameters of the desirable justification-frame structure for both 1.544 Mbit/s and 2.048 Mbit/s primary PCM standards, and Figs. 2 and 3 illustrate the detailed frame formats.

Main features can be summarized as follows:

- Type-A in Table I is a design based upon a TDMA system with a frame length of 750 μ s, in which a positive justification technique is used. On the other hand, a positive/negative justification technique is used for Type-B frame format.
- Gross bit rates are 1.6 Mbit/s for the 1.544 Mbit/s primary system, and 2.112 Mbit/s for the 2.048 Mbit/s primary system, which correspond to 25- and 33- PCM channels, respectively.
- The justification control signal is composed of 5 bits, and each bit is arranged to have the same interval in the justification-frame shown in Figs. 2 and 3.

4. An experimental DDI equipment

An experimental DDI equipment for a 1.544 Mbit/s primary PCM system has been developed based upon the Type-A frame format shown in Table I.

Fig. 4 shows the simplified block diagram. On the transmit side, 1.544 Mbit/s PCM signals sent from terrestrial side are converted into 1.6 Mbit/s PCM signals using a positive justification technique, and after being compressed in terms of time by the compression buffer they pass to the TDMA terminal. On the receive side, PCM signals sent from the TDMA terminal are converted into continuous 1.6 Mbit/s at the expansion buffer. The justification service digit (JSD) is then extracted from the 1.6 Mbit/s PCM signals using control timing signals sent from the TDMA terminal. The JSD detector decides whether the justification digit time slot is an information bit or a dummy bit, and the original 1.544 Mbit/s PCM signal is recovered.

TABLE 1 — Examples of justification-frame structure

	Units	Type A	Type B	Type A	Type B
Input PCM bit rate	Mbit/s	1.544		2.048	
Gross bit rate	Mbit/s	1.6		2.112	
Justification technique		positive	pos./neg.	positive	pos./neg.
Justification frame	s	93.75	120	83.3	120
Information bit	bits/frame	144	192	170	255
Justification service digit	bits/frame	5	5	5	5
Justification time slot	bits/frame	1	2	1	2
Spare bit	bits/frame	150	200	176	264
Stuff ratio		0.25	(0.5)	0.33	(0.5)

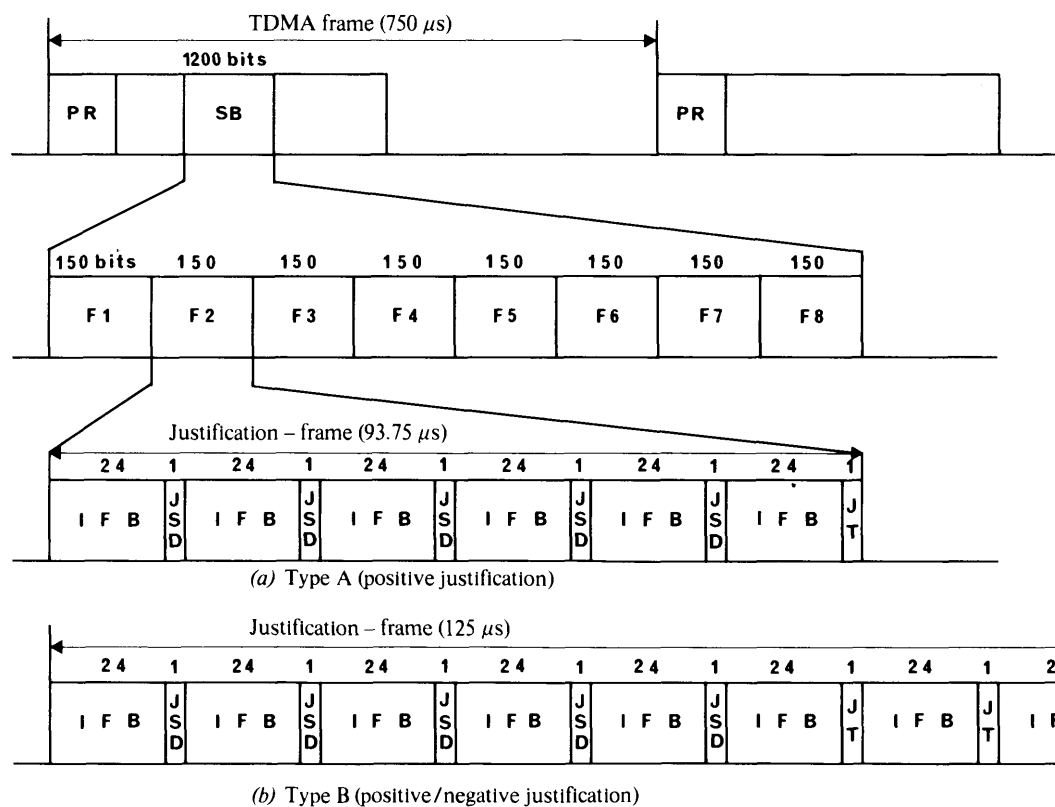


FIGURE 2 — Frame structure for 1.544 Mbit/s DDI

IFB: Information bits
 JSD: Justification service digit
 JT: Justification time slot
 SP: Spare bits
 PR: Preamble

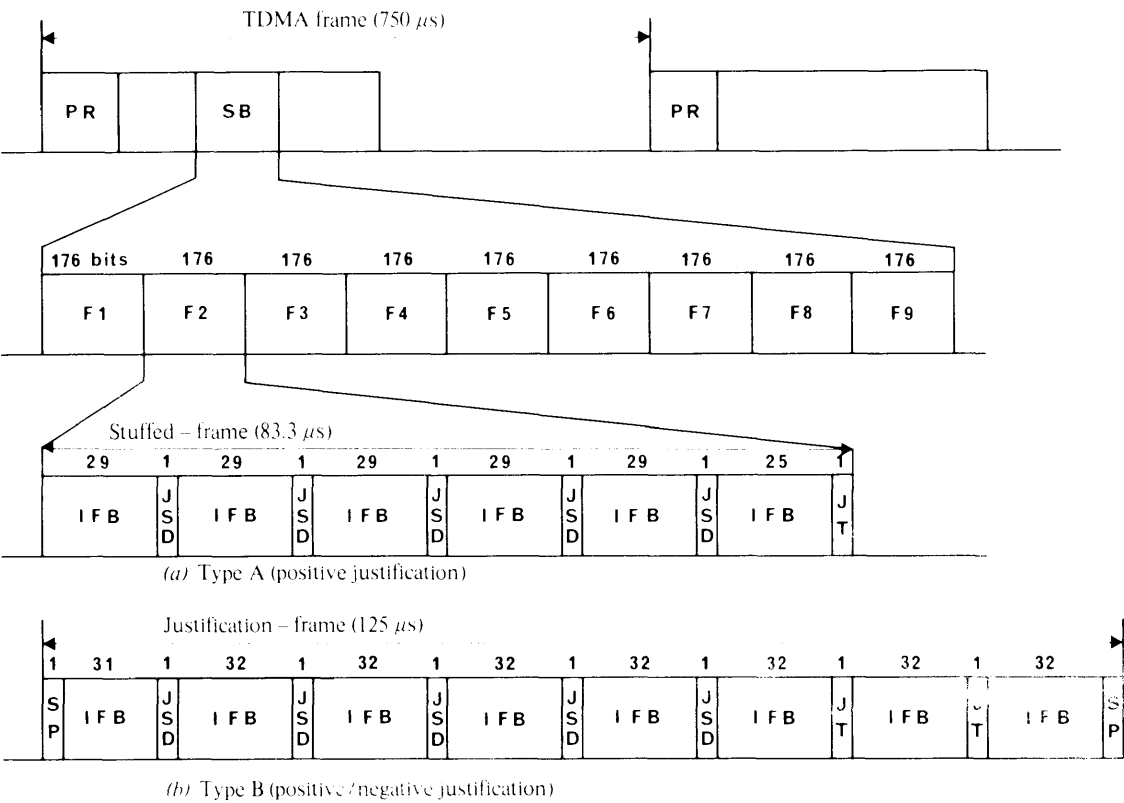


FIGURE 3 — Frame structure for 2.048 Mbit/s DDI

IFB: Information bits
JSD: Justification service digit
JT: Justification time slot
SP: Spare bits
PR: Preamble

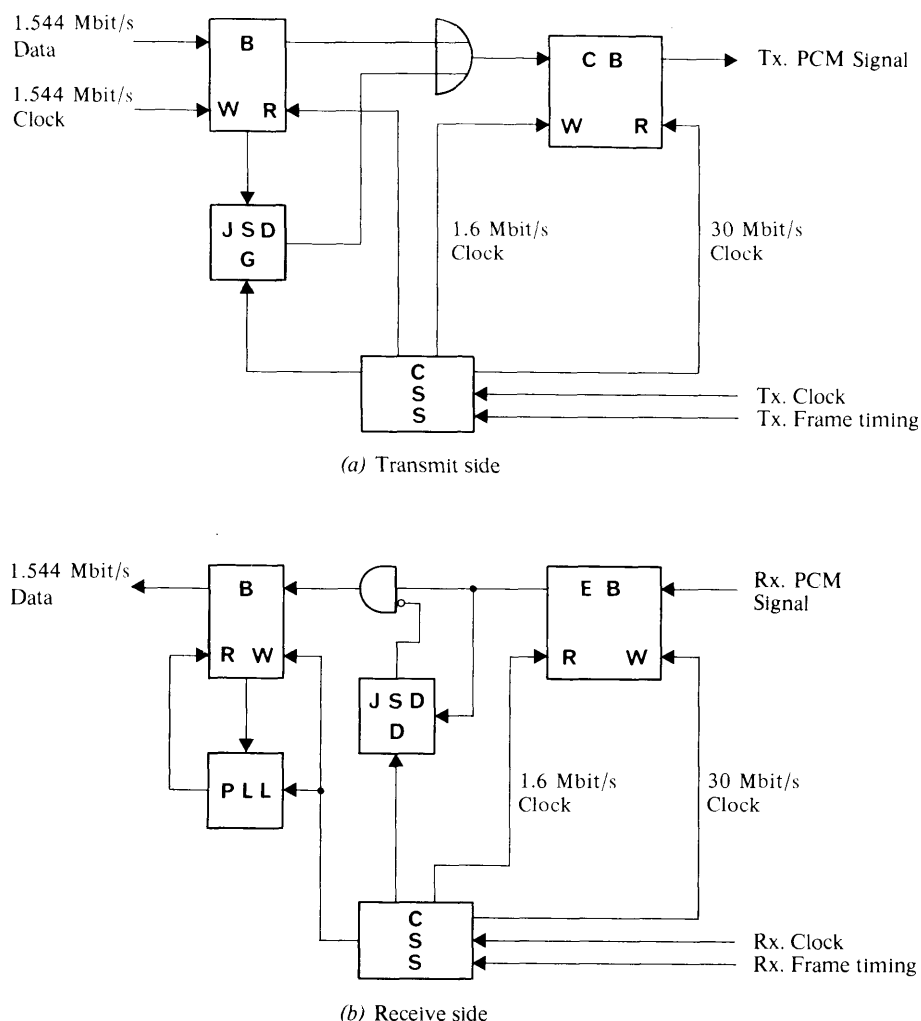


FIGURE 4 — Block diagram of DDI

JSD: Justification service digit
 PLL: Phase locked loop

ANNEX II

TRANSMISSION OF SIGNALLING AND ALARM CONDITIONS OF PCM PRIMARY MULTIPLEX IN DIGITAL SATELLITE LINKS

1. Introduction

The CCITT has defined the characteristics needed for the digital PCM multiplex equipment used in telecommunication networks, but with reference to only one end-to-end transmission section. In satellite communications there are sufficient grounds for referring to three transmission sections — two national and one international. However, from the switching point of view the link between TCs constitutes one section.

A method is proposed for PCM multiplex transmission by satellite which takes into account both TDMA/DSI techniques and the need to meet other requirements specified by the CCITT.

It is assumed that there is a digital link between international exchanges in which the terrestrial line between the TC and the earth station is synchronized with the TDMA equipment. Only the interface with the primary PCM multiplex equipment at 2048 kbit/s is considered. If the terrestrial multiplex equipment is at a higher order, it is assumed that interfacing is at the primary multiplex level.

2. Digital satellite systems

TDMA systems planned, may make use of DSI modules for up to 240 terrestrial channels that are converted into up to 120 satellite channels. In order to increase the real capacity of the satellite, only those terrestrial channels that are in service should be transmitted, while those that are not in operation should be withdrawn from the space link. In addition, the reduction in capacity due to the transmission of the synchronization and signalling channels used in PCM multiplex systems must be kept as small as possible.

The multi-destination advantages provided by satellites must not be limited by the structure used in terrestrial networks. Multi-destination should therefore be provided at the primary multiplex level and if possible even at the channel level. Furthermore, the solution adopted for the satellite system should enable any signalling system that is compatible with the satellite transmission delay to be used.

3. PCM multiplex equipment at 2048 kbit/s

In PCM multiplex equipment at 2048 kbit/s, channel times slot 0 of every other frame is used for the frame alignment signal, while the even numbered frames contain an international alarm bit and several spare bits for national use.

It is not necessary to transmit the frame alignment signal via the satellite since the TDMA system has its own frame synchronization signal defining the exact position of the individual telephone channels within the TDMA frame; the PCM multiplex frame can therefore be regenerated in the receiving earth station. However, in order to be able to dispense with the transmission of the frame alignment signal, a number of aspects relating to transmission and signalling alarms have to be taken into account.

For switching systems with channel associated signalling, channel time slot 16 is used. This consists of a multiframe formed by 16 consecutive frames. The multiframe alignment signal is 0000, which occupies time slot bits 1 to 4 of frame 0. In this frame 0, bits 5, 7 and 8 are spare and bit 6 is used to indicate to the distant end, the loss of multiframe alignment. The remaining 15 frames are each sub-divided into two blocks of 4 bits and each block is allocated to one of the 30 telephone channels.

4. CCITT requirements for alarm transmission

CCITT Recommendation G.732 refers to the transmission over the link between two multiplex equipments of a signal that has not been subjected to any keying.

In a satellite system based on TDMA/DSI techniques, the primary PCM groups could be transmitted without any modifications other than those required to insert them into the TDMA frame; but it would then be necessary to allocate channel time slots 0 and 16 permanently, and without interpolation, to two channels. Assuming an advantage of 2 : 1 due to DSI, the reduction in satellite capacity would then amount to 12%. This loss of capacity can be avoided by not transmitting the frame adjustment signal and by rearranging the information contained in channel time slots 16 so that only one TDMA signalling channel is used per DSI module. The loss of transmission capacity can thus be kept below 1%.

With this structure the satellite link uses its own frame information and the PCM frame alignment and multiframe alignment signals do not have to be transmitted between earth stations. The circuit between TCs must therefore be considered as being formed by three sections in series: two national sections, between TC and earth station, and one international section between earth stations. Hence the following faults on the national section should be detected in each earth station: loss of frame alignment, loss of input signal at 2048 kbit/s, excessive error transmission in the frame alignment signal and loss of multiframe alignment signal (if channel time slot 16 is used). The alarm signal should then be transmitted to the distant end of the national section.

For the international section between earth stations the TDMA/DSI equipment is provided with an alarm system comparable to that of the PCM multiplexes.

From the signalling point of view there is only one section between the two TCs, hence the need to develop a philosophy for the transmission of alarms from one section to the other. In CCITT R-2 systems, any failure triggering a service alarm to indicate that the circuit is not available for service, must be transmitted forward to the following sections so that the switching and signalling equipment receives the relevant indication.

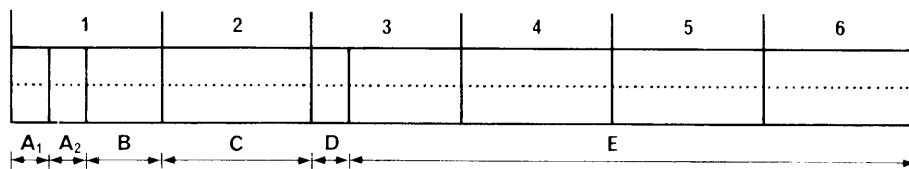
5. TDMA channel for the transmission of alarm and signalling signals

The solution outlined in this Report has the following characteristics:

- The satellite capacity is not seriously impaired (less than 1%) by the use of only one TDMA channel per DSI module of 240 telephone channels.
- In systems with channel-associated signalling, the transmission of group alarms is not delayed for longer than 1.5 ms in relation to the signalling information.
- Channels with different signalling or data transmission systems can be mixed in the terrestrial PCM multiplexes without any of the channels being affected by alarm transmission.

In the satellite system, each DSI module of 240/120 circuits should be equipped with a TDMA channel dedicated permanently to the transmission of group alarms and signalling messages. Such a DSI module can accommodate 8 PCM terrestrial multiplexes of 30 channels, or a higher number of terrestrial multiplexes provided that not all the channels of each multiplex are in service.

The structure proposed for this channel is the following:



A_1 : Function

- 00 – Signalling transmission.
- 11 – Group alarm transmission.

A_2 : Sub-function

- 11 – Forward alarm. Interruption of service.
- 00 – Forward alarm. Loss of multiframe signal.

B: Spare bits

C: Identification of the multiplex (1 to 8)

Each bit identifies a multiplex, hence alarm signals affecting more than one of them can be transmitted simultaneously. A zero transmitted in the bit corresponding to the particular terrestrial multiplex indicates that no fault condition exists, or that a fault condition has disappeared.

D: Identification of the signalling bit

- 00 – bit *a* of TS 16,
- 01 – bit *b* of TS 16,
- 10 – bit *c* of TS 16,
- 11 – bit *d* of TS 16.

E: Signalling information of the 30 telephone channels of the PCM multiplex selected

As far as the spare bits B are concerned, the following options are open:

- extension to 12 PCM multiplexes, each bit corresponding to one of the four multiplexes added.
- further extensions, in which case the bits of B can indicate the group of PCM multiplexes to which the information corresponds.
- other functions to be specified.

As the TDMA frame is of 750 μ s duration, covering 6 PCM frames of 125 μ s, the 48 bits can be transmitted in a TDMA frame in those corresponding to a telephone channel. However, given the need to protect this information from random errors, it is advisable to apply an error-correcting code. Since a Hagelbarger code with 24 information bits and 24 parity bits is used in DSI equipment for the assignment channel, it is advisable to use the same scheme for this new signalling channel. The TDMA frames will therefore be needed to complete the transmission of the 48 bits containing the alarm and signalling message.

6. Transmission of group alarms

The order of priority for the transmission of alarms and signalling bits should be as follows:

- forward alarm indicating that the PCM multiplex is out of service;
- forward alarm indicating that there is a fault in the multiframe of TS 16;
- signalling bits.

The forward alarm indicating that the PCM multiplex is out of service should be applied on detection of a fault affecting the entire group (e.g. loss of frame alignment signal) or when an Alarm Indication Signal (AIS) has been applied to the bit stream at 2048 kbit/s, if higher order multiplexes are being used between the TC and the earth station. In the latter case it is important to prevent the transmission of the corresponding telephone channels whose bits are all at state 1 due to the application of the AIS, otherwise the DSI equipment would be unnecessarily overloaded. It is also advisable to avoid their transmission in the former case so as to reduce traffic activity at the DSI equipment input. DSI equipment currently provides such blocking facilities. In order to transmit this alarm forward from the receiving earth station to the international switching exchange an AIS should be applied to the bit stream at 2048 kbit/s.

The TS 16 multiframe loss indication can be transmitted forward from the receiving earth station to the switching exchange through bit 6 of frame 0 of TS 16, which in the CCITT Recommendation is provided for the transmission of the alarm to the distant end.

Under the proposed structure for the satellite signalling channel, several group alarms can be transmitted simultaneously whenever the groups affected belong to the same block (8 groups per block). If more than 8 groups are assigned to each DSI module there is a possibility that an alarm might occur simultaneously in two groups belonging to different blocks; however, the likelihood of such a situation is virtually negligible unless the fault is due to a failure of a higher order PCM multiplex. The alarm transmission delay will therefore not exceed 1.5 ms under normal conditions.

This information must be transmitted via the satellite whenever there is a change in the condition of any of the groups or channels. In addition, to ensure the continued reliability of the information, refreshment messages should be transmitted redescribing the situation of the PCM channels or multiplexes when no other information needs to be transmitted over the signalling channel.

7. Transmission of the channel signalling

Some systems are based on channel associated signalling. Such signalling can be transmitted by means of the bits allocated to each telephone channel in TS 16. As this information is related to the setting up or cutting off of telephone calls, the proposed structure can more than meet the information transmission requirements, since the mean statistical duration of a call, including cases in which the call is not put through, can be set at about 2.5 minutes.

The Hagelbarger code protects this channel against possible bit errors and ensures that the information is as reliable as that of the DSI assignment message.

SECTION 4D: METHODS OF MODULATION AND MULTIPLE ACCESS

Report

REPORT 708 *

MULTIPLE-ACCESS AND MODULATION TECHNIQUES
IN THE FIXED SATELLITE SERVICE

(Study Programmes 2D-1/4 and 2E-1/4)

(1978)

1. Introduction

Multiple-access is the ability of a large number of earth stations to interconnect their respective transmission links simultaneously through the same satellite [Puate *et al.*, 1971]. This capability is important in a satellite system because of the large coverage area achievable by the satellite antennae. A transmission from one earth station can be received at many different locations.

In this Report different multiple access techniques will be discussed. Because the efficiency of any particular multiple access technique is closely tied to the choice of modulation, it is necessary also to discuss modulation methods. However, it must be emphasized that multiple access and modulation are two different concepts. Multiple access is essentially a traffic feature, whereas modulation is essentially a transmission feature. Both however, are very important in optimizing the utilization of a satellite system and it is often implicitly assumed that a given modulation method is inherent in a particular multiple access technique.

This Report will discuss first of all the characteristics of the baseband signals which are normally transmitted through a satellite multiple access system. Such signals are often subject to some form of processing before being transmitted to the satellite. Such processing is sometimes inherent in the terrestrial interconnection link (e.g. Pulse Code Modulation (PCM)) but is sometimes applied to increase the traffic carrying capacity of the satellite system (e.g. Speech Interpolation (SI)).

The Report will then discuss the most common forms of modulation used in multiple access systems, leading into a general discussion of multiple access systems. This part will cover the most commonly used systems, i.e. Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA), as well as some less common systems.

No single multiple access system can meet all the requirements which the operation of a system could have. In most networks it may be found that the optimum configuration of the network will employ several different multiple access techniques. In general the optimization of the following parameters will have to be considered for typical systems:

- capacity,
- efficient use of the radio frequency spectrum,
- efficient use of satellite radiated power,
- required interconnectivity,
- ability to adapt to traffic and network changes,
- ease of handling various types of traffic,
- problems of interface with terrestrial connections,
- economic viability.

Some transmission analysis examples and a comparison of typical systems conclude the Report.

2. Baseband signals and processing**2.1 Baseband signals and service**

One can identify four different services normally carried over satellite circuits in the Fixed Satellite Service:

- telephony,
- television programme exchange,
- sound programme exchange,
- data.

* This Report replaces Reports 211-3 and 213-3, Geneva, 1974.

The performance of international circuits for these services is the subject of continuous work within the CCITT and the CCIR. Hypothetical reference circuits have been defined for telephony and television (CCIR Recommendation 352-3) and sound programme exchange (CCIR Recommendation 502-1, CCITT Recommendation J.11). There is a need for a hypothetical reference circuit for data, especially in view of the fast growing special data networks, where satellites could be employed to provide part or all of the data connection.

Recommendations for performance criteria for the satellite link have been agreed in CCIR for the more commonly used services:

- Frequency-Division Multiplex (FDM) telephony: Recommendation 353-3;
- PCM telephony: Recommendation 522;
- analogue television: Recommendation 567;
- analogue sound programme exchange: Recommendation 505-1.

2.2 Baseband processing

The baseband signals used to provide the services mentioned in § 2.1 may have been subject to processing. This may be inherent in the transmission methods used in the terrestrial interconnection links. It could also have been done to improve the performance of the satellite network. In either case the use of baseband processing can lead to substantial improvement in the utilization of the satellite network and consequently to considerable reduction in the cost of a satellite circuit.

Some of the most important methods of baseband processing are:

2.2.1 Comanding

A compandor is an example of a combination of non-linear devices capable of linear behaviour when viewed from the input and output terminals. Compandors can be classified as instantaneous or syllabic. Instantaneous compressors and expanders are zero-memory non-linear devices which can be represented by characteristics of the form:

$$r(t) = F[s(t)]$$

where $r(t)$ and $s(t)$ are output and input wave forms respectively and $F[s(t)]$ is the expression function.

The difficulty with instantaneous companding is that the compressed wave must be transmitted through the channel without distortion of waveform. Otherwise the expression function would not recover $s(t)$. The bandwidth occupied by $F[s(t)]$ is, in general, greater than that of $s(t)$ because a non-linear operation on sinusoidal components produces harmonics as well as sum and difference products outside the original band.

In a syllabic compandor the gain changes are made slowly under control of the envelope of the speech wave rather than the instantaneous values. The bandwidth of the compressed signal is only slightly increased, and no new requirements on waveform preservation are introduced. The operation can be illustrated by considering an idealized case in which a signal is represented over a finite time interval by a sine wave, say:

$$s(t) = A \cos \omega t.$$

A syllabic compressor is designed to give a response of form $F(A) \cos \omega t$ to this wave instead of $F(A \cos \omega t)$ as would occur in an instantaneous compressor. The syllabic device has the advantage that no harmonics of ω are produced. If A changes slowly with time, there is only a slight spreading of the spectrum of the compressed wave about the frequency ω .

Nearly Instantaneous Companding (NIC) is a source coding technique for reducing the bit rate needed for PCM transmissions [Duttweiler and Messerschmitt, 1976]. This is achieved by rescaling the quantizing range of a block of PCM samples according to the magnitude of the largest sample in the block. The rescaling information is transmitted as a control word for the block of samples. The receiver uses the control word to convert the received bit stream to the normal PCM form. It is expected that NIC would make possible the transmission of good quality speech at bit rates of between 34 and 42 kbit/s.

2.2.2 Voice activation

In speech transmissions some bandwidth/power advantage can be gained by connecting a speech channel to a transmission (satellite) channel only when speech is present (e.g. speech interpolation). Another method of achieving a bandwidth/power advantage is to maintain the speech channel/transmission channel association for the duration of the telephone connection but to withdraw the transmission

channel from the satellite network during pauses in speech (e.g. SPADE *). The basic device for the implementation of such schemes is the voice operated switch whose characteristics are carefully chosen so as to achieve maximum system advantage without appreciable degradation of speech quality [Richards, 1973]. The fundamental parameters of a voice operated switch are shown in Fig. 1. There,

V_{th} : threshold level above which speech is assumed to be present (typically -35 to -40 dBm0 for a fixed threshold level switch).

T_O : voice switch operate time; the time taken by the voice switch to operate on detection of speech (typically 6 to 10 ms),

T_H : hangover time; the time during which the voice switch remains activated after the cessation of a speech burst on a speech channel (typically 150 to 200 ms).

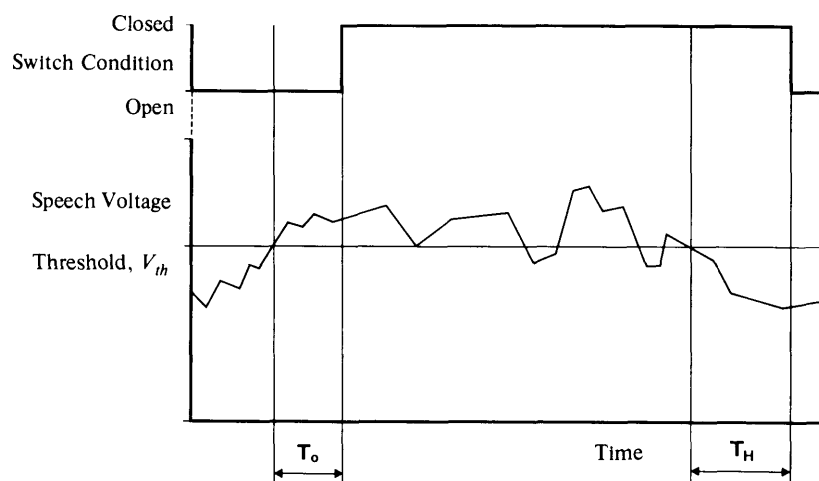


FIGURE 1 — Voice operated switch parameters

V_{th} , the threshold level, needs to be set fairly low to avoid missing large portions of the start of a speech burst (speech clipping) and low speech levels. This makes the voice switch susceptible to high noise levels, thus reducing the net system advantage.

A new generation of voice activated switches giving high noise immunity with minimal noise clipping has been developed. These have the capability to adjust the threshold level continuously with changing noise levels and are intended for use with digitized speech signals [Jankowski, 1976].

The use of voice activated switches to control speech signal transmission has found practical application in speech interpolation systems and single channel per carrier systems such as SPADE [Werth, 1969] and has been proved to be a valuable form of signal processing.

2.2.3 Speech Interpolation

Speech Interpolation (SI) techniques are based on the fact that, in a normal two-way conversation, each speaker actually engages the telephone circuit for only about half the total time taken up by the conversation. Furthermore, gaps between syllables and words, and also the pauses between phrases, add to the idle time, so that in a normal one-way telephone channel the channel is active, on the average, only for 35 to 40% of the time during which the circuit is connected [Bullington and Fraser, 1959].

Accordingly, if the same transmission channel can be assigned to different speakers on a voice activated basis, the transmission channel is better utilized. This brings a significant gain in the number of conversations which can be routed over the same channel in a given time period, thus leading to a gain in traffic capacity [Bullington and Fraser, 1959]. The theoretical speech interpolation gain (G) is defined by the ratio between the number of speakers (input trunks, N_i) and the number of transmission channels (N_c) required to service them.

* SPADE — Single channel per carrier PCM multiple Access Demand assignment Equipment.

In the case of analogue systems such as FDM/FM, the increase in channel loading due to speech interpolation requires an increase in bandwidth, approximately proportional to the square root of the increase in activity factor, or a proportional power increase; but for a digital system such as TDM/PCM/PSK, the overall gain in the system capacity using speech interpolation requires no increase in bandwidth or power. Consequently, other things being equal, the net capacity gain for a TDM/PCM/PSK system with speech interpolation is greater than that obtained for an FDM/FM system using this technique [Lyghounis and Costa, 1971].

Speech interpolation can be implemented in a number of different ways. Annex I describes some techniques for use in a digital systems.

2.2.4 Pulse Code Modulation (PCM)

In PCM, the baseband signal is sampled periodically and quantized in an agreed manner. In general the PCM processing of a voice signal includes companding. CCITT Recommendation G.711 specifies the PCM format to be used in international connections of voice signals. The sampling rate is 8000 samples per second, and each sample is coded into 8 bits giving a total bit rate of 64 kbit/s per speech channel. The 8-bit PCM standard is designed to be able to handle up to 14 PCM systems in tandem. However, another PCM standard is used in the INTELSAT Single-Channel-Per-Carrier (SCPC) system. A sampling rate of 8000 samples/second and a coding standard of 7 bits per second is used in this system, giving an information transmission rate of 56 kbit/s per channel. It uses voice activation and each speech burst is separately synchronized. Initial synchronization is achieved by transmitting a sequence of carrier and clock recovery bits (preamble) at the start of a speech burst and frame synchronization for sampling is maintained using a special synchronization word transmitted at regular intervals during the speech burst. The gross digit rate of this system is 64 kbit/s per channel. The choice of 7 bits instead of 8 is considered to give sufficiently high quality to the SCPC connection. It is reasoned that since the great circle distance between the transmitting earth station and the receiving earth station is large the probability of getting more than four systems in tandem is negligible [Puente *et al.*, 1971].

Another use of PCM is the direct encoding/decoding of a Frequency Division Multiplex (FDM) signal. This is likely to be done at super group level or higher. There are no internationally agreed standards for encoding an FDM signal. However, it is considered that a linear encoding law using nine bits per sample would be suitable for FDM/PCM.

2.2.5 Delta Modulation (DM)

DM is a way of further reducing the bandwidth required for a speech connection, taking advantage of the sample-to-sample correlation to remove redundancy. There are many different ways of implementing DM using adaptive methods to improve the signal to noise ratio. For a comparison of different ways to digitally encode speech, see [Jayant, 1974].

In delta modulation the analogue signal is sampled at a rate much greater than for PCM, typically 24 to 40 kHz for good quality speech, and a one-bit code is used to transmit the change in input level between samples.

The effect of transmission errors in delta modulation systems is not as serious as in PCM systems. This is because all the transmitted bits in delta modulation systems are equally weighted and are equivalent to the least significant bit of a PCM system. For equivalent transmission rates, below about 40 kbit/s, delta modulation has been shown to be superior to PCM.

The main drawback of DM systems is the difficulty of interconnecting them in a general way in an international network using analogue and digital links.

2.2.6 Differential Pulse Code Modulation (DPCM)

DPCM is a method that can be used for speech as well as for television signal coding.

Efficient speech coding can be achieved by ADPCM (adaptive DPCM). Conceptually ADPCM is similar to ADM (adaptive DM). The basic difference is that the "error signal" (which is the difference between the signal at the system input and the signal at a predictor output), in an ADM system, is codified with a single bit at a high sampling rate, while in an ADPCM system it can be codified with 4 bits at the same sampling rate usually adopted in PCM (8 kHz); as a consequence the conversion from PCM to ADPCM is fairly simple.

The quantization step of the coder is automatically adjusted on the basis of the transmitted signal only, and therefore the receiver does not need any additional information to set up the decoder.

The performance of such a system has been assessed by means of extensive objective and subjective measurements conducted in Italy [Copperi *et al.*, 1975]. The results have indicated that, with ADPCM, a telephone signal can be transmitted at a rate of 32 kbit/s with the same subjective quality achieved by a standard PCM signal at the rate of 64 kbit/s; the improvement in bit rate is therefore equal to 2. In addition a 32 kbit/s ADPCM system can transmit data in the voice band at a rate of up to 2400 bit/s, with the same performance achieved by a 64 kbit/s PCM system.

2.2.7 Error control coding

The two main classes of error control are Forward Error Correction (FEC), using a self-error-correction code, and Automatic Repeat Request (ARQ), using an error-detecting code, together with an auxiliary feedback channel to initiate a retransmission of any block of bits received in error. The former, FEC, is the more suitable for telephony purposes although the latter may have its uses in other applications, e.g. data.

The choice of an FEC code for a particular application is influenced by link bit error conditions that are likely to exist in the absence of error control. This is because, in practice, most codes tend to worsen the error performance when the transmission link error rate exceeds a "threshold" value for the code. In general, the link error rate at which this threshold occurs increases with increasing complexity of the code. This is illustrated in Fig. 2 for a BCH * code having the capability to correct one and two errors respectively in a transmitted data block of 127 bits.

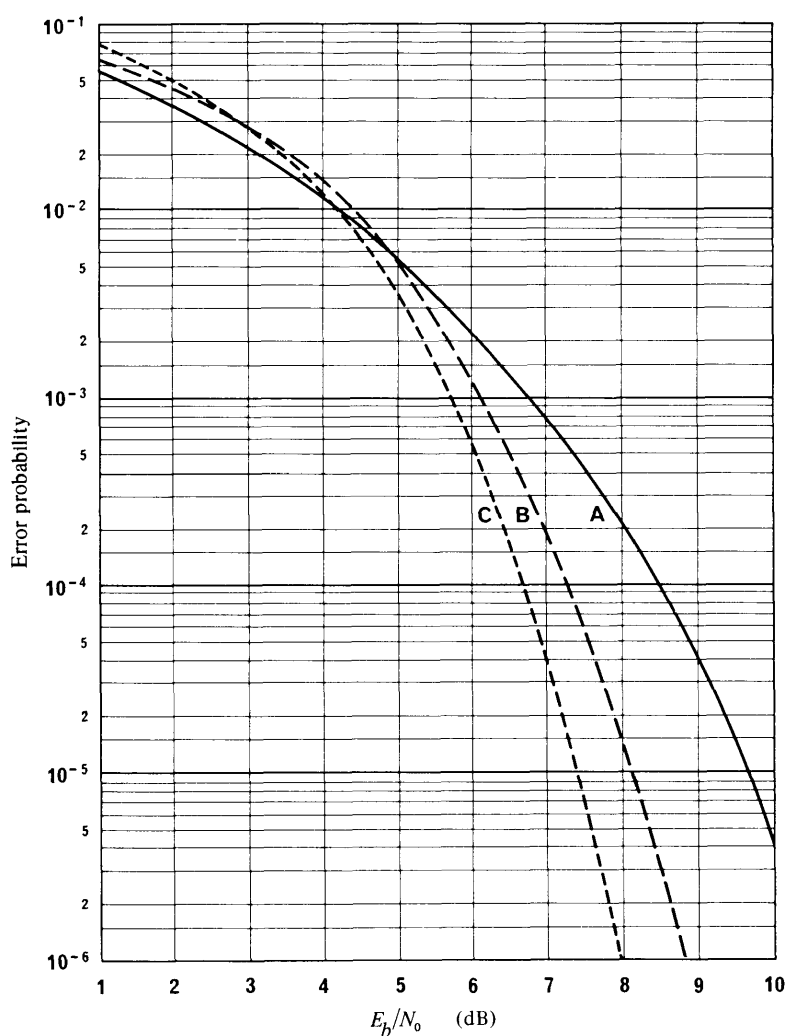


FIGURE 2 — Coding advantage of BCH block codes using a block of 127 bits

Curves A: No coding
 B: One bit error correcting code (120 information bits, 7 parity bits)
 C: Two bit error correcting code (113 information bits, 14 parity bits)

* BCH — Bose Chaudhuri Hocquenghem.

Convolutional FEC codes are gaining popularity for use in satellite systems [Heller and Jacobs, 1971]. Fig. 3 shows the theoretical performance of three such codes.

- rate 7/8 convolutional encoding with hard decision decoding,
- rate 3/4 convolutional encoding with hard decision decoding,
- rate 1/2 convolutional encoding with Viterbi decoding [Heller and Jacobs, 1971].

Reading horizontally, Fig. 3 shows the reduction of required E_b/N_0 for a given error rate; vertically, Fig. 3 shows the improvement achieved on a given link by introducing FEC coding. FEC can thus be used to adjust a given link to a desired error rate.

An application of coding is to improve a link during poor propagation conditions. Error correcting codes are then employed to maintain the required system performance Report 552-1, Annex II. The extra bit capacity required for error correction could in this case be traded against a reduction in the system throughput, i.e. incoming lines could be busied out, and the extra bits made available to augment the remaining circuits with error correction capability [Gordon *et al.*, 1974].

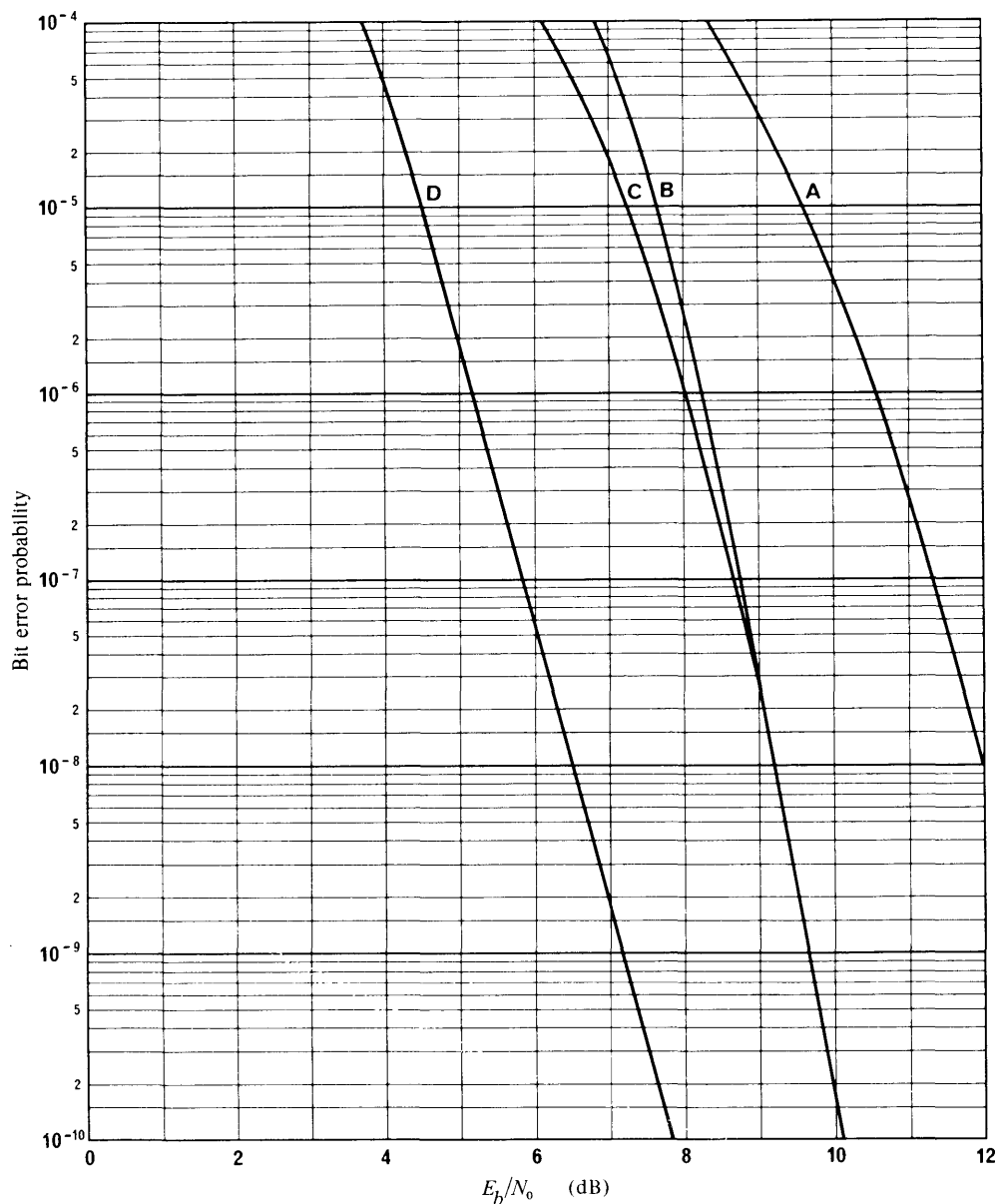


FIGURE 3 — Coding gain

Curves A: No coding resulting from various code rates
 B: Rate 7/8 coding
 C: Rate 3/4 coding
 D: Rate 1/2 coding

3. Modulation methods

The baseband signals have to be modulated onto radio frequency carriers to be transmitted to the satellite. The most common methods considered in this Report are:

3.1 Frequency Modulation (FM)

FM is the most popular method of transmitting signals at microwave frequencies. For a satellite user it affords the possibility of compromising between power utilization and bandwidth by increasing the frequency deviation. In a single carrier per repeater system the constant envelope of the FM signal allows the power amplifiers to operate at saturation thus making maximum use of the available power.

3.2 Phase Shift Keying (PSK)

PSK modulation is an efficient method of modulating a carrier with digital information. In a 2-phase system one phase of the carrier is used to represent one binary state and a phase 180° apart from the first one, is used for the other binary state. Higher order PSK schemes exist. Theoretically 4-phase PSK requires the same power, but half the bandwidth, as 2-phase PSK for a given link performance. Higher order (greater than 4-phase) PSK systems are more susceptible to noise and, therefore, need more power than either 2 or 4 phase systems to achieve the same standard of performance. For most purposes 4-phase PSK gives the best power-bandwidth compromise. In a wide band channel a PSK signal can be designed to have a small envelope variation thereby minimizing the effect of non-linearities in the channel.

In band limited channels the PSK signal will have some amplitude variations. Optimizing such a channel involves trading off non-linear in-channel distortion for adjacent channel interference.

3.3 Single Sideband (SSB) amplitude modulation

Single-sideband transmission is simple in concept and has the merits of greatest economy in bandwidth. Unlike frequency modulation it is not subject to threshold effect.

On the other hand, single-sideband modulation has certain disadvantages relative to FM and PSK, e.g. it requires higher transmitter power than wide deviation frequency modulation, it is more sensitive to non-linearity and it requires highly accurate frequency synchronization, which is particularly difficult to achieve with non-geostationary satellites. It is also both more susceptible to interference than wide deviation frequency modulation and will produce more interference when its signals fall within one baseband-bandwidth of the carrier of other systems.

Similar noise allocations can be considered for single-sideband as for frequency modulation, although for single-sideband, it may be more difficult to provide the necessary linearity.

In a single-sideband transmitter, it is necessary to consider both mean power and peak power. Peak-to-r.m.s. voltage ratios for SSB transmitters can be of the order of 10 to 13 dB.

3.4 Combined Amplitude and Phase Modulation (APM)

Combined amplitude and phase modulation includes various modulation formats with two dimensional (amplitude and phase) signal constellations. This modulation format can be applied to digital data transmission and analogue data transmission as well. APM has the merits of great economy in bandwidth and power. It achieves the baseband signal to noise power improvement at the expense of introducing a demodulator threshold. It is more sensitive to non-linearity relative to frequency modulation and is suited for multi-carrier operations [Thomas *et al.*, 1975].

Recently an engineering model of a 2-pulse amplitude and phase modulation modem (2P-PAPM) for 120 channel FDM telephony has been developed and tested via a Pacific Ocean INTELSAT-IV satellite [Walti, 1973; Chakraborty *et al.*, 1977]. In this modulation system, the FDM telephony signal is first sampled at an appropriate rate. The sampled signal is approximated by the nearest of seven possible voltage levels. A first carrier pulse, having one of seven possible amplitude-and-phase combinations to represent this coarse level, is transmitted. The difference between the actual signal sample and the coarse approximation is then represented by the closest of three possible levels. Finally, the remainder is also measured. A second carrier pulse is formed by combining a cosine and a sine wave. The amplitude of the cosine wave represents one of three possible levels described above, and the sine wave amplitude is directly proportional to the remainder.

4. Multiple Access Methods

4.1 General

The satellite in a system in the Fixed Satellite Service acts as a relay station and is a nodal point in the circuits to the earth stations involved. It will contain one or more repeater chains each of which has a capability of frequency translating, amplifying and re-transmitting the signals received from earth stations in the system. The number of repeater chains in a satellite depends on the particular system and is a compromise based on technical

and economic considerations. Generally the bandwidth available per chain is greater than that needed by most earth stations for their individual use. Therefore, in order to fully utilize the available repeater capability more than one earth station is allowed to access a repeater chain with either single destination or multi-destination transmissions. This use of a repeater chain by more than one transmitting earth station is called *multiple-access*.

Fig. 4 shows a general multiple-access network and the signal flow in such a network. At the multiple-access terminal the signals are provided with address information and processed into the transmission format used within the satellite system. Depending on the type of multiple access system the terminal can have varying degrees of sophistication. In its simplest form it would just be a cable connection of the baseband signal to a particular transmission chain including the modulator, etc.

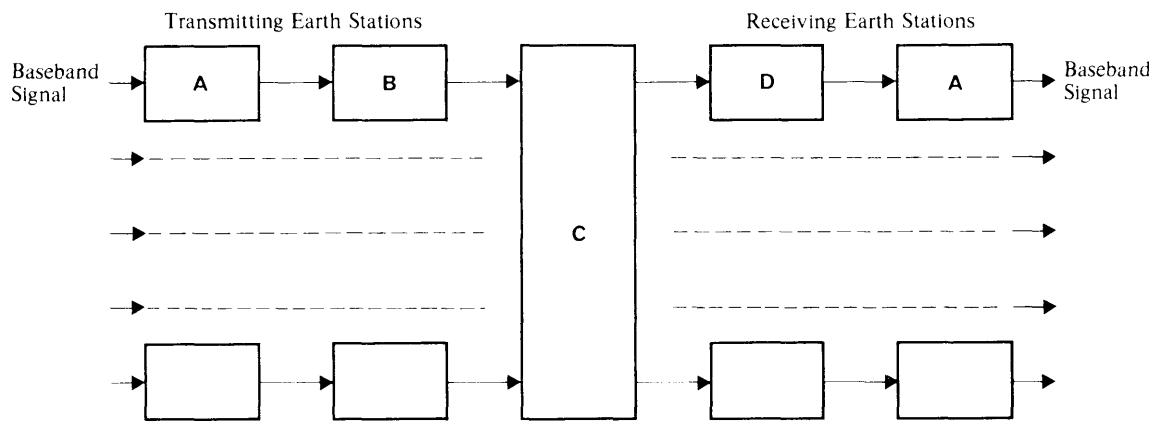


FIGURE 4 — Generalized multiple access signal flow

A: Multiple Access Terminal
B: Transmitter
C: Satellite Repeater
D: Receiver

A more complicated terminal may have to perform the following tasks:

- interfacing with terrestrial network,
- appending and extracting address and system information,
- in digital systems acting as a buffer for timing variations and bit rate conversions,
- associating bursts of information with particular transmission chains (e.g. TDMA systems, see section 4.2.2).

Many different transmitted signals go through the same satellite repeater channel. Ideally each transmitted signal must have a structure such that:

- it will be possible for a receiver to separate it from the composite channel signal,
- it will interfere as little as possible with the reception of the other signals, [Schwartz and Munter, 1973].

Two different categories of multiple-access techniques can be identified. The first one comprises techniques where the signals are nominally not interfering with each other. The signals transmitted to the satellite are orthogonal such that in an ideal channel the detection of one signal would automatically exclude the others. Techniques using non-interfering signals are Frequency Division Multiple-Access (FDMA) and Time Division Multiple Access (TDMA).

The other category comprises techniques where the signals are interfering with each other but the interference is kept sufficiently low by proper signal design. Techniques using interfering signals include Spread Spectrum Multiple Access (SSMA) and Pulse Address Multiple Access (PAMA).

For general communications purposes, non-interfering multiple access systems are preferred. They are inherently more efficient in the utilization of the available bandwidth than interfering multiple access systems.

One important design constraint is the limited power available onboard a satellite. It is highly desirable to operate the satellite power amplifier as close to its saturated output power as possible. Similarly it is often desirable to operate the power amplifier at the transmitting earth station near its saturated output power. In a multiple carrier system considerable back-off from the saturation point is required in order to keep the intermodulation distortion down to an acceptably low level.

One method of reducing this back-off requirement is for carriers to access the repeater on a time sequential basis such as in TDMA systems where PSK (phase shift-keying) is most likely to be the method of modulation employed. However, a PSK signal in a bandwidth limited system will exhibit amplitude modulation and will therefore undergo non-linear distortion in the satellite power amplifier. The bandwidth of the distorted signal is usually greater than the undistorted signal bandwidth. Therefore, a TDMA system employing PSK modulation may suffer some degradation from non-linear effects in the satellite and may also impose interference on the adjacent radio frequency channels. Depending on the bandwidth of the filter following the power amplifier, this interference can become a limiting factor in the performance of an FM/FDMA system operating in a channel adjacent to a PSK/TDMA system.

4.2 Description of Systems

4.2.1 Frequency Division Multiple-Access (FDMA)

The most commonly used multiple-access technique thus far is FDMA. With this technique several different carriers, separated in frequency, share a common satellite repeater chain.

The use of a travelling-wave tube or other saturating power amplifier causes several types of transmission impairment which must be considered in designing a multiple-access system using frequency division. Depending on the type of modulation employed, e.g. FDM/FM or PCM/PSK, etc., the operating parameters of the satellite repeater should be optimized to minimize intermodulation, intelligible cross-talk or other interference effects caused by repeater amplitude and phase non-linearities, by taking into account the number and size of carriers expected to have access to the repeater. These impairments are then kept within desired bounds by operating the travelling-wave tube at the minimum input back-off necessary to ensure performance objectives are met. Multiple carrier operation always results in less capacity being available, when compared to the single-access mode, due to the power back-off.

The power transmitted by an earth station depends on the number of voice channels modulating the carrier. To ensure that all carriers arrive at the repeater with appropriate power relative to one another, it is necessary, in multiple-carrier operation, to control the power of each carrier transmitted to the repeater from each earth station. In frequency bands above 10 GHz, fading due to precipitation can be large and therefore power control techniques will need to be used to achieve the input power stability required at the satellite.

Many baseband modulation combinations are used. Typical examples are:

4.2.1.1 Frequency Division Multiplex/Frequency Modulation (FDM/FM)

Considerable experience has been gained in utilizing FDM/FM carriers in the multiple-access mode, and present systems are being designed to maximize the satellite capacity while taking into account all relevant transmission impairments.

The channel capacity of a satellite repeater with FDM/FM carriers will normally vary as a function of the number of accesses and the traffic distribution patterns. The variation will depend to some extent on limitations in the system design, including both earth station and satellite characteristics. A typical example is shown below. This also assumes that all earth stations have identical receiving systems.

Number of carriers in one repeater	Channel capacity relative to single-carrier operation (%)
1	100
2	90
4	60
8	50
16	40

4.2.1.2 Single-Channel-Per-Carrier (SCPC)

In an SCPC system each carrier is modulated by one voice channel. The voice channel can be processed in a number of ways. Typical SCPC systems use companding and frequency modulation (CFM) [Evans and Kernot, 1975], delta modulation (DM) or pulse code modulation (PCM).

SCPC-CFM systems are in use in various places, e.g. Algeria and Alaska. The threshold behaviour of demodulators is a limiting factor in the operation of FM systems. The use of threshold extension techniques for SCPC applications is under study.

SCPC-DM-PSK for voice service has several systems advantages for SCPC applications and few drawbacks are noted. These techniques have been applied in operational systems. One system uses DM-SCPC-FDMA to communicate to the far north of Canada. Another system is used to communicate to oil platforms in the North Sea.

The main drawback of such systems is the difficulty of interconnecting them in a general way in an international network using analogue and PCM links. The two systems above are end circuits where the incoming voice is digitized at the earth stations.

SCPC-PCM-PSK systems have gained wide acceptance. A typical system is the INTELSAT SCPC system [Puente *et al.*, 1971]. The system can be used in either a pre-assigned or a demand assigned mode (SPADE). The maximum capacity in a 36 MHz transponder is 800 carriers spaced 45 kHz apart.

4.2.1.3 Time Division Multiplex – Pulse Code Modulation – Phase Shift Keying (TDM-PCM-PSK)

In this technique a carrier is phase modulated by a baseband signal in the PCM multiplex hierarchy. The CCITT has agreed on certain bit rates and formats for the international PCM network.

In order to minimize the cost and complexity of interface equipment at the earth station, it is advantageous to use, as far as possible, the terrestrial TDM-PCM multiplex signals directly in modulating the carriers.

The direct digital interface is under study in the CCIR (Study Programme 2N/4).

TDM-PCM-PSK-FDMA has several advantages, but of particular importance is the ability of a user to introduce digital links gradually without going to a full scale TDMA system (see below). Other advantages may be:

- capacity increase over FDM-FM of about 2 to 1 by using Digital Speech Interpolation (DSI),
- compatibility with FDM-FM in the same repeater [Davis and Fang, 1975].

4.2.2 Time Division Multiple Access (TDMA)

TDMA is a multiple access technique whereby stations communicate with each other on the basis of non-overlapping transmission bursts through a satellite repeater. The baseband signals can be many, but before modulation they have to be converted to digital signals. TDMA is therefore uniquely suited for transmission of digital signals such as TDMA-PCM telephony or data signals. TDMA has been used in a number of systems, e.g. signalling and access information channels in the SPADE and MARISAT systems [Lipke and Swearingen, 1974].

This report will concentrate on TDMA systems for telephony using 4-phase coherent (C) PSK. Such systems are in use, e.g. in Canada, and are being tested elsewhere.

TDMA is characterized by the durations of the time-frame and the time-slot (see Fig. 5). The time-slot allocated to an earth station consists of a guard time, a preamble and the information to be transmitted. The preamble contains auxiliary information for system organization such as synchronization and routing information. The time allocated to the guard time and the preamble is to a high degree dependent on the principle used for system organization. The message information may consist of a number of basic channel units. A basic channel unit is an encoded sample of a telephone channel or a digital baseband signal. In a system in the Fixed Satellite Service employing TDMA each participating earth station may be assigned more than one time-slot. One complete sequence of earth station transmissions is the time-frame. The time-slots of different earth stations can differ in their time duration, depending on the amount of traffic to be transmitted. The duration of the time-frame is limited by the maximum permissible transmission delay.

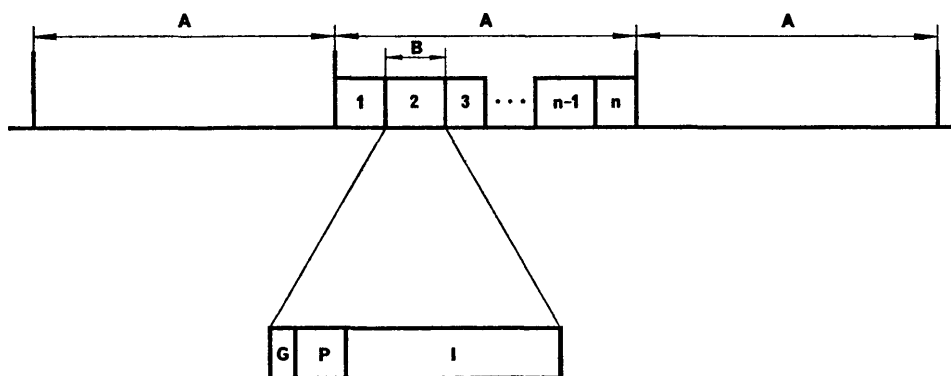


FIGURE 5 — Format of a time-division multiple-access system

- A: Recurring time frame
- B: Time-slot allocated to an earth station — within the time-slot the earth station transmits information as a burst of pulses
- G: Guard time, separating successive transmissions from earth stations
- P: Preamble containing auxiliary information for system organization
- I: Information

A particular earth-station receiver identifies the desired transmission by observing the information in the periodically recurring time-slots associated with the corresponding earth station. A minimum system bandwidth is achieved when the same radio-frequency carrier is used by all earth stations.

Considerations of synchronization and timing set a minimum limit for the duration of the time assignment to an individual earth station. This limitation plus the necessity for time compression of the baseband signals for discontinuous transmission leads to a time-division technique in which pulses corresponding to more than one sample of a speech channel can be transmitted during each time-slot. The time-slot content is limited only by the modulation formats which can be transmitted therein. Propagation time is the largest delay factor in the case of the geostationary satellite. Thus geostationary satellite systems handling voice traffic cannot allow excess delays from other sources which approach an appreciable fraction of the transmission delay. This determines a maximum value of the time-frame. However, in practice, the optimization of the time-frame from the present time leads to time-frames much less than this maximum value. This is described below for a multi-frame system.

In the following discussion of time-division multiple-access, it will be assumed that the information has been sampled and converted to a pulse format.

In TDMA systems, preamble requirements cause a decrease in the available telephone capacity so that the frame efficiency (ϵ), defined as the usable fraction of the frame capacity, decreases as the number of stations in the system increases, as shown in Fig. 6. A suitable method of limiting this loss of efficiency is to lengthen the time-frame by using buffer store circuits. This method of operation, called the "multi-frame" mode offers increasing advantages as the number of stations per frame and preamble length per station increase. Alternatively, a system employing clock coherent operation among the time-slots allocated to a given earth station allows shorter preambles and thus increases the frame efficiency [Takada and Doi, 1969]. Generally the frame efficiency increases with increasing TDMA frame length as shown in Figs. 6 and 7 [Quaglione *et al.*, 1972]. It is seen that the point at which this increase becomes insignificant is a function of the preamble length and the number of stations in the system. In practice the optimum TDMA frame length for a particular system will be determined by the operational and earth segment equipment requirements as much as by the need to have a high frame efficiency.

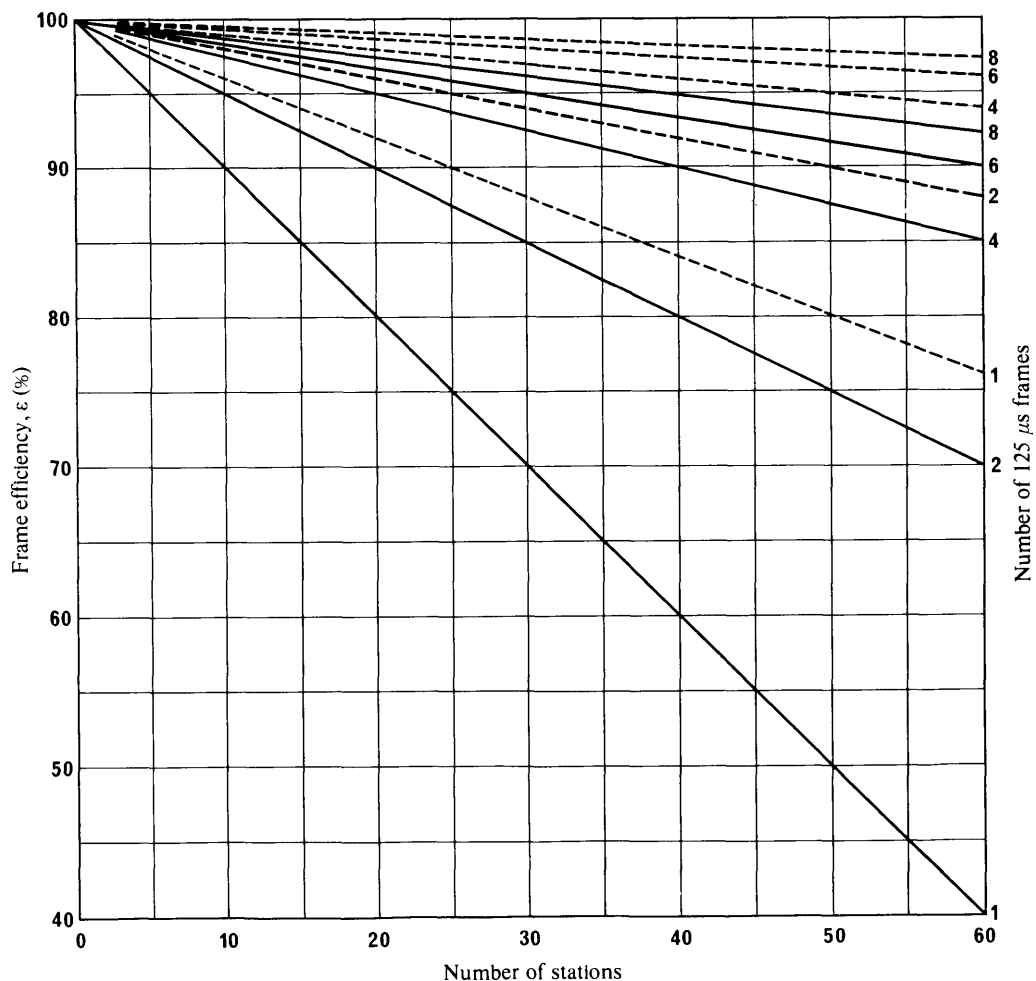


FIGURE 6 — Frame efficiency in TDMA systems

- Preamble length: 40 symbols (80 bits)
(Clock asynchronous operation)
- Preamble length: 16 symbols (32 bits)
(Clock coherent operation)

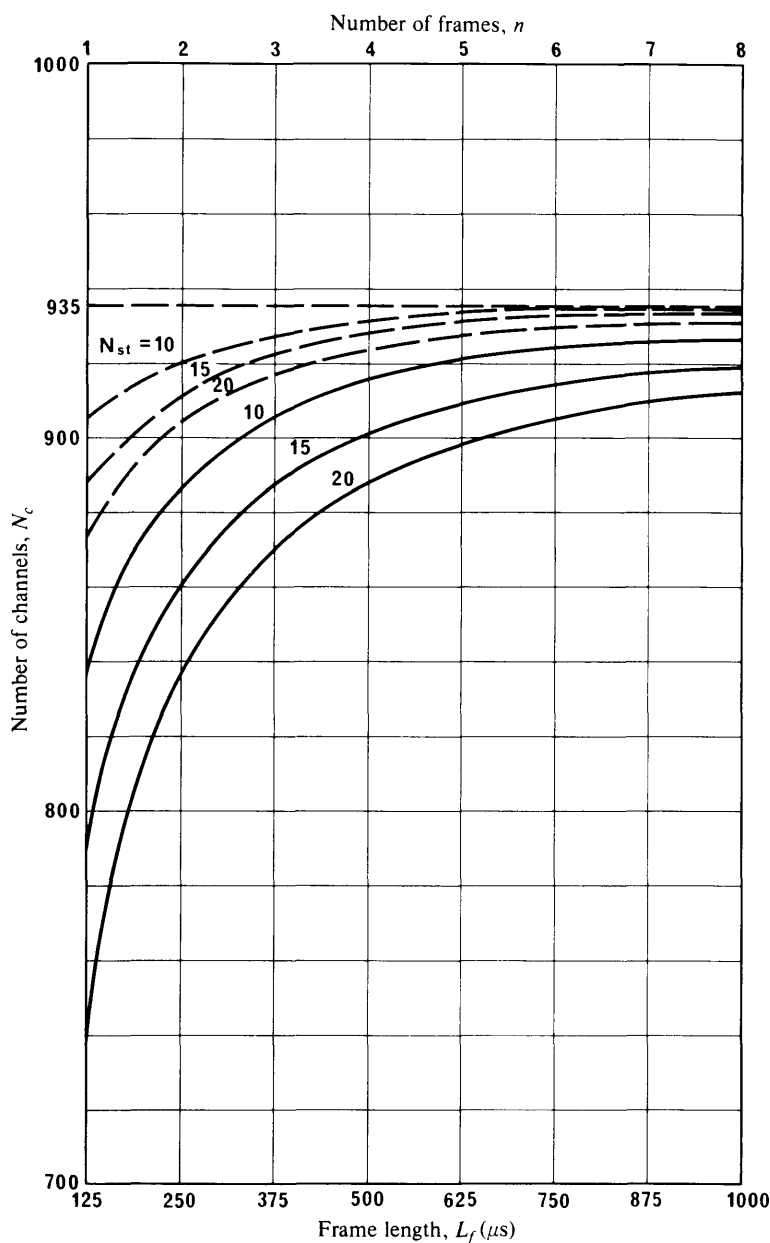


FIGURE 7 — Net channel capacity of a TDMA system on a 36 MHz satellite transponder vs. frame length (L_f)

Link bit rate: 60 Mbit/s

N_{st} : number of stations in the system

- Preamble length: 40 symbols (80 bits)
(Clock asynchronous operation)
- - - Preamble length: 16 symbols (32 bits)
(Clock coherent operation)

In TDMA systems a reference timing signal has to be provided. This frame reference signal usually originates in a selected earth station and is relayed by the satellite to the other earth stations.

Transmitted time-slots are synchronized to the frame reference by correcting for path variations at a rate equal to the derivative of the path delay. This can be performed by extracting the timing error of the transmitted signal from the received TDMA signal, when the transmitted signal from an earth station is

sent back to the same earth station via satellite. However, this condition cannot always be satisfied when the TDMA system is operated with spot beam satellite antennae. In this case several techniques can be employed to provide synchronization. They are:

- the timing error can be measured at the addressee earth station and sent back to the transmitting earth station;
- if the TDMA terminals of an earth station are operated in a global coverage antenna as well as in spot beam antennae, the timing error can be derived from the TDMA terminal operating with the satellite global coverage antenna. The timing of the TDMA signal which is transmitted to the spot beam antenna can be slaved to that of the global beam antenna by adopting common frame synchronization over the whole TDMA system.

The derivation of the timing information in this case could either be performed by using a TDMA burst, or by means of a separate frequency modulated carrier, using a small portion of the capacity in a FDMA global transponder [White, 1975];

- the accurate position of the satellite is measured at the reference station and the information is provided along with frame-timing to all stations;
- the earth station determines its own propagation delay to the satellite very accurately before transmission of its own signal and the stations are synchronized passively [Nuspl, 1972].

In systems for digital radiocommunication, it is desirable to select modulation and detection methods which give the minimum bit error rate for a given satellite power. PSK modulation and coherent detection present advantages in this respect. However, because the transmitted signals are burst mode PSK and because carrier and clock timing among earth stations are mutually non-coherent, recovery of the reference carrier for coherent detection and recovery of the clock timing for signal decision are necessary at the beginning of each burst.

Some TDMA systems under consideration anticipate having clock synchronism thereby reducing the need for extra bits for bit timing recovery [Watanabe and Izumi, 1975]. This will also of course, increase the frame efficiency.

From a traffic point of view a TDMA system has greater flexibility than an FDMA system. Transmission of a burst is done at the bit speed used by the TDMA system. (A disadvantage of the TDMA system is that this will require high power transmission at each participating earth station regardless of traffic requirement.) A station requiring a change in the number of channels transmitted needs to change the burst length only. This flexibility, especially in a demand assigned system where the number of traffic channels per earth station can be varied, requires the establishment of general network discipline. This function can, depending on the system organization, be performed by a central network control station or in a decentralized system by the ground terminals in a prearranged network discipline.

In either network organization there must be order-wire communications between the participating earth stations. The fraction of time allocated to order-wire need be quite small.

4.2.3 *Spread Spectrum Multiple Access (SSMA)*

SSMA makes use of a deterministic noiselike signal structure to spread the narrow-band information over a relatively wide band of frequencies. The receiver correlates this operation to obtain the original information signal. The spectrum spreading is achieved by one of a series of complex codes, so that a coded signal entering a receiver using a different code will not be correlated. Because the generated codes in an SSMA system are pseudo-noise in character, an interfering code is rejected in proportion to the ratio of the spread-spectrum bandwidth to the information bandwidth. In the spread-spectrum system, synchronization of the receiver code generator to the incoming signal is necessary.

SSMA has been used in cases of extremely power limited satellites. It would seem unattractive for public communication networks because of its large multiple-access loss [Schwartz and Munter, 1973].

4.2.4 *Pulse Address Multiple-Access (PAMA)*

PAMA is a technique used for unco-ordinated communication between computer systems [Schwartz and Munter, 1973]. It can also be thought of as an unco-ordinated TDMA system. A user will transmit a burst of data (one or many packets), complete with address information, at a time determined only by the need for communication at the originating end and regardless of whether or not there may be another user accessing the repeater. The acceptable probability of collision of bursts will determine the maximum data transmission capacity of the system. As can be expected the utilization of the repeater capacity is low for such a system. This is weighed against the simplicity of the system.

An increase in utilization can be achieved by initiating transmission of a burst only at periodic time intervals, i.e. use of a frame structure, but retaining the unordered access to a frame. This will improve the utilization. A further improvement will be achieved by going to an organized (but uncomplicated) TDMA system.

5. Examples of transmission analysis

5.1 FDM-FM

The basic relationship between the carrier-to-noise and signal-to-noise ratios in a conventional frequency-modulation system can be expressed as:

$$S/N = (C/N) \times \frac{3(F_{ch})^2}{f_2^3 - f_1^3} \times B_{RF} \times p \times W \quad (1)$$

or

$$S/N = (C/N) \times \frac{(F_{ch})^2}{(f_m)^2 + \frac{b^2}{12}} \times (B_{RF}/b) \times p \times W \quad (2)$$

When the value of f_m is more than about four times the value of b , the foregoing relationship may be replaced with negligible error by the following approximate relationship:

$$S/N = (C/N) \times (F_{ch}/f_m)^2 \times (B_{RF}/b) \times p \times W \quad (3)$$

where,

- S/N : the ratio of test-tone (i.e. 1 mW at the point of zero relative level) to the psophometrically-weighted noise power in the highest telephone channel,
- C/N : the carrier-to-noise ratio in the bandwidth B_{RF} ,
- B_{RF} : the radio-frequency bandwidth (Hz),
- f_2 : the upper frequency bound of the passband of the highest baseband channel (Hz),
- f_1 : the lower frequency bound of the passband of the highest baseband channel (Hz),
- $f_m = (f_2 + f_1)/2$: the mid-frequency (arithmetic mean) of the highest baseband channel (Hz),
- $b = (f_2 - f_1)$: the bandwidth of the telephone channel (Hz),
- F_{ch} : the r.m.s. test-tone deviation per channel (Hz),
- p : the pre-emphasis improvement factor,
- W : the psophometric weighting factor.

Typically the value of b is 3100 Hz and in this Report p and W are assumed to have the numerical values of 2.5 (4 dB) and 1.8 (2.5 dB) respectively.

In the expression given above only B_{RF} and F_{ch} are unknown. To solve for F_{ch} and hence B_{RF} , it is necessary to find an additional relationship between these two variables. It is assumed that the bandwidth B_{RF} is given by:

$$B_{RF} = 2(\Delta F + f_m) \quad (4)$$

(i.e. the "Carson's rule bandwidth"), where ΔF is the multi-channel peak deviation.

To restrict the intermodulation noise due to bandwidth limiting ("truncation noise") to a tolerable level, it is necessary to define a suitable relationship between ΔF and F_{ch} . A formula in common usage for frequency-division multiplex basebands is as follows:

$$\Delta F = F_{ch} \times g \times L \quad (5)$$

where,

- ΔF : peak deviation in Hz
- g : "peak-to-r.m.s." factor as a numerical ratio. Thus, for a peak-to-r.m.s. value of :
 13 dB, $g = 10^{13/20} = 4.47$;
 10 dB, $g = 10^{10/20} = 3.16$.

$$L = \left. \begin{aligned} &10^{\frac{-15 + 10 \log n}{20}} \text{ for } n \geq 240 \text{ channels} \\ &10^{\frac{-1 + 4 \log n}{20}} \text{ for } n < 240 \text{ channels.} \end{aligned} \right\} \quad (6)$$

Earlier system designs utilized a peak-to-r.m.s. factor of 13 dB but later systems have used 10 dB with satisfactory results. In general, it can be expected that for carrier capacities below about 120 channels the 13 dB figure is more appropriate, while for those of higher capacity 10 dB is preferred.

Frequency modulation systems have a characteristic threshold of operation and originally an operating margin (m) of 6 dB above threshold in the satellite to Earth link was assumed. It is assumed that for conventional demodulators FM threshold occurs at a carrier-to-noise ratio of 10 dB. The threshold corresponding to the radio frequency bandwidth B_{RF} can be extended by such techniques as frequency feedback or phase-locked demodulators so that threshold occurs about 4 dB lower than in conventional demodulators.

The use of threshold extension demodulators in frequency modulation systems does not modify the basic relationship between signal-to-noise (S/N) and carrier-to-noise (C/N); it merely permits the use of lower C/N ratios than would otherwise be possible.

Fig. 8 shows the relationship between S/N and C/N in an FM system. Above the breakpoint S/N is directly proportional to C/N . Three different criteria for different time percentages have to be satisfied. These three are shown as horizontal lines. The problem in designing an FM system is how to choose C/N properly during clear weather so as to have S/N above the three different lines for given percentages of time according to Recommendation 353-3.

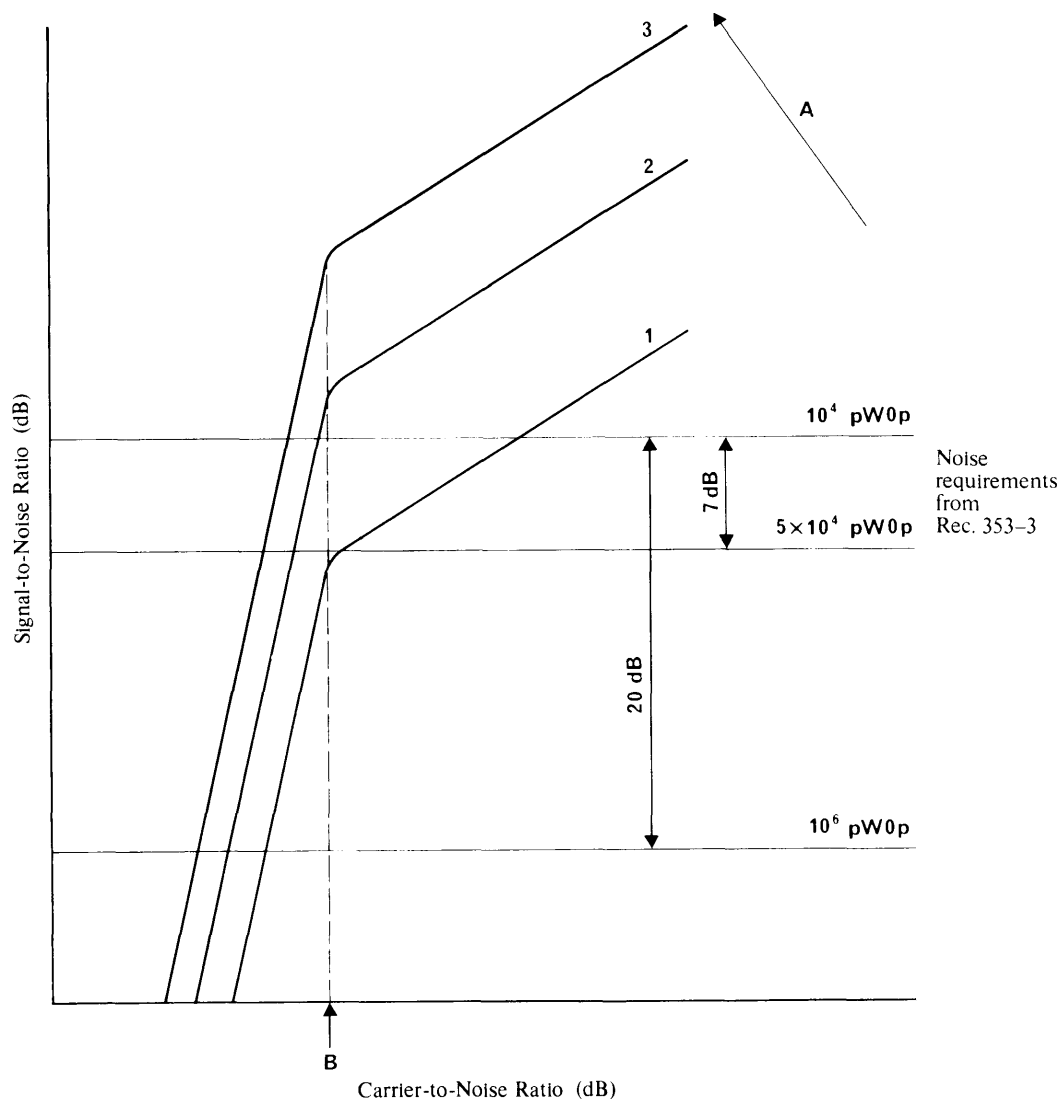


FIGURE 8 — *Signal-to-Noise Ratio, vs. Carrier-to-Noise Ratio in FM Systems*

Curves A: Increasing deviation (i.e. bandwidth)
B: Breaking point

At frequencies where the fading of the satellite signal is negligible, this is a straightforward process. In this case C/N remains constant and a deviation can easily be chosen so that S/N is above the line corresponding to 10 000 pW0p. The curves in Fig. 8 then represent three possible cases:

- Curve 1: Band limited system
- Curve 2: Power and band limited system
- Curve 3: Power limited system

When the system is operating at frequencies where fading is significant (e.g. 11/14 GHz) the power/bandwidth optimization becomes more complicated. An iterative procedure with varying deviation will then have to be employed. A bandwidth is chosen corresponding to a certain deviation. S/N is computed for different time percentages and checked against the different criteria. Depending on whether all S/N are above the respective criteria or whether any one is below, the deviation is then reduced or increased. A boundary condition is that the maximum allowable bandwidth must not be exceeded.

Of great interest in bandwidth limited systems is the minimum amount of "guard band" required between carriers in a transponder. Present systems are designed to keep the "Carson's rule bandwidth" of each carrier to the middle 90% of the allotted bandwidth unit and to provide a band limiting filter at each transmit earth station, thus holding the adjacent carrier interference to tolerable limits. The filter, however, may cause impulse noise on the carrier passing through it due to its truncating effect. Therefore the carrier bandwidth and carrier separation should be based on careful trade-off studies between noise due to adjacent carrier interference including impulse noise and that caused by the bandpass filters. The use of threshold extension demodulators at the receive earth station has also been found to be superior to available conventional demodulators for reducing the adjacent carrier interference.

5.2 4-Phase PSK

In this Section PCM telephony only will be considered. Recommendation 522 specifies the performance criteria for such circuits. As with analogue circuits there are three different criteria corresponding to different percentages of time. The following theoretical ratios (energy per bit/noise spectral density) are required to obtain the respective bit error rates:

$$10^{-3} : E_b/N_0 = 6.7 \text{ dB},$$

$$10^{-4} : E_b/N_0 = 8.4 \text{ dB},$$

$$10^{-6} : E_b/N_0 = 10.4 \text{ dB},$$

where,

E_b is the energy per information bit,

N_0 is the noise power per Hz.

In computing the necessary C/T , margins have to be added to the theoretical values to account for degradations other than thermal noise. As long as these other degradations are small compared with the thermal noise they can often be regarded as having Gaussian distributions, and be added to the thermal noise on a power basis. However, the additional degradations will often not be small, in which case a combination of analysis, computer simulations and measurements will be necessary [Lundquist *et al.*, 1974; Lundquist, 1974; Muratani *et al.*, 1972; CCIR, 1974-78].

In deriving the required C/T , for a particular bit error rate the following effects causing signal impairments will have to be considered:

- filter distortions,
- non-linear power amplifiers in the satellite and the transmitting earth station,
- adjacent channel interference (ACI),
- co-channel interference (CCI),
- foreign system interference,
- multipath transmission within the satellite,
- power amplifier back-off due to modulation,
- post power amplifier filter losses.

Note that E_b/N_0 , as described here, is referred to the input of the receiver filter. E_b is thus the energy per bit of the modulated carrier. If an unmodulated carrier is used in measuring E_b then a suitable margin has to be added to take into account losses in the filters and the TWT's output back-off due to modulation. Some authors prefer to include these losses and define E_b as the saturated power amplifier output with an unmodulated carrier.

The minimization of the total degradation is a very complicated procedure involving compromise between many different parameters and is subject to many boundary conditions such as available bandwidth, available power, etc.

For a typical system operating at 60 Mbit/s, using channel spacing of 40 MHz, as well as using cross polarization in the satellite, the necessary margin over theoretical is about 4 dB [CCIR, 1974-78]. The optimum operating point of the satellite power amplifier for this system is at saturation.

A TDMA system will be operating in burst mode. Carrier and bit synchronization will then have to be performed at the beginning of each burst. If the transmission system is well optimized, the design of the synchronization circuit mainly influences the transient behaviour of the system, and items such as filters and TWT's can be designed based on continuous transmission performances [Lundquist *et al.*, 1974; CCIR, 1974-78].

5.3 Multi-carrier intermodulation

Intermodulation in multi-carrier satellite systems is one of the most severe degradations in terms of power loss. In general, a substantial back-off is necessary to reduce the level of intermodulation distortion. It is sometimes possible to reduce intermodulation degradation by clever frequency assignments so that offensive intermodulation products fall away from the information bearing carriers [Babcock, 1953]. However, the optimum utilization of both power and bandwidth by necessity means a relatively dense packing of carriers in the allocated band and consequently clever frequency arrangements are seldom possible.

The optimization of the power utilization or maximization of satellite capacity means maximizing the carrier to total noise power ratio for each carrier. (For the moment it is assumed that all carriers are equal.) Since intermodulation depends greatly on how closely the amplifier is working to its saturated output power, intermodulation can be reduced by backing off the power amplifier. This however, reduces the available output power, and for a given multicarrier configuration a point is reached beyond which the reduction in intermodulation power is not sufficient to justify the loss in output power.

The point of optimum back-off depends strongly on the number of carriers and will vary from system to system. It is also a function of the specific characteristic of the power amplifier. In any practical system, the optimization procedure is therefore rather complicated and it is difficult to give anything but general guidelines on how to proceed. A great deal of effort has gone into theoretical and computer analysis as well as laboratory experiments.

Fig. 9 has been derived from [Berretta and Gough, 1976]. It shows an example of intermodulation noise in a case of equal carriers, equally spaced in a repeater using a typical TWT amplifier. From this example one sees that intermodulation noise is very high unless the TWT is operated well below saturation. (Note that Fig. 9 cannot be used directly in optimizing a system, since the information about output power, as a function of input power, is missing [Berretta and Gough, 1976]).

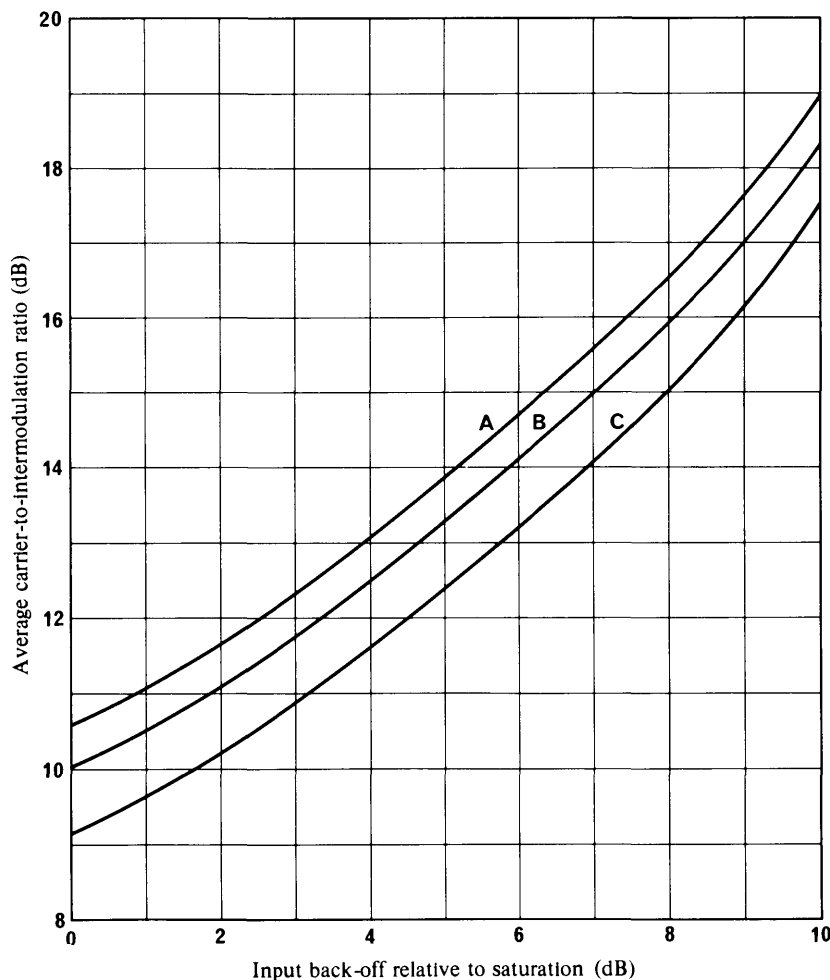


FIGURE 9 — Intermodulation in a typical TWT

Curves A: 6 carriers
 B: 12 carriers
 C: 500 carriers

A further complication is introduced by considering a case where carriers have unequal amplitudes and carry different signals using different modulations. Propagation may also have different influences depending on the location of different earth stations.

The effect of the intermodulation products falling into a particular transmission channel will depend on the type of modulation used and the relative level of the product. Different ways to decrease the level of intermodulation are being investigated. One method is the use of pre-distortion devices to linearize the overall amplifier characteristic [Bremenson *et al.*, 1974]. The result of one such system tested showed an improvement in respect of output back-off of about 3 dB, or a minimum of about 6 dB on the intermodulation level. Details of these results are given in Annex II.

In SCPC systems using voice activation the effect of intermodulation is reduced. This is because the carriers are activated at random and, therefore, the instantaneous distribution of intermodulation products is also random. This results in an intermodulation reduction of about 3 dB [McClure, 1970].

In a satellite system taking full advantage of extra margins available by using voice activation, it will be difficult to introduce circuits with high activity such as data circuits.

In analysing a PSK system the effect of intermodulation depends very much on its statistical distribution. The effect of a peak-limited intermodulation product is similar to that of interchannel interference and some of the results of Report 388-3 are applicable. Note, however, that there may be statistical correlation between the intermodulation product and the wanted carrier, because part of the intermodulation product emanates from the wanted carrier.

In conclusion it is thought that the complete analysis of intermodulation effects for a specific system will require the use of sophisticated theoretical and computer analysis, taking into account all the various considerations discussed here.

6. Typical system comparisons

Figs. 10 to 12 give capacities for typical examples showing the relation between the number of channels and the sum of the satellite e.i.r.p. (in dBW) and the earth station figure of merit G/T in dB (T expressed in K).

In the derivation of these curves the following assumptions are made:

FDM-FM-FDMA

- noise allocation is as follows:
 - 1000 pW0p interference from terrestrial systems,
 - 1000 pW0p group delay and intermodulation noise arising in the earth station,
 - 3000 pW0p thermal noise in the up-link and intermodulation noise arising in the common repeater,
 - 5000 pW0p thermal noise in the down-link;
- multi-carrier output back-off is 3 dB,
- peak-to-r.m.s. ratio is 10 dB,
- guard bands required are 25% of the occupied bandwidth, hence the usable bandwidth per carrier based on 40 MHz satellite repeater bandwidth, B_{RF0} is:

$$B_{RF0} = 32/N \quad \text{MHz, where } N \text{ is the number of carriers.}$$

For comparison two examples with PSK modulation are considered:

PCM-PSK-FDMA

- operating bit error rate is 1×10^{-6} ,
- assumed margin above theoretical E_b/N_0 is 6 dB,
- number of carriers is 10,
- the assumptions concerning multi-carrier back-off and guard bands are the same as those above.

PCM-PSK-TDMA

- there are up to 10 earth stations accessing a 40 MHz repeater in the satellite. This assignment requires a minimum of 10 time-slots per frame;
- each earth station can transmit up to 600 one-way telephone channels. It does so in an assigned time-slot of variable duration where the duration is determined by the number of telephone channels being transmitted;
- the time-frame is limited to 125 μ s (the sampling period);
- 100 ns guard time is required between time-slots;
- 800 ns is allowed for carrier and time-slot synchronization, preamble and system co-ordination.

In the PSK examples considered here it is assumed that the system is only subjected to thermal noise. An extra margin is used in the signal-to-noise ratio to take into account other effects.

The numbers of phase positions considered in the examples are 2, 4, 8 and 16 (see Report 793). For PCM-PSK it is assumed that the radio-frequency bandwidth required for transmission (B_{RF}) is 1.2 times the symbol rate. For a given carrier-to-noise ratio, the space-station transmitter power required is proportional to the radio-frequency bandwidth and, therefore, to the number of channels, n .

With PCM-PSK by synchronous detection, it is the post-detection baseband signal-to-noise ratio which determines the noise power in a speech channel. Analysis shows that, irrespective of the number of channels, a bit error probability of 10^{-4} corresponds to a noise power of approximately 50 000 pW0p in a telephone channel. This statement holds with negligible error both for TDM-PCM and FDM-PCM.

One advantage of the PCM encoded systems used with PSK modulation is that they lend themselves to the use of DSI (see § 2.2). This means approximately a doubling of the capacity. This is illustrated in Fig. 10. The steps in the PSK curves in Figs. 10 and 12 are a consequence of the limiting of the satellite bandwidth to 40 MHz.

The capacity of an FDMA system can be increased by using APM on one or two carriers. For a 14-carrier system increases of up to 100% have been reported.

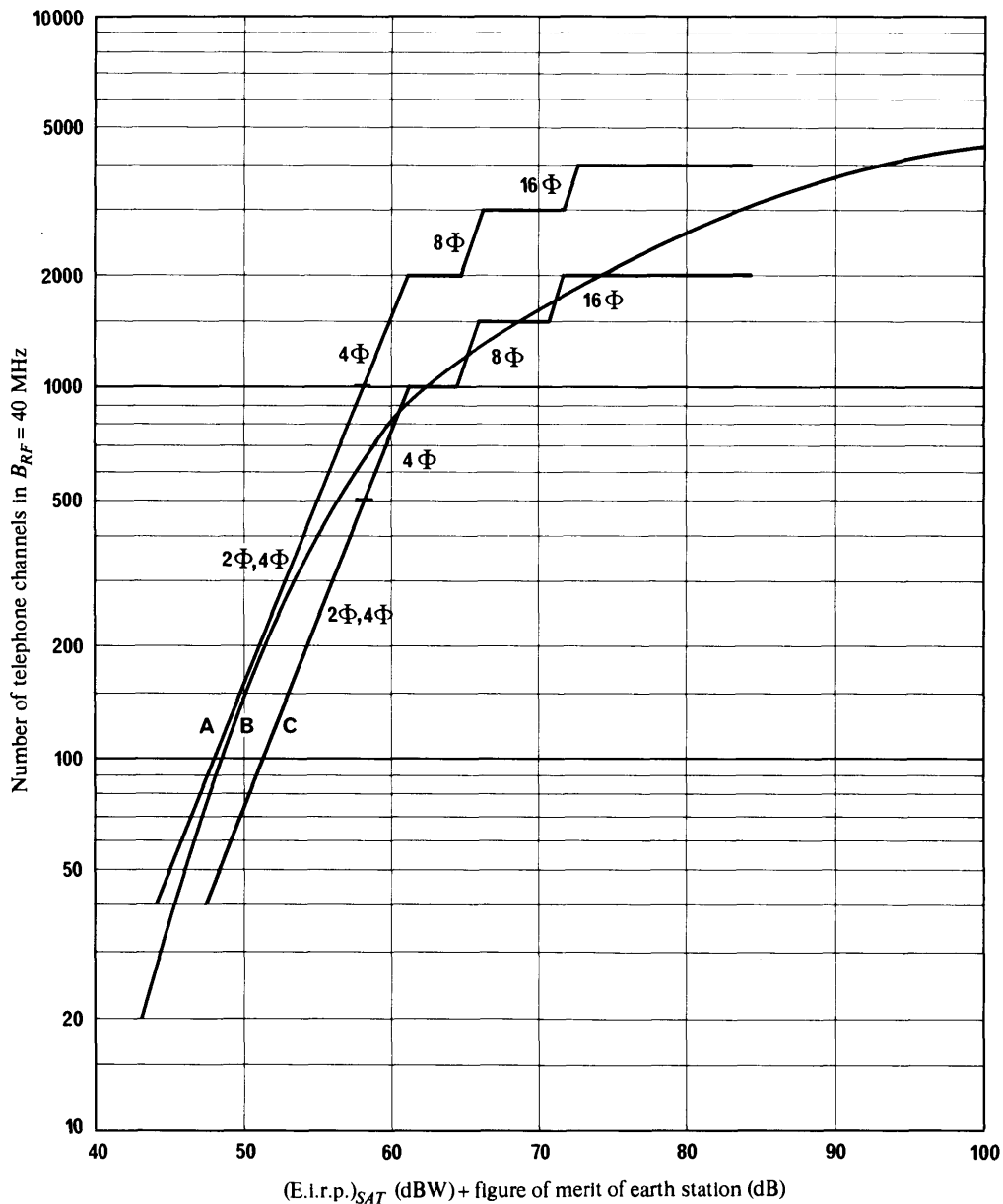
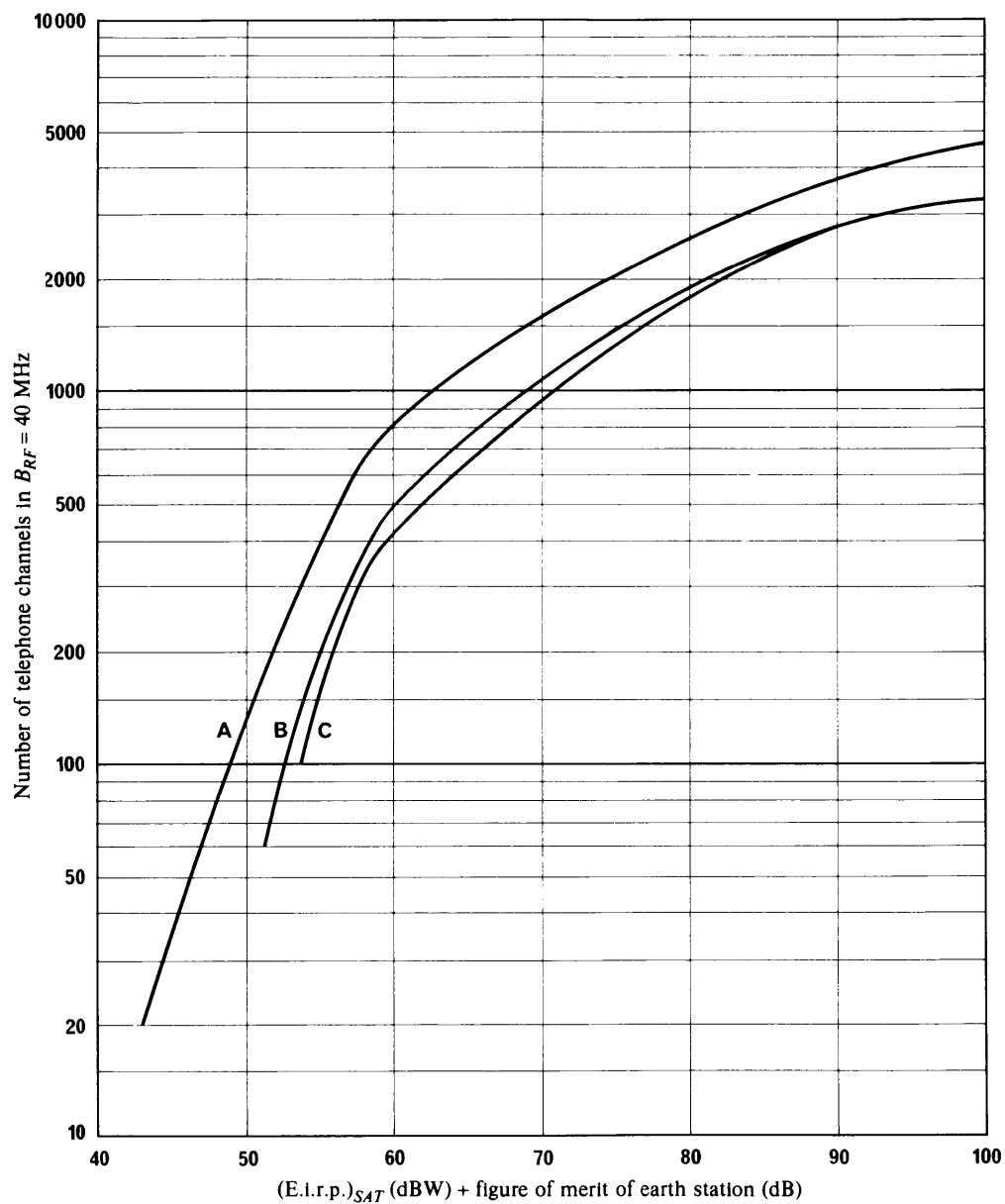


FIGURE 10 — *Single access*

Curves A: TDM-PCM-DSI-CPSK
 B: FDM-FM
 C: TDM-PCM-CPSK

FIGURE 11 — *FDMA capacity*

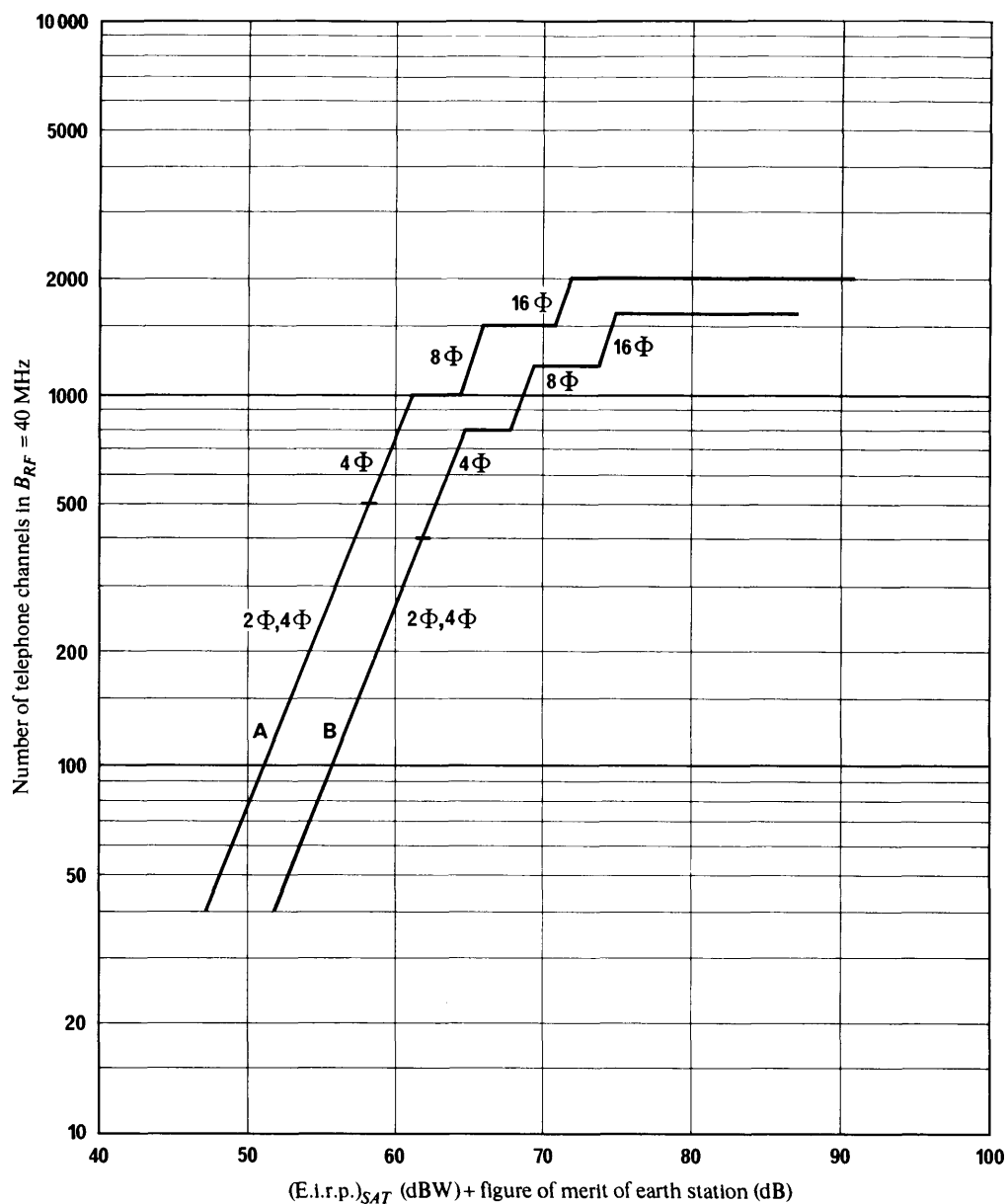


FIGURE 12 — Multiple access, examples

Curves A: TDM-PCM-CPSK-TDMA
Curves B: TDM-PCM-CPSK-FDMA

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ANNEX I

DIGITAL SPEECH INTERPOLATION TECHNIQUES

1. System function and transmission modes

The basic functions necessary for the operation of a digital speech interpolation (DSI) system can be grouped under two broad categories corresponding to the two practical systems so far developed.

In the first system, specified by INTELSAT, at the transmission side the activity of each input trunk is detected periodically and only the active input trunks are connected to the available transmission channels. At the reception side, the received signals from the transmission channels are connected to the proper output trunks according to the received DSI assignment message which provides information on the status of the connections performed at the transmitting side.

In the second kind of DSI system called SPEC (Speech Predictive Encoding Communication system), the speech is detected at the transmitting terminal, and the speech sample is transmitted only when the difference in level between the actual sample and the preceding one exceeds a given amplitude. The transmitted sample is stored in a memory at the receiving terminal. Depending on the information contained in the assignment signalling message, this stored sample is used for the reconstruction of the succeeding untransmitted samples [Sciulli and Campanella, 1973].

There are two ways of incorporating a digital speech interpolation (DSI) facility into a digital system:

- the DSI technique is applied individually to each bundle of circuits all having the same destination. This mode is referred to as “point-to-point” DSI.
- the DSI technique is applied globally to several bundles of circuits having different destinations. This mode is referred as “multi-destination” DSI.

2. DSI gain and speech quality

In the DSI system, the theoretical capacity gain has its limit set by the inverse of the mean activity factor of the input trunks. DSI, however, may introduce some degradation of the voice signal of the systematic or sporadic type.

The system degradations are due to the voice detection process and to the internal signalling message and can be reduced or even partially eliminated by employing suitable hardware solutions [Poretti *et al.*, 1972; Quaglione *et al.*, 1972].

The sporadic degradations are due to the statistical behaviour of traffic which causes system overload to occur when the number of active input trunks is higher than the number of available transmission channels. The degradations introduced in this case are directly related to the DSI gain and therefore to the system capacity.

When the system goes into overload, clipping is introduced whose average value is referred to as freeze-out (Φ). Practical tests on users' reactions to the presence of speech degradation introduced by DSI show that the speech degradation is unnoticeable by an average listener as long as the freeze-out fraction is less than 0.5%. Theoretically the DSI gain G and the freeze-out fraction Φ are related to the mean voice activity A , the number of input trunks N_i and the number of transmission channels N_c [Guinand and Penicaud, 1973].

Fig. 13 shows G as a function of N_c , when $A = 35\%$ and $\Phi \leq 0.5\%$ and $\leq 1.0\%$. From this curve it appears that the DSI advantage increases as the number of transmission channels increases.

A bit reduction strategy can be employed to reduce the freeze-out fraction further. With this strategy the eighth bit of the various normal channels is used to yield additional transmission channels when all of the normal channels of 8 bits are overloaded.

In this case the degradation introduced consists of a decrease of the S/N ratio of the channels involved, which is limited to the overload time, and a possible residual freeze-out, which is qualitatively similar to that which occurs without the bit reduction strategy.

Subjective tests performed in Italy on equipment with and without the bit reduction strategy under the same operational conditions, i.e. with “ N_i ”, “ A ” and “ G ”, revealed that the voice quality obtained by means of the bit reduction strategy is better than that achieved without the bit reduction strategy [Poretti *et al.*, 1972]. For example, for the system with bit reduction, a freeze-out fraction of less than 0.05% can be expected, compared with 0.5% for the system without bit reduction but of the same DSI gain. Moreover, a higher DSI gain and therefore a greater total system capacity is achieved through the bit reduction strategy as compared with the normal DSI for the same voice quality, other conditions being equal [Poretti *et al.*, 1974]. Fig. 14 compares, as an example, the channel capacities using TDMA multiframe and DSI, for the two strategies, assuming equivalent subjective quality of service.

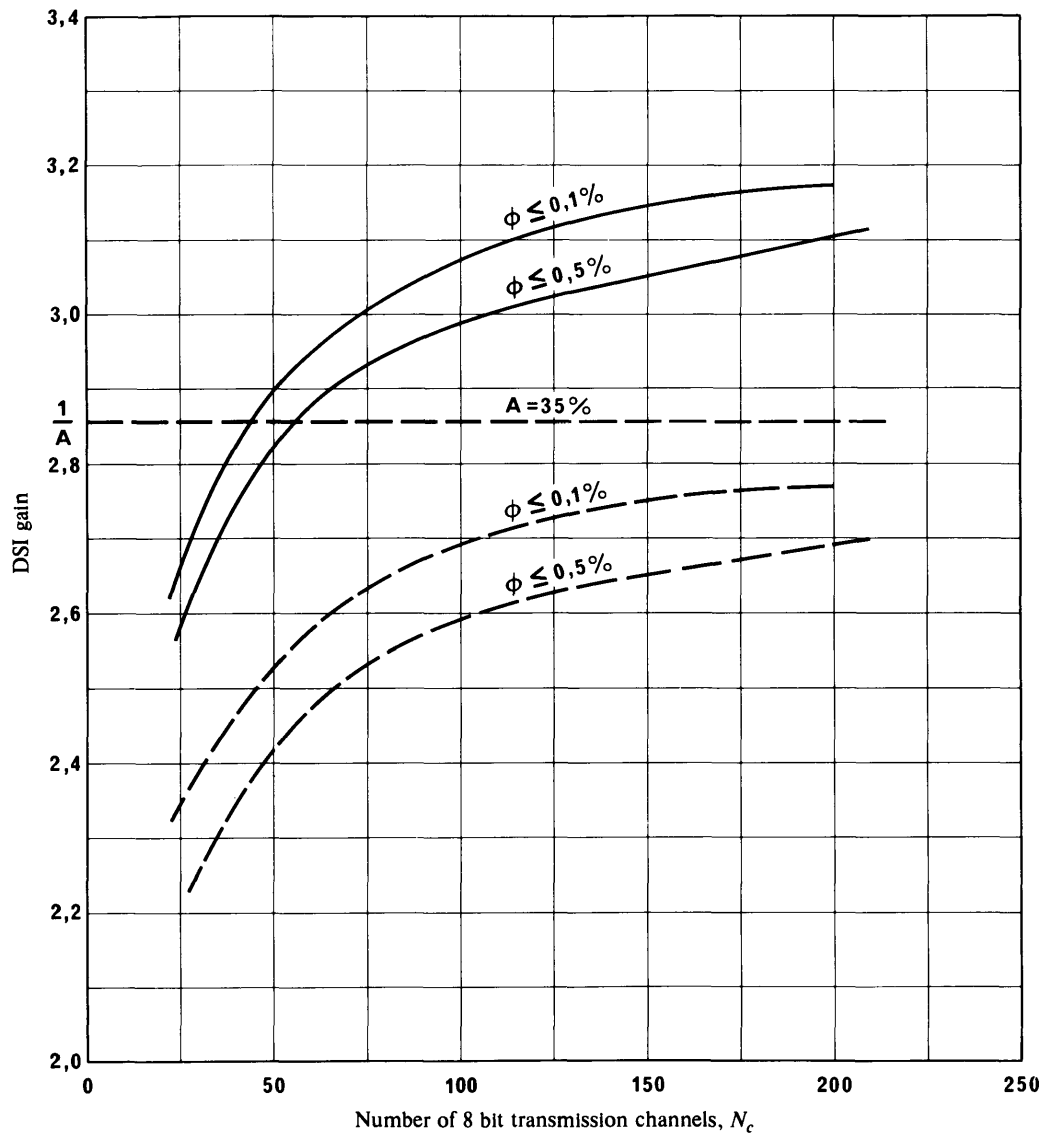


FIGURE 13 — DSI gain for different numbers of transmission channels (N_c)

— bit reduction strategy
- - - normal DSI

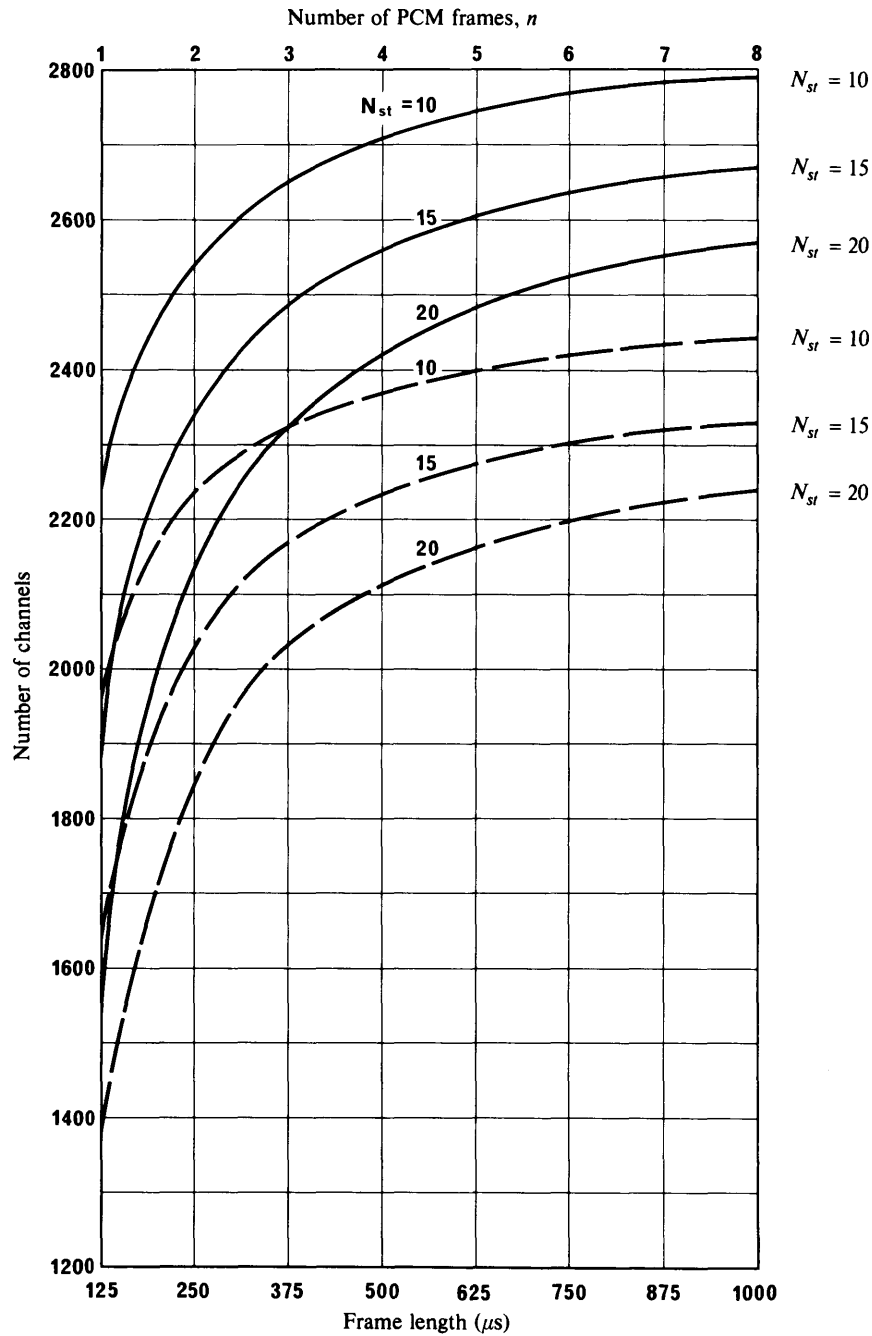


FIGURE 14 — Net channel capacity of a 36 MHz satellite transponder for a TDMA system equipped with a DSI device when adopting different DSI strategies, assuming $A = 35\%$

- concentrated freeze-out strategy: $\Phi \leq 1\%$
 — bit reduction strategy: $\Phi \leq 1\%$
 N_{st} : Number of stations in the system

3. Data transmission via DSI

The effects of DSI on data signals in overload conditions depend on the SI philosophy adopted. If a bit reduction philosophy is adopted the data signals are always transmitted even if over a lower resolution channel. Tests carried out on a 1200 bit/s voice-band data signal have ascertained that the increase in quantizing noise due to bit reduction limited to the overload condition periods, does not impair the transmission of data signals, in practice, even in the extreme overload condition. When the bit reduction strategy is not employed, as in systems like the SPEC, the data signals are noticeably degraded during the overload intervals. Laboratory tests [Poretti, *et al.*, 1972] provided evidence on the different behaviour of the two systems with respect to data transmission and on the different performances achieved. High speed data up to 64 kbit/s is exclusively used on dedicated channels. Therefore, they will not undergo the interpolation process and will use 8 bit time slots, assigned on a permanent basis.

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ANNEX II

TRAVELLING WAVE TUBE LINEARIZATION

In order to improve the performance and capacity of both frequency division multiple access (FDMA) and time division multiple access (TDMA) communications-satellite systems, a number of methods of improving the TWT linearization have been investigated. Fig. 15 shows the levels of improvement obtained for third and fifth order intermodulation products with one method using pre-distortion. In FDMA the use of the linearizer results in an average improvement of 3 dB in output back-off or, depending on the carrier configuration and for a given output power, an improvement of about 10 dB in the intermodulation levels [Bremenson and Jaubert, 1974].

In FDMA network this improvement will allow operation of earth station and satellite TWT's closer to saturation and will substantially improve overall system capacity.

In the case of TDMA, TWT linearization may, in certain systems, be used to improve transmission performance. With only one carrier accessing the satellite repeater at a time, the TWT can be operated near saturation, thus avoiding the FDMA power loss. However, this advantage is partially offset by the fact the quadri-phase shift keyed (QPSK) wave used in TDMA undergoes distortion in the non-linear TWT of the satellite; this gives a degraded reception error rate at a given bit energy, to spectral noise density ratio (E_b/N_0).

Furthermore, in systems operating at frequencies above 10 GHz and in view of the power of the available emitting tubes and the parameters envisaged for these systems, the earth station TWT is likely to operate at a low back-off and sometimes even at saturation power (when precipitation occurs on the earth-to-satellite path). In this latter case, the impairment introduced by the satellite repeater and earth station TWTs will be cumulative and the use of linearizers may prove useful [Denance, 1972].

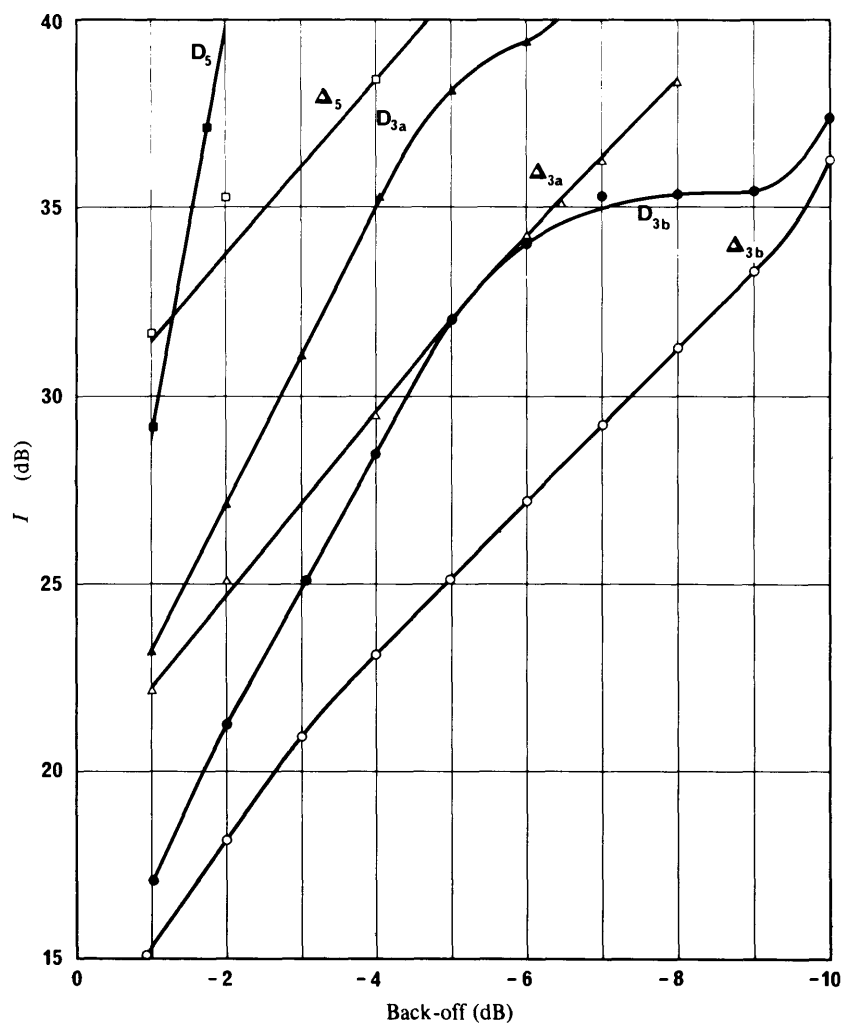


FIGURE 15 — Four-carrier intermodulation at 6000 MHz (total frequency difference 10 MHz) with a 250 W TWT:

D: with compensation; Δ: without compensation

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SECTION 4E: CHARACTERISTICS AND MAINTENANCE OF EARTH STATIONS

Recommendations and Reports

RECOMMENDATION 465-1

**REFERENCE EARTH STATION RADIATION PATTERN
FOR USE IN COORDINATION AND INTERFERENCE ASSESSMENT
IN THE FREQUENCY RANGE
FROM 2 TO ABOUT 10 GHz**

(Study Programme 1A-1/4)

(1970 - 1974)

The CCIR,

CONSIDERING

- (a) that, for coordination studies and for the assessment of mutual interference between radiocommunication-satellite systems and between earth frequency band, it may be necessary to use a single radiation pattern for the earth station antenna;
- (b) that, for the determination of coordination distance and for the assessment of interference between earth and terrestrial stations, a radiation pattern based on the level exceeded by a small percentage of the side-lobe peaks may be appropriate;
- (c) that, for coordination studies and for the assessment of interference between earth stations and space stations, a radiation pattern for the region near the main beam based on the envelope of the peak power of the side lobes in this region may be appropriate;
- (d) that, at angles relative to the axis of the main beam where effects peculiar to the particular feed system used do not contribute appreciably to the power in the side lobes, the radiation patterns for numerous existing earth station antennae show only moderate scatter about a simple generalized radiation pattern, at least within the frequency range 2-10 GHz;
- (e) that, for systems of the Cassegrain type over the range of angles relative to the axis of the main beam where contributions to the side-lobe power occur primarily as a result of spill-over, the patterns of a number of existing antennae also show reasonable agreement;
- (f) that, at large angles, the likelihood of local ground reflections must be considered;
- (g) that the use of antennae with the best achievable radiation patterns will lead to the most efficient use of the radio-frequency spectrum and the geostationary satellite orbit,

UNANIMOUSLY RECOMMENDS

1. that, in the absence of particular information concerning the radiation pattern of the antenna for the earth station involved, a single reference radiation pattern should be used for:
 - 1.1 coordination studies and interference assessment between earth stations in the fixed satellite service and stations of other services sharing the same frequency band;
 - 1.2 coordination studies and interference assessment between systems in the fixed satellite service;
2. that the reference radiation pattern as shown in Fig. 1 (taken from Report 391-3) should be provisionally adopted for angles between the direction considered and the axis of the main beam where those angles are greater than 1° , at least for frequencies in the range of 2 to 10 GHz, when the antenna diameter/wavelength ratio D/λ exceeds 100.

Note 1. — The reference radiation pattern should be assumed to be rationally symmetrical.

Note 2. — The reference radiation pattern should be used with caution over the range of angles for which the particular feed system may give rise to relatively high levels of spill-over.

Note 3. — Limited data suggests that the reference radiation pattern as shown in Fig. 1 could provisionally be used also for frequencies in the range 10 to 30 GHz.

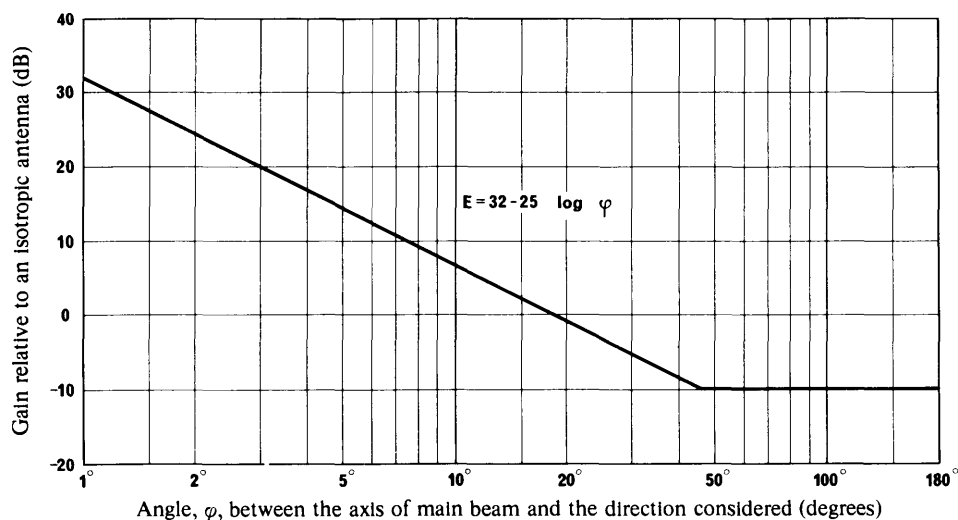


FIGURE 1 — Provisional reference radiation diagram

$$E = 32 - 25 \log \phi$$

REPORT 391-3

**RADIATION DIAGRAMS OF ANTENNAE FOR EARTH STATIONS IN THE
FIXED SATELLITE SERVICE FOR USE IN INTERFERENCE STUDIES
AND FOR THE DETERMINATION OF A DESIGN OBJECTIVE**

(Question 1-2/4 and Study Programme 1A-1/4)

(1966 - 1970 - 1974 - 1978)

1. Introduction

In the determination of co-ordination distance or for the assessment of interference between earth stations and radio-relay stations, and for co-ordination studies between earth stations and space stations of different satellite systems sharing the same frequency bands; it is required that the gain of the earth station antenna be known in the relevant direction. It is also desirable that radiation characteristics in planes other than the principal planes be known, particularly in the case of interference calculations between satellite systems.

In addition, as discussed in Report 390-3, it is necessary to assemble data on the side-lobe performance of new antennae in order to establish an appropriate design objective for sidelobe levels.

2. Characteristic radiation patterns of antennae

For co-ordination distance calculations and assessment of mutual interference between earth stations and terrestrial radio-relay stations, data on the earth-station antenna radiation diagram are required. Preferably data from the actual radiation diagram should be used.

In cases where data from the actual radiation diagram are not available a reference radiation diagram can be used. The reference radiation diagram representing a level exceeded only by a small percentage of the side-lobe peaks seems suitable. If such a reference radiation diagram is used for co-ordination distance and interference calculations there is a sufficiently small risk that the actual antenna will give interference levels exceeding the calculated values.

2.1 Representation of measured data on antenna of large diameter to wavelength ratio ($D/\lambda > 100$) by a reference radiation diagram

Data were obtained in 1976 for 18 large earth stations with the ATS-6 satellite at 6.4 GHz for antennae of 26 to 32 metres in diameter ($D/\lambda = 550$ to 670). The level exceeded by 10% of the peaks for each antenna at each frequency has been plotted in Fig. 1. Also presented in the figure is the reference radiation diagram:

$$G = 32 - 25 \log \varphi \quad \text{dB} \quad (1)$$

where G is the gain relative to isotropic antenna and φ is the angle (in degrees) between the axis of the main beam and the direction in question. It should be noted that this formula should be assumed to apply only to the region beyond the first side-lobe peak, that is, at and beyond φ (degrees) $\approx 100\lambda/D$. In addition it should never be assumed that the reference antenna gain falls below -10 dB relative to isotropic. The range of φ is considered to the point where the gain is -10 dB, this limit being chosen to take account of ground reflections.

In cases where D/λ is not given, it may be determined from the expression $20 \log (D/\lambda) \approx G_0 - 8$, where G_0 is the main lobe antenna gain in dB.

This reference radiation diagram can be expected to represent the level exceeded by 10% of the side-lobe peaks of the actual radiation diagrams of large earth station antennae.

In the region closest to the main beam ($0.2 < \varphi < 1.0$ degrees), the 10% value is essentially equivalent to the absolute peak value due to the small number of peaks in this region. The median value, i.e. the value exceeded by 50% of the peaks, lies approximately 5 dB below the reference radiation diagram over the angular region where φ is greater than 1° and less than 10° . Within this angular region, some of the largest peaks may exceed the reference diagram by 10 dB.

Moreover, some data on antenna radiation patterns in the frequency band above 10 GHz with D/λ greater than 100 are also available, and they are all in good agreement with $32 - 25 \log \varphi$ as shown in Fig. 2.

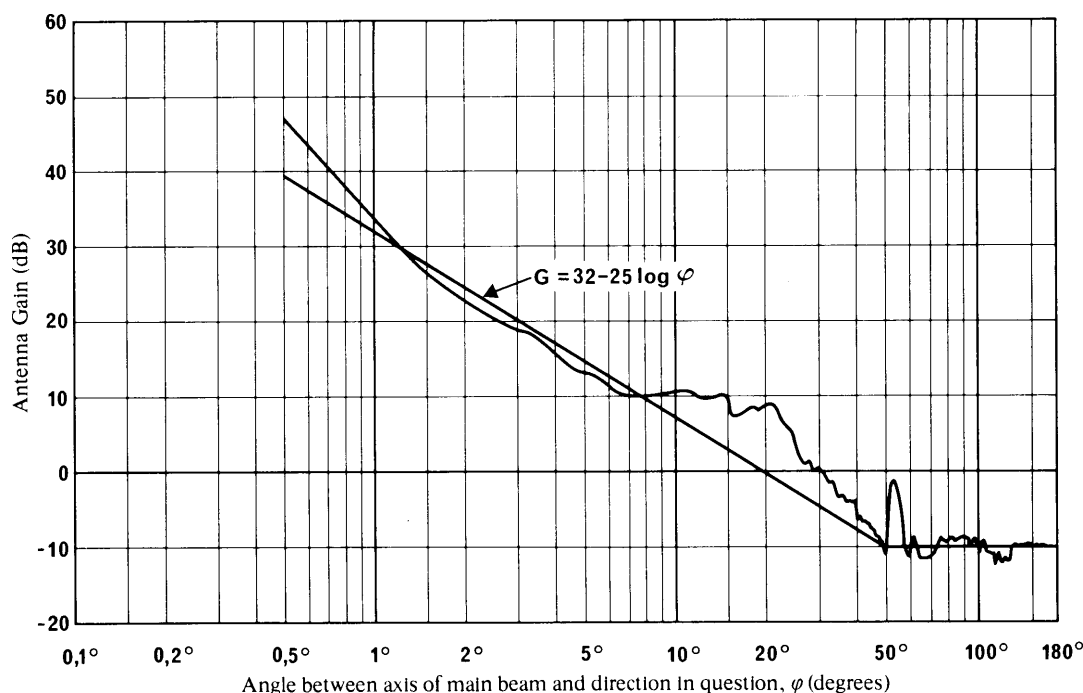


FIGURE 1 — Statistical data for Cassegrain antennae of 18 large earth terminals at 6.4 GHz ($D/\lambda = 550$ to 670). Levels exceeded by 10% of the side-lobe peaks are averaged over one degree intervals

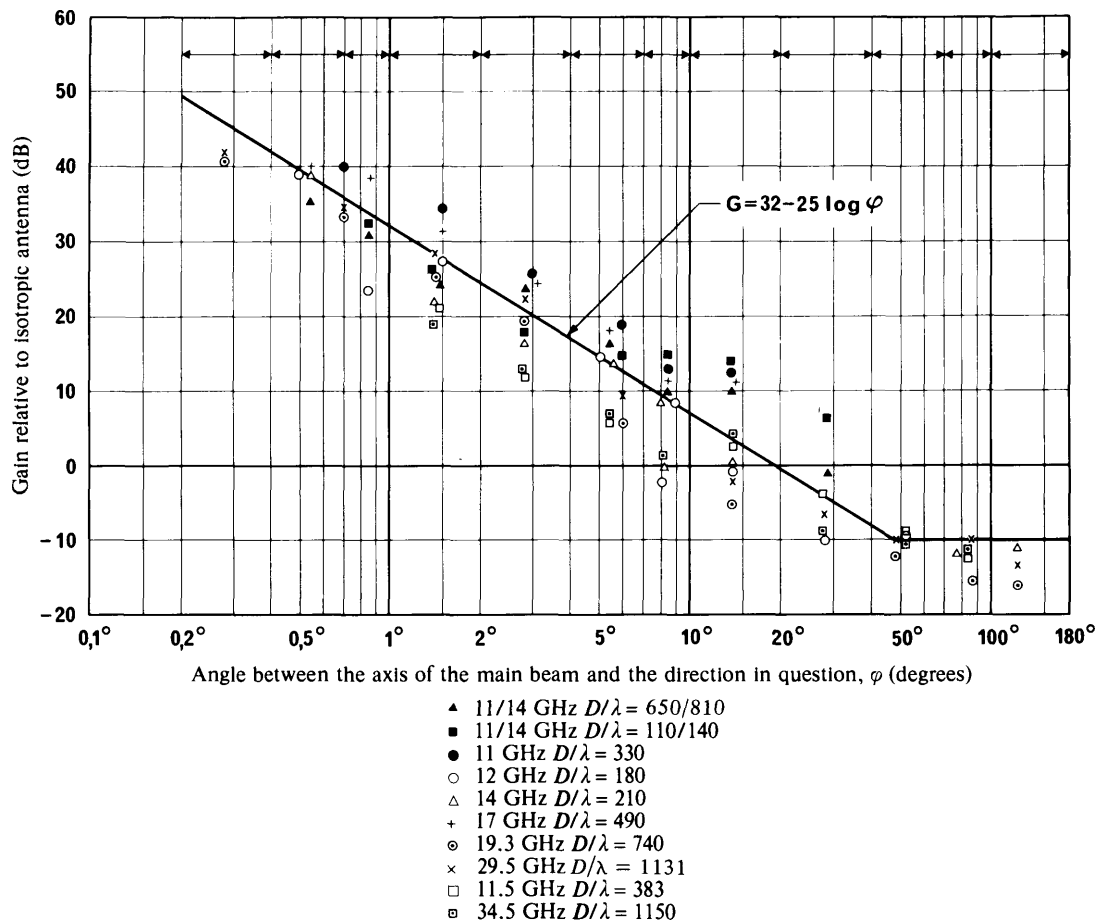


FIGURE 2 — Statistical data from earth-station Cassegrain antenna diagrams above 10 GHz

Levels exceeded by 10% of the side-lobe peaks

Note. — It should be noted that the various points in the figure may represent different angular sample widths and number of peaks.

2.2 Reference radiation pattern for $D/\lambda < 100$

Theoretical considerations and the available data concerning radio-relay antennae (Report 614-1) suggested that the reference diagram given by the formula in § 2.1 above may lead to error if attempts are made to apply it to antennae with $D/\lambda < 100$, and a new formula for the reference radiation diagram has been suggested. This is given by:

$$G = 52 - 10 \log (D/\lambda) - 25 \log \varphi \quad \text{dB} \quad (2)$$

As an example, results of measurements of the statistical distribution of the side-lobe peaks for a small antenna with a conventional front-fed parabolic reflector of 2.44 m diameter ($D/\lambda = 65$) is given in Fig. 3.

Further details about the theoretical background for such a formula can be found in the Annex to Report 614-1. This formula should not be used for $D/\lambda > 100$.

It should be noted that this formula should be assumed to apply only to the region beyond the first side-lobe peak, that is, at and beyond φ (degrees) $\approx 100\lambda/D$. In addition, it should never be assumed that the reference antenna gain falls below -10 dB relative to isotropic.

In cases where D/λ is not given, it may be determined from the expression $20 \log (D/\lambda) \approx G_0 - 8$, where G_0 is the main lobe antenna gain in dB.

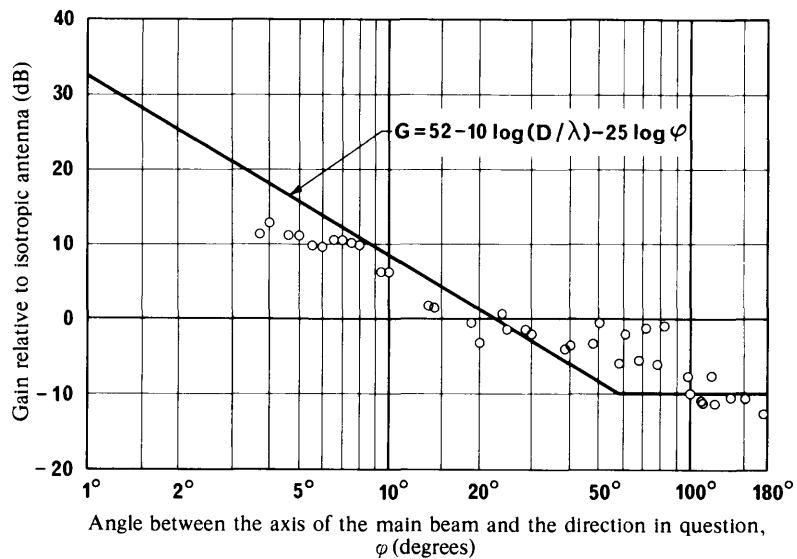


FIGURE 3 — Statistical data from a small earth-station Cassegrain antenna diagram ($D/\lambda = 65$). Frequency: 7.5 GHz

Levels exceeded by 10% of the side-lobe peaks

2.3 General statistical properties of antenna side-lobes

In calculating mutual interferences between radio-relay systems and satellite communication systems, it is preferable that the statistical properties of antenna side-lobe levels, as well as those of side-lobe peaks, are known. This is particularly true when there is more than one interfering source. Measurements made on a number of existing antennae, also theoretical studies, have shown that the statistical distribution of the antenna side-lobe amplitudes are approximately expressed by the Rayleigh distribution function. The median (50%) value of the side-lobe peaks is about 2.0 dB higher than that of the side-lobe level distribution.

Using the above information, reference curves for earth station antenna side-lobe characteristics have been computed and are shown in Fig. 4 [Shinji, *et al*, 1976].

A similar relation is expected to be found for smaller antennae of $D/\lambda < 100$.

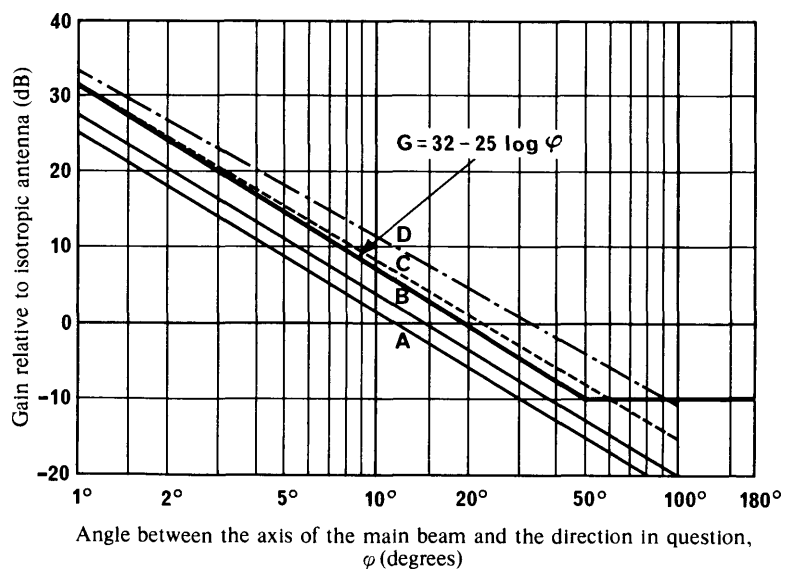


FIGURE 4 — Statistical side-lobe relationships for typical earth station antennae

- A = Median (50%) of side-lobe level distribution
- B = Median (50%) of side-lobe peak distribution
- C = Worst 10% of side-lobe peak distribution
- D = Worst side-lobe peak distribution value

2.4 Antennae with improved side-lobe characteristics

For some future applications small earth station antennae with improved side-lobe characteristics may be necessary. As an example, the statistical distribution of side-lobe peaks measured on a specially designed antenna with an off-set feed is presented in Fig. 5. Further details about this type of antennae can be found in Annex I of Report 390-3.

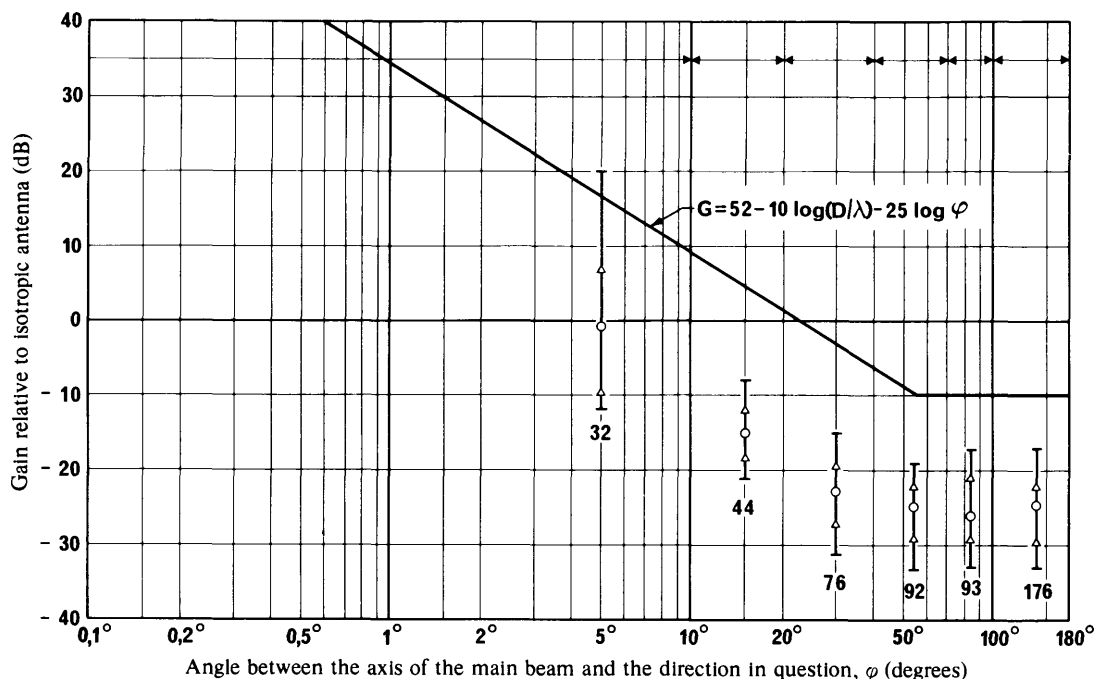
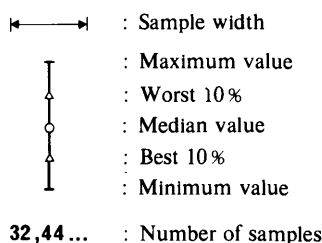


FIGURE 5 — Statistical distribution of side-lobe peaks for a specially designed antenna with $D/\lambda = 66$



2.5 Polarization considerations

The reference radiation diagram is that which is obtained in the principal plane of the antenna with a co-polarized test antenna. Mutual interference between stations, particularly earth stations and space stations in different systems, is directly dependent upon the discrimination obtained through the side lobes of the respective antenna system. For the co-polarized case (i.e., matched polarization) the reference radiation diagram given in the formula in § 2.1 is appropriately used. When systems operate in orthogonal polarizations, this discrimination is expected to be enhanced. Few data are available at the present time and it is not possible to develop a similar reference diagram. The question of polarization is discussed in detail in Report 555-1.

3. Conclusions

The reference radiation diagram given by the formula in § 2.1 is representative of typical earth station antennae of $D/\lambda > 100$ and of current design. It can, therefore, be used for co-ordination and mutual interference studies between earth stations and either terrestrial stations or space stations.

Because of the wide variety of applications when sharing of frequency bands is involved, studies are needed, especially for antennae with $D/\lambda < 100$, so that the most useful and practical reference radiation diagram is available. Annex I to Report 390-3 gives a useful discussion of the characteristics in the side-lobe regions.

To ensure that the information contained in this Report (as well as in the resulting Recommendations) be representative of current practice, Administrations are requested to submit measured antenna pattern data, particularly in regard to peak side-lobe characteristics and polarization pattern characteristics. The side-lobe pattern gains should be given relative to isotropic gain referred to the feed horn flange. Administrations are also requested to provide brief technical descriptions of the antennae with particulars of the steps taken to ensure a low side lobe performance.

Preferably the peak side-lobe data should be given as the statistical distribution of the peaks within suitable sample widths of the angle relative to the main beam axis (see Fig. 6). The information should be suitably annotated with relevant data such as antenna diameter, frequency of operation, type of antenna, polarization, and if possible, including some indication of site effects.

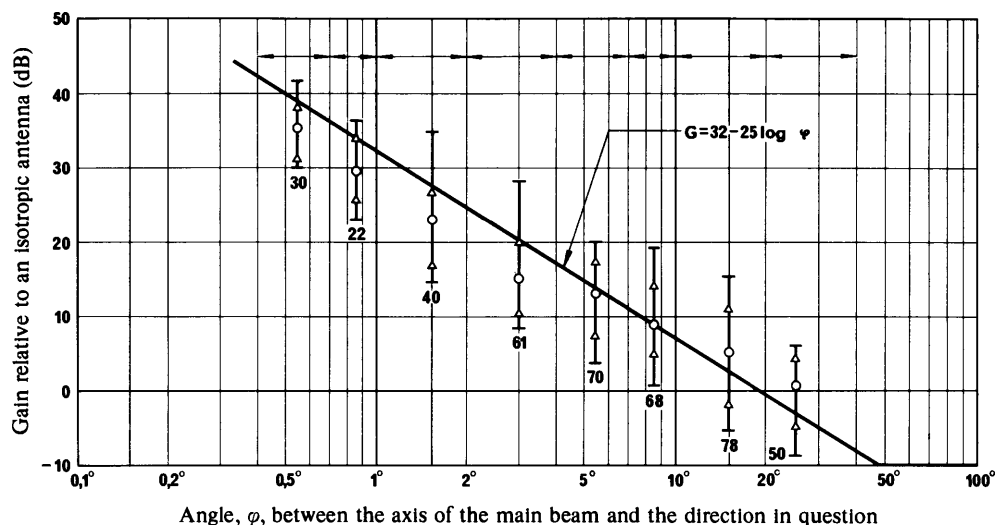
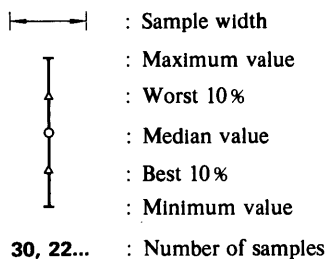


FIGURE 6 — Example of distribution of side-lobe peaks



REFERENCE

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REPORT 390-3

EARTH-STATION ANTENNAE FOR FIXED SATELLITE SERVICE

(Question 1-2/4)

(1966 - 1970 - 1974 - 1978)

1. Introduction

The desired characteristics for most earth-station antennae are:

- high gain in the direction of wanted signals;
- low gain in the direction of unwanted signals;
- high efficiency;
- low effective noise temperature for the entire receiving system;

- steerability over the expected range of satellite positions;
- continuous pointing towards the satellite with the required accuracy;
- minimum variation in performance due to local conditions of wind and weather;
- minimum variation in illumination of the satellite by the earth station;
- high discrimination between orthogonally polarized signals.

For some applications, multi-beam and/or multi-band antennae will be advantageous.

2. Mechanical and structural aspects

2.1 Construction of reflectors and associated support structures

The design of support structures must ensure that the shape, relative position and relative attitude of the various reflecting surfaces is very accurately maintained in spite of changes in elevation angle, wind velocity, ambient temperature, ice load and solar heating.

2.2 Surface accuracy of reflectors

The shape of reflecting surfaces must be accurately set and maintained under all operating conditions to avoid loss of gain and a consequent increase in side-lobe levels. This loss may be conservatively estimated from [Ruze, 1966] by:

$$\text{loss of gain} = 0.00761 e^2 f^2 \quad \text{dB} \quad (1)$$

where,

e : surface r.m.s. error, in mm;

f : frequency in GHz.

For example, at 11 GHz, an error of only 1 mm may reduce the gain by as much as 1 dB.

At 4/6 GHz, errors in the main reflector profile of approximately 1 mm r.m.s., correlated over distances of about 1.5 m, make a major contribution to side-lobe levels within about 2° of the axis; errors of 0.5 mm r.m.s. within individual reflector panels make a significant contribution to the side-lobe level between 2° and 10° off axis. Improvements in panel profile accuracy can therefore lead to a useful reduction in overall side-lobe level, dependent on contributions from other sources.

2.3 Antenna pointing and tracking requirements

For many systems, loss of signal due to imperfect pointing must be held to a few tenths of a dB. For a 30 metre diameter antenna operating at 4 GHz, this would dictate a pointing accuracy of about 0.01°. This can be accomplished either by automatic tracking of a beacon signal or by computer programme steering.

Automatic correction, or automatic tracking, may be carried out not only by means of satellite beacon signals but by also using wideband working signals. The pointing inaccuracy of an antenna equipped with an autotrack system should be defined not only by the angular misalignment between the equi-signal direction and the satellite direction, but also by the gain losses in the satellite direction as compared with the maximum gain.

For smaller antennae operating with geostationary satellites, manual positioning at infrequent intervals might suffice.

If the satellite position is maintained within a narrow angular range, economy may be effected by limiting the operative pointing angle of the antenna. A polar mount type antenna fed by a system of reflectors may be one of the various possibilities for such a limited steerable antenna. It should however, be realised that limited steerability may impose penalties on certain operational features of the earth station, e.g. in respect of maintenance and testing using a radio star.

2.4 Weather protection

The possibility of ice formation on antenna surfaces and the effects of frozen precipitation such as snow, sleet and freezing rain are additional factors which affect the design of antennae for operation in freezing climates. Some additional considerations in respect to these factors are:

- satisfactory operation during snow, sleet and freezing rain can be ensured by heating the reflector surfaces and critical portions of the support structure;
- the antenna should be designed to withstand extreme conditions of combined wind and ice loading.

The provision of a radome for weather protection of a steerable antenna is no longer thought necessary and has the serious disadvantage of degrading the system performance.

Rain on reflector surfaces of Cassegrain antennae causes distortion of the antenna radiation patterns. Both the main-lobe direction and the tracking beam minimum are shifted but the effect is small and can be ignored in practice. More important effects are the degradation of gain and increase of the minimum of the tracking lobe, and they can be significant at frequencies exceeding 10 GHz [Maričić and Popović, 1975].

3. Performance of earth-station antennae

3.1 Types of antennae

Several kinds of earth-station antennae are now in use: parabolic reflectors with Cassegrain, Gregorian or focal point feeds; and horn reflectors.

Parabolic reflectors with Cassegrain feeds are the most common and can be divided into several types: near field and point source feed, both designed for high efficiency. Multi-reflector feeds of the near field type are expected to come into common use.

3.2 Gain of the main lobe

The maximum gain achievable is largely a function of the uniformity of illumination of the antenna aperture and the accuracy of the reflector surface. High efficiencies may be achieved by suitably shaping the main and sub-reflectors, so that they no longer are truly paraboloidal or hyperboloidal respectively. Shaping results in an almost uniform illumination while still maintaining a plane wave front.

3.3 The level of side and back lobes

The side-lobes of earth-station antennae have a direct influence on the level of inter-network interference. This is particularly important for those antenna side-lobes that lie within a few degrees of the direction of the geostationary orbit. Every effort should therefore be made to develop earth-station antennae with the lowest practicable side-lobe envelope gains.

The side and back lobes of an antenna depend primarily on the amount of energy which spills over the edges of primary and secondary reflectors, the amount of energy obstructed by and reflected by various parts of the structure and the primary feed pattern; these factors are discussed in detail in Annex I.

In the case of a small antenna ($D/\lambda < 100$), the side-lobe level in the angular region near the principal axis is generally higher than that of a large antenna. An off-set dual reflector antenna, such as an off-set Gregorian or off-set Cassegrain antenna would however have superior side-lobe characteristics relative to the conventional symmetrical reflector systems in the angular region quoted above viz. that region which is of concern in systems using closely spaced satellites.

Existing earth-station antennae exhibit radiation patterns which generally follow the reference radiation diagram expressed by the equation:

$$G = 32 - 25 \log \phi$$

indicated in Recommendation 465-1. However, recent experimental data (Annex I and Report 391-3) suggest that earth-station antennae designed to achieve low side-lobe levels could satisfy a more stringent design objective than the one described by the present reference radiation pattern.

Further data are required to establish an appropriate design objective. Administrations are therefore encouraged to submit measured radiation patterns of earth-station antennae as requested in Report 391-3. It is particularly necessary to obtain data on antennae covering a wide range of D/λ and frequencies so that the range of application of the design objective can be established.

3.4 Noise temperature

All side and back lobes of an antenna, as well as the main beam, contribute to its noise temperature. For most purposes it is sufficient to assume that side-lobes at elevation less than -10° "see" ground at a temperature of 290 K. Between -10° and 0° the temperature may be taken to be 150 K; between 0° and 10° to be 50 K and between 10° and 90° to be 10 K. The power in the side-lobes may be expressed as a percentage of the total power and divided among these four regions.

Noise temperature contributions due to extraterrestrial sources are discussed in more detail in Annex II to this Report.

A typical breakdown of noise temperature for a large Cassegrain antenna designed for a 4 GHz, and operating at 5° angle of elevation might be:

Main beam	25 K
Near side-lobes	2 K
Sub-reflector spill-over	8 K
Main reflector spill-over	5 K
Sub-total	40 K

Typical cryogenically cooled preamplifiers have a noise temperature of about 20 K, bringing the total system noise temperature, including waveguide losses to about 70 K. If a non-cryogenically cooled (uncooled parametric) preamplifier were to be used, the system noise temperature might be of the order of 80 to 120 K.

3.5 *Figure of merit of the system*

A very useful indication of the performance of an earth station is the figure of merit defined as:

$$G/T = 10 \log \left[\frac{\text{antenna power gain}}{\text{system noise temperature (K)}} \right] \quad (2)$$

Antenna power gain and system noise temperature are conveniently referred to the input of the low-noise receiver, noting that the noise contributions of the receiver stages following the reference point are included. Thus, in the case of an antenna of 58.8 dB gain and a system temperature of 65 K, the value of G/T would be 40.7 dBK.

The G/T of an antenna may be measured directly by the use of a radio star as a reference source. This procedure is outlined in Annex III.

Alternatively, the G/T of an earth station may be determined by separate measurement of system noise temperature and of antenna gain, where the antenna gain is measured by conventional techniques.

3.6 *Multi-band antennae*

Additional factors must be taken into account if the antenna is to be usable over a wide range of frequencies without appreciable degradation of its characteristics. Paraboloidal antennae with focal point feeds are not suitable for multi-band operation. Horn reflectors are suitable for multi-band use, but they present difficult construction and structural problems.

Cassegrain antennae can be used for multi-band operation by optimizing the design of the primary feed horn and the sub-reflector system. Such an antenna has been designed and built for operation at 4, 6, 20 and 30 GHz [Mori, 1973]. This 12.8 m diameter antenna has a focussed beam feed, with the band separation equipment located in the fixed antenna pedestal. Aperture efficiencies, excluding band separation system losses are between 50 and 62%. Median values of side-lobe peaks are almost always below the value $32 - 25 \log \phi$ (dB) where ϕ is the angle between the axis of the main beam and the direction in question; noise temperatures are 48 K and 68 K at 4 and 18 GHz respectively, at an angle of elevation of 5° .

3.7 *Polarization discrimination*

In many situations earth-station antennae may be required to provide a high degree of discrimination between orthogonally polarized signals, of the order of 30 to 35 dB; this is discussed further in Report 555-1.

4. *Radiation hazards associated with earth-station antenna systems*

The transmitter powers required at earth stations may be of the order that will produce high power flux-densities in specific areas in the near and far field of the antenna system, which may be a hazard to humans. A method of predicting the power flux-densities for a 30 m antenna system is described in Annex IV, which will be of assistance in determining whether or not a safe radiation level will be exceeded.

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ANNEX I

RADIATION CHARACTERISTICS OF ANTENNAE OF EARTH STATIONS OUTSIDE THE MAIN BEAM

In the planning and construction of earth-station antennae, with respect to the most effective use of the geostationary orbit, it is necessary to have an understanding of the factors contributing to the generation of side-lobes and methods of reducing these side-lobes by special techniques or the use of different types of antennae.

1. *Factors which influence side-lobe levels*

1.1 *Influence of aperture illumination*

Various techniques, such as tapered illumination, can be used to obtain low side-lobe levels.

In the choice of illumination functions, a compromise has to be made between side-lobe suppression and aperture efficiency. If it is, for instance, desired to minimize side-lobes near the main lobe, an illumination function has to be chosen which leaves the edges of the feed and the reflectors practically free of current, resulting

in lower aperture efficiency. The design objective is an illumination which is as symmetrical with respect to rotation as possible, so that the illumination of the H-plane of the aperture is equal to that of the E-plane; this symmetrical illumination can be achieved by dual mode excitation and/or hybrid mode excitation of the feed system.

1.2 *Influence of spillover*

To illuminate the sub-reflector of a symmetrical Cassegrain antenna, a feed radiating in the direction of the main beam of the antenna is required. Hence, there are interfering radiation contributions in the forward direction due to spillover of the feed main lobe past the sub-reflector and to side-lobes of the feed itself.

In large antennae the influence of spillover is considerably lower than that of other phenomena for angular directions within about 5° of the main beam (see Fig. 1), but becomes increasingly significant beyond this angular direction. One approach to reducing this effect is by ensuring that the sub-reflector extends to at least the -20 dB point of the feed radiation pattern.

For some large antennae, side-lobes of the feed dominate the antenna side-lobe pattern at angles between 20 and 80 degrees from the main lobe. This contribution to the antenna side-lobe pattern can only be avoided by the use of feeds with inherently low side-lobes.

It is possible to direct spillover radiation away from the main beam by employing an offset type antenna. Offset feeding also allows the use of a larger sub-reflector, which will intercept a very high proportion of the feed main lobe radiation, without incurring the penalty of high aperture blockage.

1.3 *Influence of blockage and diffraction*

The feed or sub-reflector placed in the aperture of a reflector antenna, together with its supports, have a serious effect on the antenna side-lobe pattern because, by blocking the antenna aperture, they alter the aperture illumination pattern and therefore the radiation pattern [Bothias and Béhé, 1971; Kreutel, 1976]. The effects of this blockage can be reduced by decreasing the blocked area of the aperture, or by using antenna types which do not have significant physical blockage, such as horns or offset-fed reflectors [Mizugutch *et al.*, 1976].

Microwave energy can be diffracted over wide angles by the edges of the sub-reflector and main reflector, the magnitude of this effect depending on the edge illumination level of these reflectors. This effect may be reduced by a attaching microwave absorber around the edges of the sub-reflector and main reflector with only a small effect on the antenna noise temperature.

1.4 *Influence of scatter*

A plane wave originated by the main reflector of a symmetrical antenna excites the feed or sub-reflector and its supports so that they radiate. If the supports are attached within the main reflector, a spherical wave originating at the focus of the main reflector is scattered additionally at the supports. These scattered radiations can contribute to the side-lobe pattern at large angles from the main beam. This scatter can be reduced by attaching a microwave absorber to the supports, but this will also increase the antenna noise temperature.

The problem of scatter may be substantially reduced by adopting an offset type of antenna. In this case also, it may be desirable to attach a microwave absorber to parts of the antenna structure which may receive microwave energy, with a small increase in antenna noise temperature.

1.5 *Influence of phase distortion on the feed pattern*

Phase distortion in the aperture illumination of a parabolic reflector results in an expansion of the main lobe and an increase of the side-lobe levels. This phase distortion may arise if the feed system has no point shaped phase centre and thus no spherical phase front.

In Cassegrain antennae, phase distortion arising in the feed horn can be equalized by changing the shape of the main reflector. It should be noted that such phase distortion can result in beam deflection in systems with multiple reflector feed systems.

1.6 *Influence of surface tolerances of the main reflector*

Surface errors due to manufacturing tolerances, wind, temperature differences and gravity, result in an increase in the side-lobe levels.

Deformation due to the weight of the upper and lower halves of the main reflector causes a cubical phase error across the aperture. This phase error produces side-lobe asymmetry in the elevation plane.

1.7 *Polarization*

Some of the above-named contributors to the antennae side-lobes in the principal plane of polarization can also give rise to side-lobe levels in other polarization planes. Further information on polarization in the side lobes is given in Report 555-1.

2. *Quantitative contributions of major contributors*

The side-lobe levels at a given angle for a large Cassegrain type antenna are a summation of the field components radiated from different parts of the antenna system simultaneously. Examples of the relative contributions of these parts are given in Fig. 1.

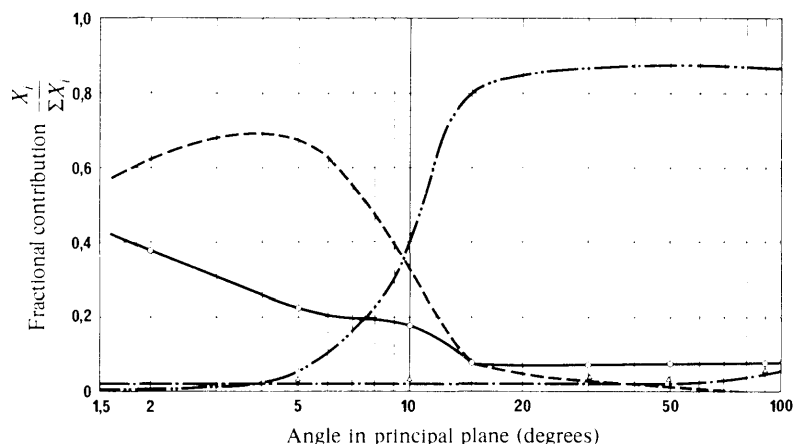
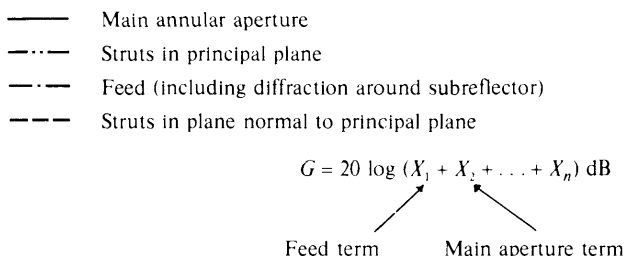


FIGURE 1 — *Relative contribution of various parts of 600 λ Cassegrain antenna to wide angle gain envelope*



3. Comparison of earth station antennae types

3.1 Comparison of types of antennae

In order to compare relative side-lobe characteristics, radiation patterns of practical antennae were measured in the United States of America according to type, as follows:

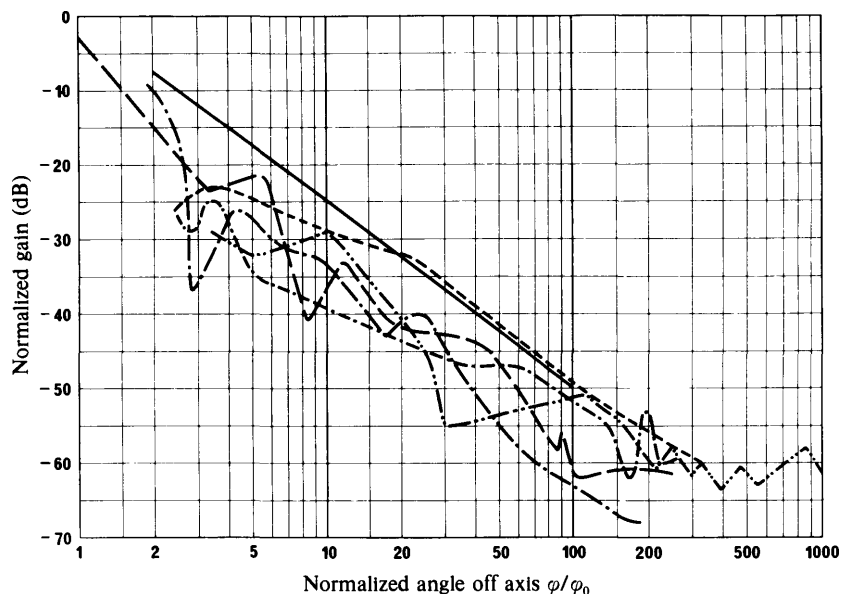
- Cassegrain antennae,
- prime focus fed antennae,
- off-set reflector antennae,
- horn reflector with conical horn feed, or
- Cassegrain feed (Casshorns).

For comparison purposes, Fig. 2 shows measured patterns of the different antennae listed above. The envelope of these patterns could be described by a general expression of the form:

$$\frac{G(\varphi)}{G} = \frac{1}{1 + \left(\frac{\varphi}{\varphi_0}\right)^n} \quad \text{for } 2 < \frac{\varphi}{\varphi_0} < 100 \quad (3)$$

with G representing the main beam gain of the antenna. (For $n = 2.5$, this formula shows the same rate of decrease in side-lobe level as a function of φ , the angle of the main beam axis, as does the formula of the reference radiation diagram, $G(\varphi) = 32 - 25 \log \varphi$.) The patterns are normalized in terms of half beamwidths, i.e., φ/φ_0 , where φ is the off-axis angle and $2\varphi_0$ is the half-power beamwidth.

The improvement of the off-set fed reflector and horn reflectors is basically due to the fact that aperture blockage is practically non-existent in these antennae, and direct radiation from the feed is reduced in the forward sector relative to Cassegrain antennae.

FIGURE 2 — *Measured patterns of various types of antennae*

- $G(\varphi) = \left[1 + \left(\frac{\varphi}{\varphi_0} \right)^{2.5} \right]^{-1}$
 - - - - - Cassegrain antenna $D = 600 \lambda$
 - · - · - Prime focus fed antenna $D = 600 \lambda$
 - · - · - Off-set reflector antenna $D = 100 \lambda$
 - · - - - Horn reflector with conical feed $D = 250 \lambda$
 - - - - - Horn reflector with Cassegrain feed $D = 128 \lambda$ (Casshorn)

3.2 Side-lobe characteristics of offset antennae

If the reduction of side-lobe levels in the near and far angle regions is required, it is preferable to employ an offset type of antenna using a dielectric-loaded horn or a corrugated horn as the primary radiator. There is no aperture blockage in these antennae as is stated in § 1.3. The use of a low side-lobe primary radiator also provides for low side-lobe levels in the near and far angular regions. The measured side-lobe envelope of an offset Gregorian antenna of $D/\lambda = 66$ is shown in Fig. 3a.

To reduce edge-diffraction and scatter, which cause some of the antenna side-lobes, a microwave absorber can be attached to the outer edges of the reflectors and to the support structure. Fig. 3b shows a comparison of the envelope patterns of an offset Gregorian antenna of $D/\lambda = 91$ with and without microwave absorber. The noise temperature increase, ΔT in the case of Fig. 3b can be estimated to be less than 4.4 K at all elevation angles. In addition, this method would not reduce the antenna gain significantly, since the microwave absorber is attached to the area where the illumination level is very low.

4. Characteristics of antenna radiation fields of special interest

4.1 Radiation fields close to earth-station antennae

There is special interest in the nature of radiation fields in the back of, and close to earth station antenna, to evaluate the possibility of re-using earth station frequencies for terrestrial systems.

Theoretical calculations of such fields have been made, and patterns have been taken to confirm them. Signal levels were measured in the rear sector of a Cassegrain antenna having a ratio of diameter to wavelength D/λ , of the order of 600. Fig. 4 shows the gain of the antenna relative to isotropic, taken on an arc some 30 m distant from the rear of the antenna. Fig. 5 shows the apparent gain measured along a straight line in the back of the antenna in the plane of the axis of the main beam. (Apparent gain is obtained from the measured field corrected for free space loss, and is given in dB above an isotropic antenna).

These measured values were of the order of those indicated by both the near-field theoretical calculations, and by the far-field radiation patterns for such antennae.

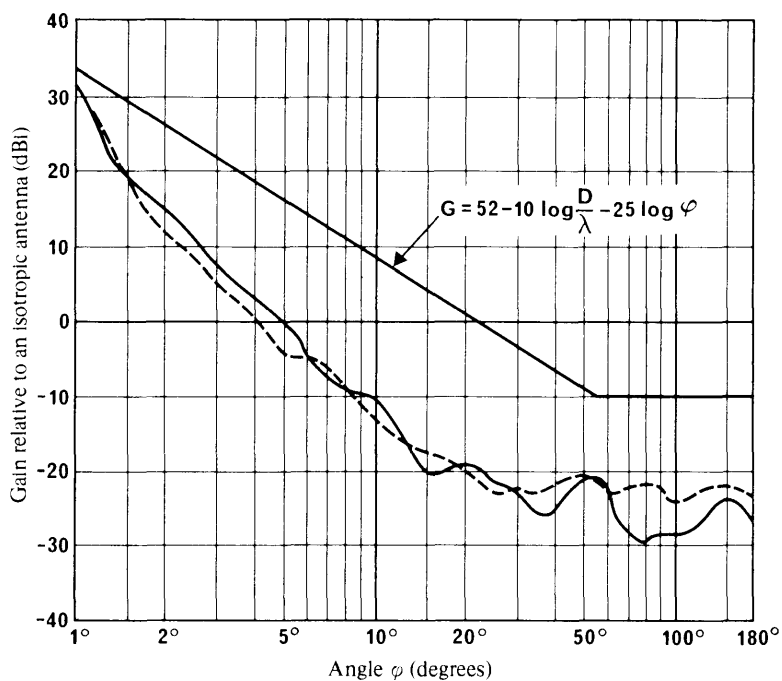


FIGURE 3(a) — Peak envelope pattern of off-set Gregorian antenna without microwave absorber ($D/\lambda = 66$, frequency = 25 GHz)

— E - plane
 --- H - plane

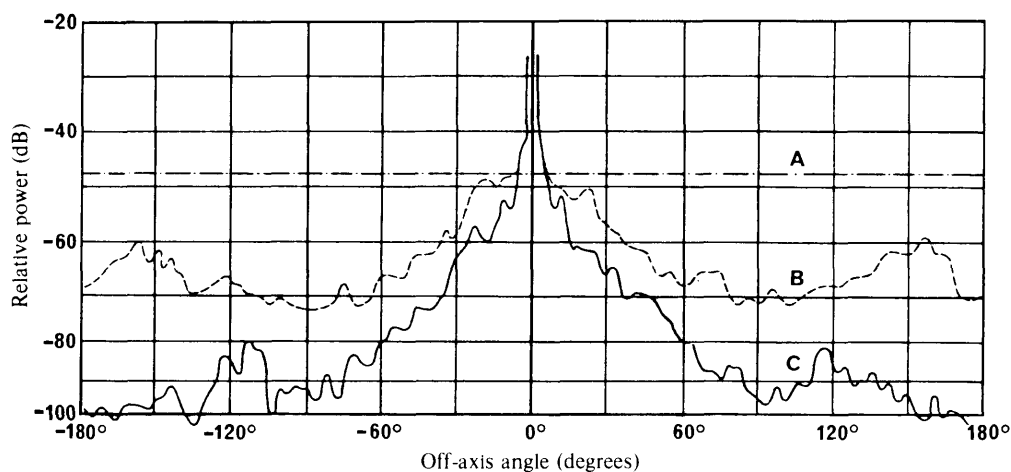


FIGURE 3(b) — Measured side-lobe patterns of the same offset Gregorian antenna as in Fig. 3(a) with and without microwave absorber ($D/\lambda = 91$, frequency = 34 GHz)

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

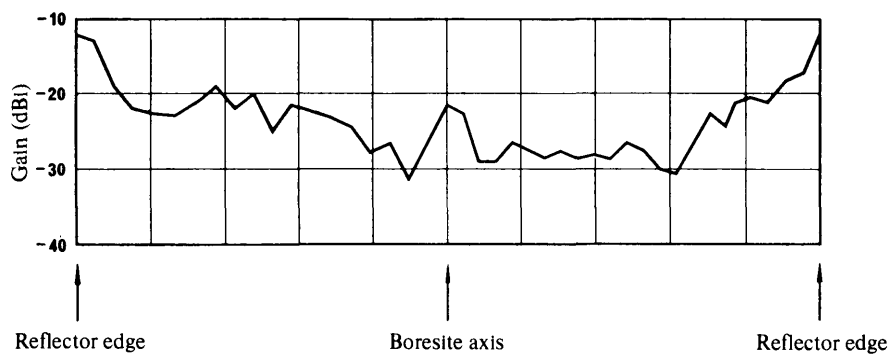


FIGURE 4 — *Ground level measurements on arc about 30 metres distant behind the antenna*

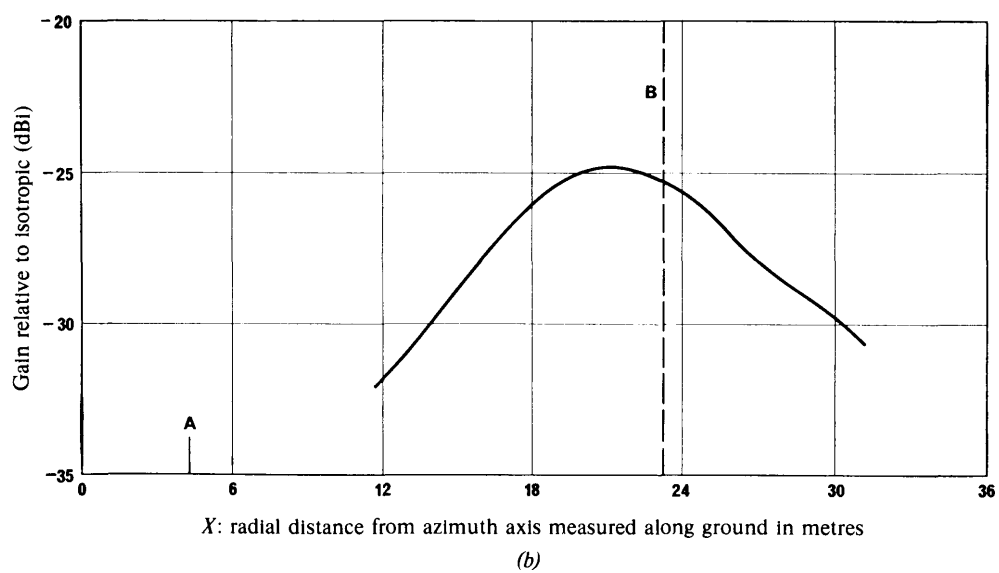
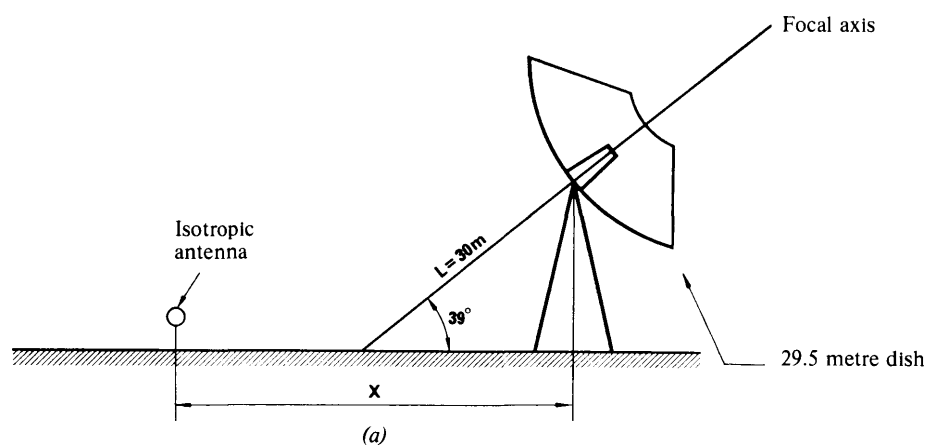


FIGURE 5 — *Apparent antenna gain behind a 29.5 metre earth station antenna*

A: Base of tower B: Approximate intersection of focal axis with ground, $L = 30$ m
 $f = 6403$ MHz

4.2 Site shielding by obstacles in the near- or far-fields

The earth station location may be selected so that it has a degree of shielding from unwanted radiations by means of obstacles in the antenna near- or far-fields. The site shielding factor may be defined as the difference between path loss over the obstacle and path loss for the same distance with no obstacle, expressed in dB.

In one example a pit was constructed to encircle a 10 metres diameter antenna which could operate with satellites in a segment of the geostationary satellite orbit. Measurements of the shielding properties of the antenna-pit combination were made in the 4 and 6 GHz fixed satellite bands. Fig. 6 shows a composite of measurements taken in the 4 and 6 GHz bands for satellites at different locations in the orbit segment. A reduction of approximately 25 dB was measured between the shielded antenna data points and the unshielded pattern.

A method of determining site shielding factor is by calculation of obstacle knife edge diffraction loss but this is inaccurate when it is applied to obstacles within the antenna near-field. A computer study based on fundamental principles has therefore been carried out [Dagleish, 1975; Streete and Shinn, 1974] on the effect of knife edge diffraction in the near-field of a large 4 GHz antenna and the results show good agreement with practical tests scaled to 9 GHz.

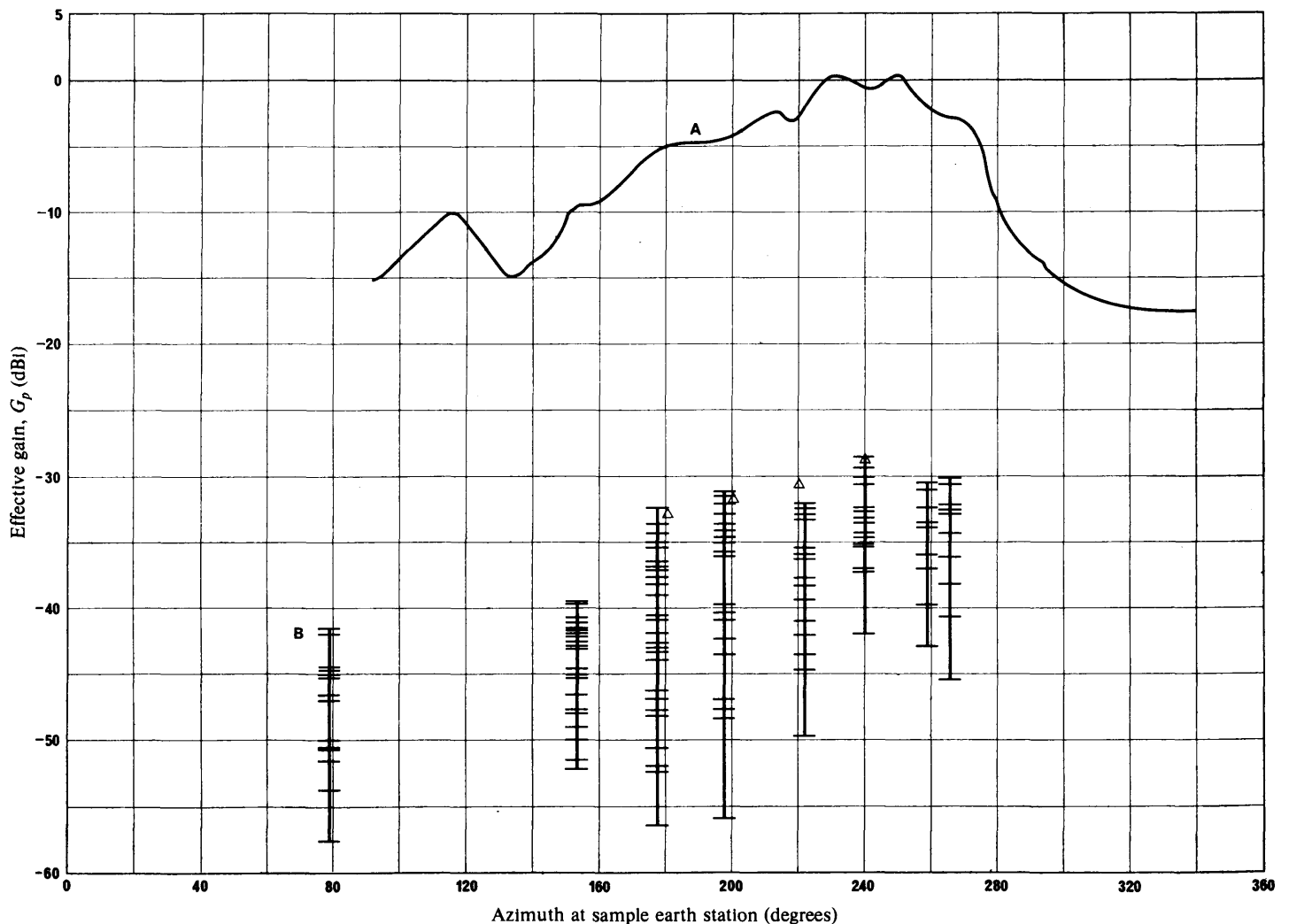


FIGURE 6 — *Effective horizontal gain pattern for different satellite positions (4 and 6 GHz)*

A: Maximum antenna gain for unshielded 10-metres antenna in the horizontal plane

B: Measured and calculated gain values of antenna pit combination (Δ calculated values)

It can further be shown that a simple modification of the basic knife edge diffraction formula may be made to take account of the expected side-lobe response of the antenna. This modification permits the calculation of site shielding factors due to nearby obstacles which, subject to certain constraints, (in particular that the obstacles are beyond the Rayleigh distance, defined as $D^2/2\lambda$, where D = antenna diameter and λ = wavelength), are within 3 dB of the computer method.

The calculated site shielding factor then becomes:

$$20 \log \left(\frac{\pi^2 \theta}{90} \sqrt{\frac{d}{\lambda}} \right) + 25 \log \left(1 - \frac{\theta}{\alpha} \right) \quad \text{dB} \quad (4)$$

where the other symbols are given the meaning shown in the legend to Fig. 7. The first part of the expression determines the basic attenuation of interference due to the knife edge ridge and the second part is the correction for the change of direction of arrival of the interference due to the obstacle.

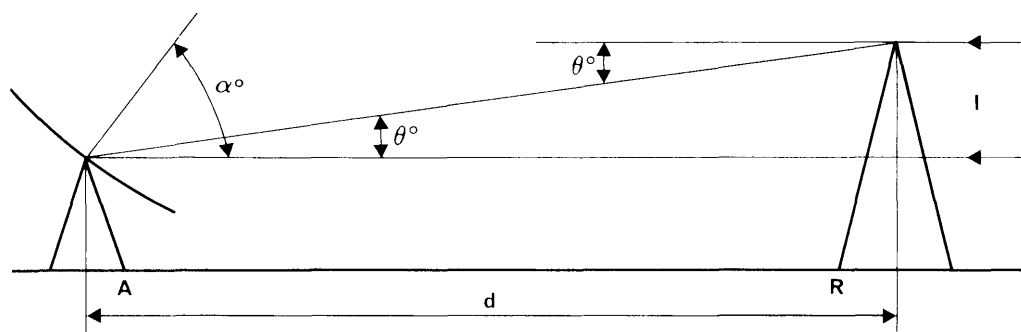


FIGURE 7 — Site shielding for earth station antennae

α : Elevation angle of antenna in degrees	A: Antenna
θ : Diffraction angle in degrees	R: Ridge
d : Distance between antenna and ridge in metres	I: Interference

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ANNEX II

NOISE TEMPERATURE CONTRIBUTIONS DUE TO EXTRATERRESTRIAL SOURCES

1. Introduction

At the frequencies of interest to the fixed satellite service, the contribution to antenna noise temperature by the background component of cosmic noise, may be neglected and only the discrete sources need be considered. These discrete sources, such as the Sun, the Moon and some of the more intense radio nebulae, such as Cassiopeia A, Taurus A, Cygnus A and Orion A, are distributed over the celestial sphere, but have small angular dimensions and are only rarely intercepted by an earth station receiving antenna.

In practice, only the Sun and the Moon will give rise to a significant contribution to the antenna noise temperature of an earth station. In the case of the Sun, its apparent temperature (the antenna temperature depends on the apparent solar temperature and the fraction of the antenna beam included) is very high, and the noise received in the side-lobes of the earth-station antenna may also be important.

The apparent noise temperature of the quiet Sun at 4 GHz varies from 23 000 K at sunspot minimum to 90 000 K at sunspot maximum. In addition, solar radio bursts may give rise to an increase in the noise temperature. These occur most frequently at sunspot maximum, when for 1% of the time the apparent noise temperature at 4 GHz will be about 50% greater than that of the quiet Sun. For smaller percentages of the time, the increase in apparent noise temperature will be considerably greater.

At maximum, noise from the Moon can increase the system noise temperature by about 250 K.

2. Occurrence of solar noise interference

A detailed study of the occurrence of solar interference in the receiving system of an earth station antenna, in the case of equatorial satellite orbits, has been carried out in the Federal Republic of Germany [CCIR, 1963-66].

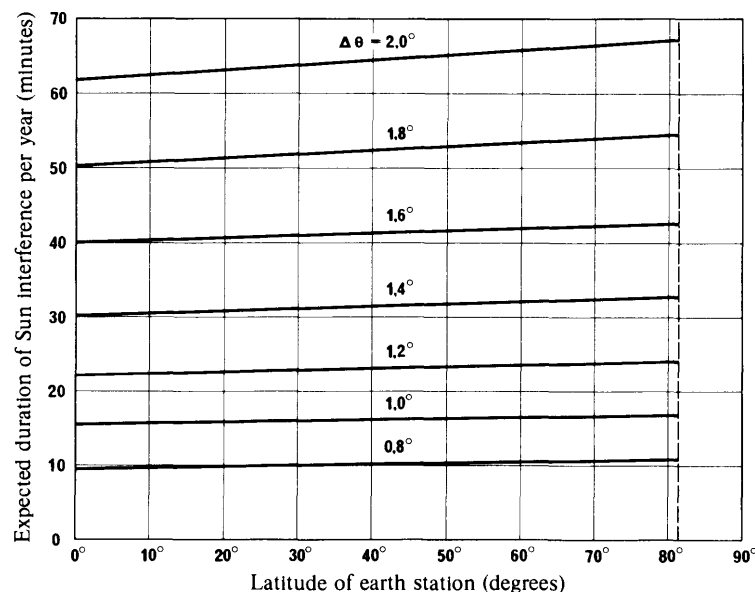
A zone of interference is defined which depends on the angular width of the source, the antenna radiation diagram, and the permissible increase in noise temperature of the earth station receiving antenna, of the order of 15 dB. This zone is approximately circular, and appears to be about 1.2° in angular diameter when received by typical 30 m antennae at 4 GHz. Interference occurs when the radio sun enters the zone of interference.

For satellites in equatorial orbits at altitudes greater than, or equal to, 10 400 km, no earth station is free from solar interference. For stations located in the northern hemisphere, interference occurs only in the six-month period between the autumnal and vernal equinoxes, and for stations in the southern hemisphere it occurs only in the remaining six months. At any station, there are two periods in the particular six-month interval in which interference occurs; each of these periods may include several consecutive days. For geostationary satellites, interference occurs once a day.

The difference in time between the occurrence of interference at two different earth stations may be calculated from a knowledge of the satellite position and the earth station co-ordinates. The time difference in occurrence between earth stations in the same hemisphere is approximately 35 minutes at maximum and shows little variation with satellite longitude over a wide range of values.

The duration of any individual occurrence of interference can be deduced from the size of the zone of interference and the angular velocities of the Sun and satellite relative to the earth station. The maximum duration of interference for an angular diameter of the zone of interference of 1.2° is about five minutes for geostationary satellites.

A study of the expected duration per year of Sun interference while operating with synchronous satellites has been carried out in Japan [CCIR, 1966-69] the results of which are shown in Fig. 8.



$\Delta\theta$ is the angular diameter of the zone of interference

FIGURE 8 — Expected duration of interference due to the Sun for a satellite in the geostationary orbit

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ANNEX III

MEASUREMENT OF THE RATIO G/T WITH THE AID OF RADIO STARS

1. Introduction

It is desirable to establish a practical method of measuring the ratio G/T with high accuracy, which will permit comparison of values measured at various stations. This Annex describes a method for the direct measurement of the ratio G/T using radio stars.

2. Method of measurement

By measuring the ratio, r , of the noise powers at the receiver output, the ratio G/T can be determined using the formula:

$$\frac{G}{T} = \frac{8\pi k (r-1)}{[\lambda^2 \Phi(f)]} \quad (5)$$

where,

k : Boltzmann's constant;

λ : wavelength (m);

$\Phi(f)$: radiation flux-density of the radio star at the frequency (f) at measurement ($\text{Wm}^{-2} \text{Hz}^{-1}$);

r : $(P_n + P_{st})/P_n$;

P_n : noise power corresponding to the system noise temperature T ;

P_{st} : additional noise power when the antenna is in exact alignment with the radio star.

G (antenna gain) and T (system noise temperature) are referred to the receiver input.

In equation (5), account is taken of the fact that the radiation of the star is generally randomly polarized and only a portion corresponding to the received polarization is received. The radiation flux-density $\Phi(f)$ is obtained by radio astronomical measurements.

This method has a basic advantage when compared with the calculation of G/T from G and T measured separately; instead of two absolute measurements, only one relative measurement is necessary to determine the ratio.

3. Suitable radio stars

The discrete radio sources Cassiopeia A, Cygnus A and Taurus A appear to be the most appropriate for measurements of G/T by earth stations. The flux-density of Cygnus A, however, may not be sufficient in every case.

The declination of all these radio stars is such that they may not be entirely suitable sources for earth stations situated in some southern latitudes.

Table I gives values of the flux-density of the radio stars indicated. [Baars and Hartsuijker, 1972; Dent *et al.*, 1974].

TABLE I — Flux-densities from radio sources

Radio Source	Cassiopeia A	Taurus A	Cygnus A
$\Phi(4)$ Flux-density at 4 GHz ($\text{Wm}^{-2} \text{Hz}^{-1}$)	1061×10^{-26} ⁽¹⁾	685×10^{-26}	489×10^{-26}
$\Phi(f)$ Flux-density at f GHz	$\Phi(4) \left(\frac{f}{4}\right)^{-0.792}$ ^{(1) (2)}	$\Phi(4) \left(\frac{f}{4}\right)^{-0.263}$ ⁽²⁾	$\Phi(4) \left(\frac{f}{4}\right)^{-1.205}$ ⁽³⁾

⁽¹⁾ Value for January 1965 (see § 4.3).

⁽²⁾ Where f is between 1 and 16 GHz. The formulae may be used provisionally up to 32 GHz.

⁽³⁾ Where f is between 2 and 16 GHz.

For the measurements at frequencies above 10 GHz, the use of the radio waves from planets, Venus for example, as well as above-mentioned radio stars is advantageous. The radio waves from planets have such advantages that flux-densities increase with frequency and their solid angle is very small giving rise to negligible correction errors due to angular extension. The flux-density $\Phi(f)$ is expressed by:

$$\Phi(f) = \frac{4\pi k Tb(f)}{\lambda^2} (1 - \cos \psi) \quad (6)$$

where,

$Tb(f)$: brightness temperature of a planet (K),

ψ : semi-diameter.

The value of $\Phi(f)$ derived from equation (6), is substituted in equation (5) to obtain the value of G/T of an earth station. The value of ψ can be found elsewhere [USA]. In the case of the planet Venus, the values $Tb(f)$ are thought to be about 580 K and 506 K at 15.5 and 31.6 GHz, respectively [Yokoi *et al.*, 1974]. Since the values of $Tb(f)$ are based on a limited amount of measured data at the two frequencies mentioned, and not yet determined for other frequencies, Administrations are urged to make and contribute studies of the value of $Tb(f)$, as a function of frequency over as wide a range of frequencies as possible, to confirm and extend the results given here.

4. Correction factors and assessment of errors

The corrected value of G/T is given by:

$$(G/T)_c = G/T + C_1 + C_2 + C_3 + C_4 \quad (7)$$

where,

C_1 : atmospheric absorption;

C_2 : correction for angular extension of radio stars;

C_3 : change of flux with time;

C_4 : change of flux with frequency.

All factors to be given in decibels.

4.1 Atmospheric absorption

A simple correction for atmospheric absorption for angles of elevation above 5° , is given by:

$$C_1 = A/\sin \alpha \quad (8)$$

where:

A is the one-way absorption for a vertical path in dB,

α is the angle of elevation.

At 4 GHz, $A = 0.036$ dB; the value at other frequencies is shown in Fig. 9.

4.2 Angular extension of radio stars

If the angular extension of the radio star in the sky is significant compared with the antenna beamwidth, a correction must be applied. This correction, C_2 , is shown in Fig. 10.

The correction factor, C_2 , has been calculated on the basis that the shape of the antenna beam can be closely approximated by the following formula over the range of angles subtended by the stars;

$$\frac{G(\varphi)}{G} = 2^{-\left(\frac{\varphi}{\varphi_0}\right)^2} \quad (9)$$

where, as before,

$G(\varphi)$: antenna gain at an angle φ off the axis of the beam;

G : antenna gain on the axis of the beam;

φ : angle off the axis of the main beam;

$2\varphi_0$: half power beamwidth of the antenna.

Curve "A" for Cassiopeia is calculated on the assumption that the star can be represented by a disc 0.072° in angular diameter which radiates in a uniform manner. This assumption is based on measurements [Thompson and Krishnan, 1965] made at a frequency of 3292 MHz. Most recent measurements [Ryle *et al.*, 1965] made with higher resolution at a frequency of 1400 MHz indicate that the radiation intensity varies by a factor of approximately 20 over various parts of the star; the measurements also show that there are significant contributions to the total radiation out to an angular diameter of approximately 0.1° . Curve "B" for Cassiopeia is calculated on the basis that these latter measurements can be assumed to apply at 4000 MHz as well as at 1400 MHz and are believed to be more accurate.

The curve shown for Cygnus A is also calculated on the basis that the angular distribution of radiation at 1400 MHz can be assumed to apply at 4000 MHz [Ryle *et al.*, 1965].

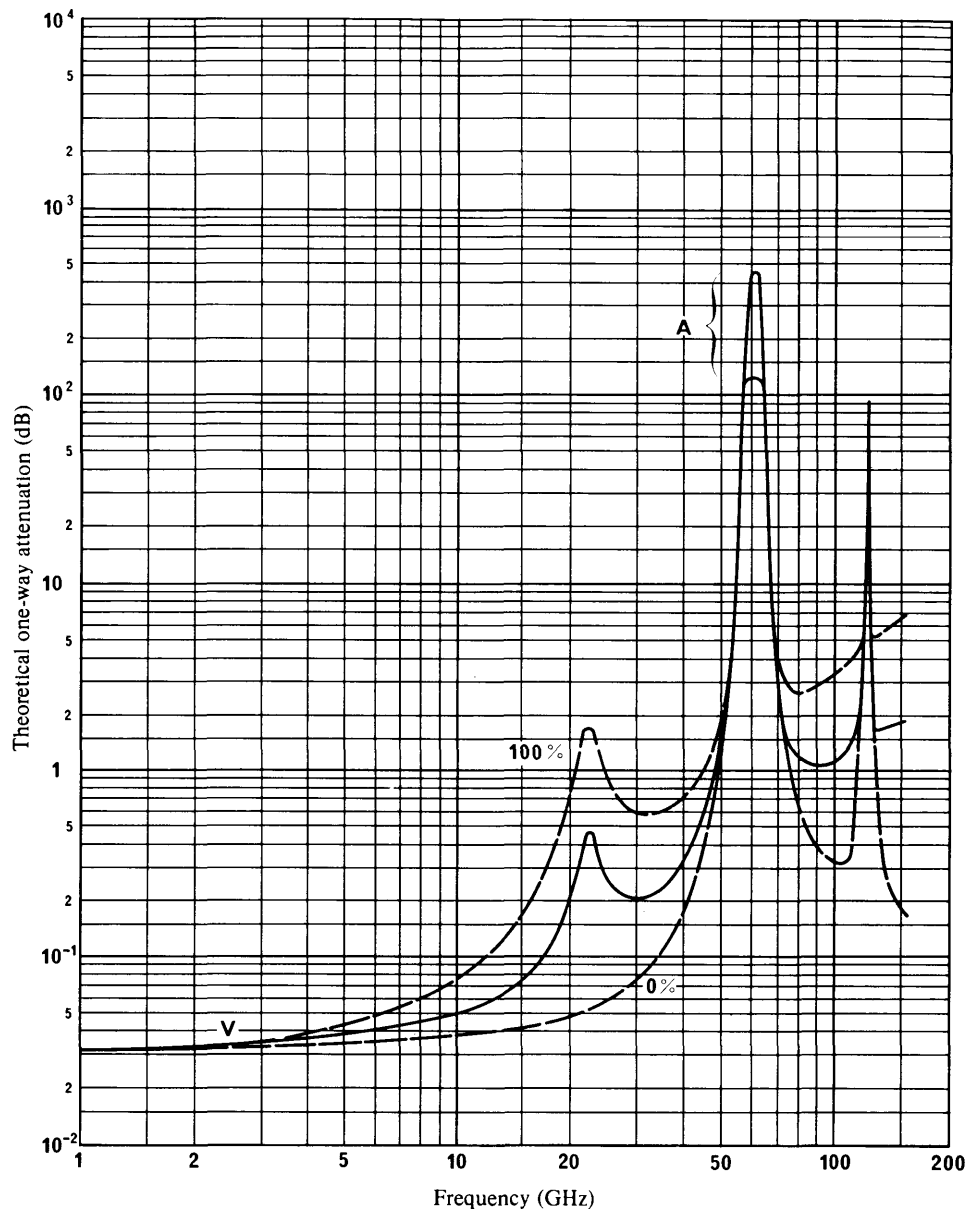


FIGURE 9 — Theoretical one-way attenuation for vertical paths through the atmosphere (calculated using the United States' standard atmosphere for July at 45°N latitude). Solid curves are for a moderately humid atmosphere, dashed curves for vertical attenuation represent the limits for 0 and 100 % relative humidity

A: Limits of uncertainty

V: Vertical

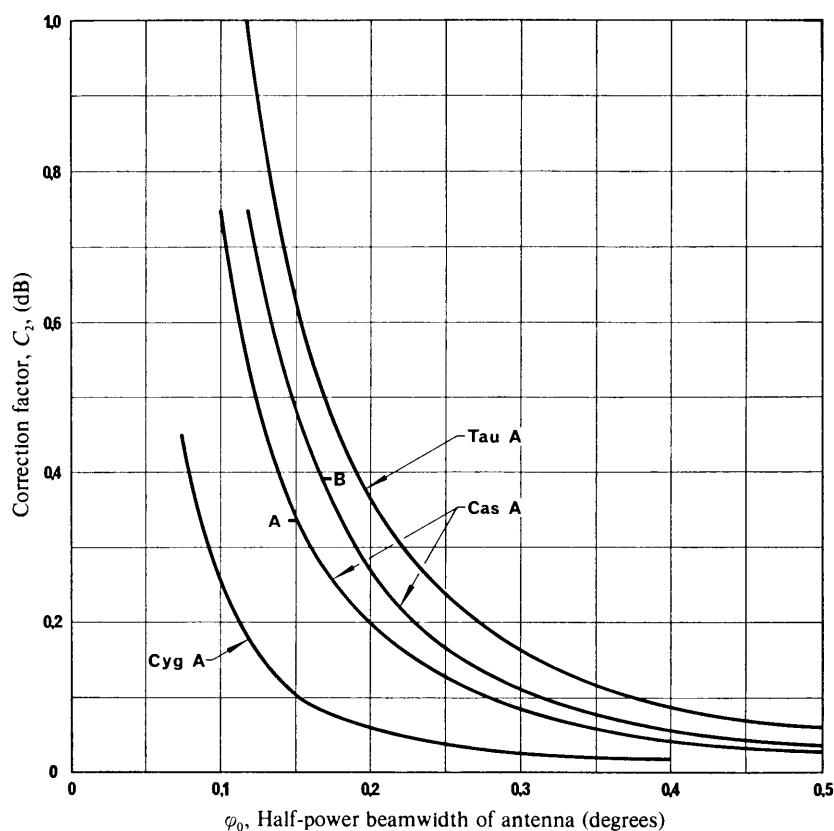


FIGURE 10 — Correction factor for the angular extension of radio stars

4.3 Change of flux with time

Cassiopeia A is subject to a frequency dependent reduction of flux with time [Dent *et al.*, 1974]. The correction may be obtained from:

$$C_3 = (0.042 - 0.0126 \log f)n \quad \text{dB}$$

where,

n : number of years elapsed, with $n = 0$ in January 1965;

f : frequency (GHz).

4.4 Change of flux with frequency

The variation of flux with frequency is also shown in Table I.

4.5 Polarization effects

Taurus A is elliptically polarized and it is necessary to use the mean of two readings taken in two orthogonal directions. These precautions are not necessary for measurements using Cassiopeia A or Cygnus A.

4.6 Assessment of errors

The maximum relative error is given by:

$$\frac{\Delta(G/T)}{G/T} = \frac{\Delta\Phi(f)}{\Phi(f)} + \frac{\Delta r}{r} \times \frac{r}{(r-1)} \quad (10)$$

where errors in $\Phi(f)$ and r are considered.

The relative error which results from the measurement of the power ratio r is particularly marked when the star noise (P_{st}) is insufficient in relation to the system noise (P_n), because $r/(r-1) \rightarrow \infty$ when $r \rightarrow 1$. The measurement accuracy would be considerably reduced when r is less than 2 dB. This would occur at the following values of G/T :

Cassiopeia A:	36 dBK
Taurus A:	37 dBK
Cygnus A:	39 dBK.

If $r = 2.5$ (4 dB), for example, r must be measured to ± 0.01 (0.05 dB) if the error term is not to exceed 0.02 (approx. 0.1 dB).

The error contribution due to:

$$\frac{\Delta\Phi(f)}{\Phi(f)}$$

is approximately 0.02. There is an additional uncertainty of ± 0.01 in the corrections applied. Thus the total maximum error, for high elevation angles, is about 0.05 or approximately ± 0.2 dB.

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ANNEX IV

SAFETY ASPECTS OF RADIO-FREQUENCY RADIATION FROM FIXED EARTH STATION ANTENNA SYSTEMS

This Annex provides information from which the maximum power flux-densities to be expected from an earth station antenna system using paraboloidal type antennae may be calculated with respect to the power radiated at the antenna feed.

The maximum power flux-densities have been evaluated for the following three zones:

- the far-field zone, defined as that extending from infinity to $(2 D^2)/\lambda$
where,
 D : antenna diameter in metres,
 λ : wavelength in metres;
- the near field zone, bounded by the antenna aperture and $(2 D^2)/\lambda$;
- the zone bounded by the feed primary (and secondary, if any) reflectors and the radiating aperture.

Ground reflections may have a significant effect on the power flux-density observed at certain locations, and in computing the expected flux-density it has been assumed that the effective flux could increase by a factor of 4 as compared with the free space field. This means that the calculation should produce conservative results.

In order to illustrate the use of the information given in this Annex an example calculation has been performed in which a maximum power flux-density of 10 mW/cm^2 has been assumed. The resulting data are shown in Fig. 11, in which for a particular value of antenna diameter, the maximum powers radiated from the antenna feed are shown for:

- the far field
- centre of aperture
- near-field peak.

The field in the zone bounded by the feed and the radiating aperture is not shown in Fig. 11. This field will be very high in certain directions and is unlikely to be intercepted by humans in the normal operation of the earth station.

Although 10 mW/cm^2 has been used in the above example, other values of the safe power flux-density can be accommodated in Fig. 11 by a simple movement of the ordinate scale. In this respect Administrations should use the value of power flux-density they consider most appropriate.

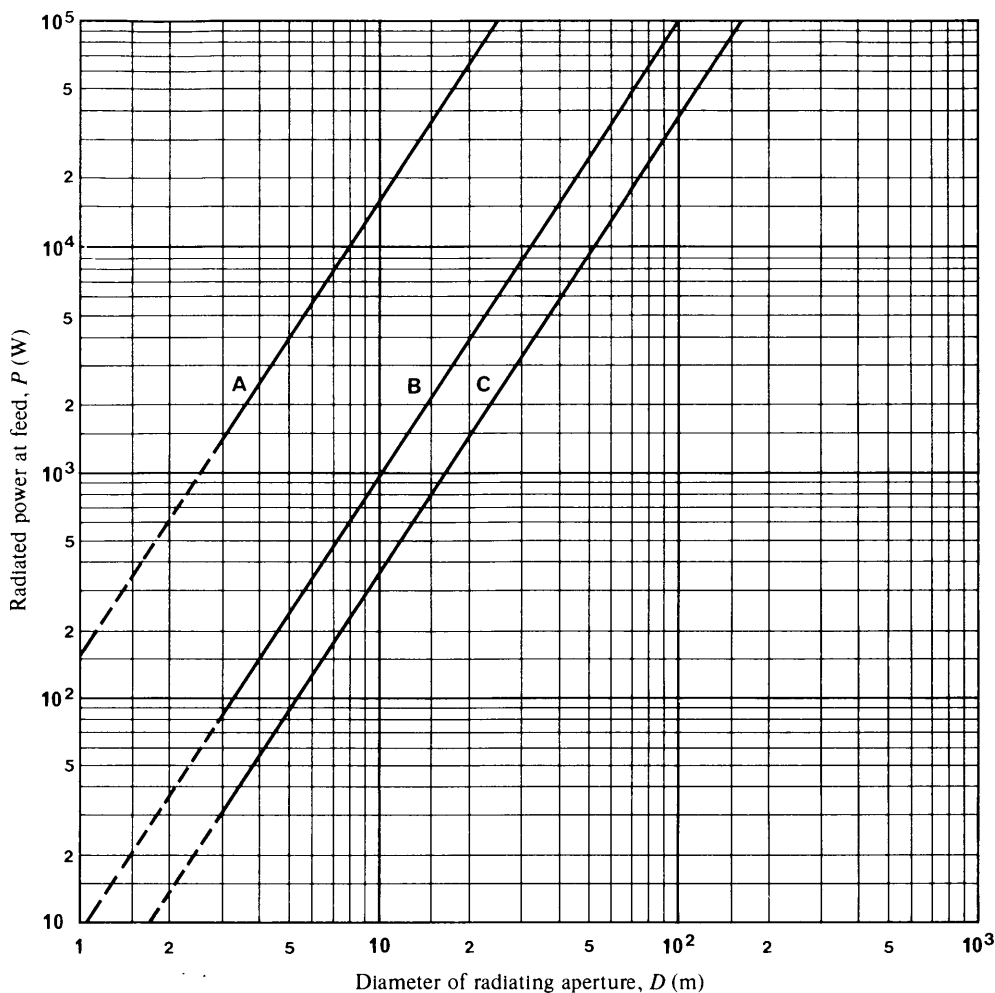


FIGURE 11 — Radio-frequency radiation hazards. Calculated levels of radiated power for the assumed maximum safe exposure limit of 10 mW/cm^2 on axis of radiated beam

A: Far-field boundary
 B: Centre of aperture plane
 C: Near-field peak

Note. — If a point is marked on the Figure to represent the antenna diameter and radiated power under consideration and this lies to the left of the curve or curves, the assumed maximum safe pfd (10 mW/cm^2) could be exceeded in the zone(s) indicated by the title(s) of the curve(s) to the right of the point.

REPORT 709

EARTH STATION ANTENNA COUPLING AND COLLOCATION IN A SHARED FREQUENCY BAND

(Study Programme 1C-1/4)

(1978)

1. Introduction

To conserve frequency spectrum and possibly to accommodate interconnection between diversity earth stations, it may be desirable to use the same frequency bands for the space and terrestrial links. To accomplish this goal without frequency restriction, it is necessary that:

- the terrestrial antenna be located in the rear sector of the earth station antenna;
- the terrestrial antenna has a high front-to-back ratio.

A measurement programme has been undertaken which provides good correlation with a derived formula predicting the on-axis coupling factor. A separate programme, demonstrating the feasibility of co-locating a terrestrial antenna sharing the same frequency band under traffic conditions has also been conducted under the following conditions:

- the terrestrial system transmits at a minimum power in the earth station receive band;
- the terrestrial system receiver at the earth station operates in the earth station transmit band;
- low coupling exists between the earth station and terrestrial antennae; and
- power relationships are critical and may require adjustment of the transmission parameters in the radio relay link.

2. Coupling factor

A relatively simple formula, for estimating the coupling factor between a large earth station antenna and an isotropic antenna located on the rearward projection of its focal axis, has been developed. Measurements have been made and it appears the coupling factor can be predicted reasonably well. Fig. 1 shows the geometry of the coupling factor given by the formula:

$$C_0 = \frac{P_r}{P_t} = \frac{\lambda^2 G_0 (1 + \cos \psi)^2}{64 \pi^2 (l_0 + \rho_0)^2} \quad (1)$$

where the angles are shown in Fig. 1 and G_0 is the feed/subreflector gain in the direction just beyond the main reflector rim. G_0 is fairly constant over most of the main reflector (especially for shaped Cassegrain systems) and has a value given approximately by $4\pi/\Omega^2$, where Ω is the included angle of the reflector. However, due to subreflector diffraction and feed pattern effects G_0 falls off very rapidly just beyond the rim, and it is this reduced value that must be used in Equation (1). G_0 may be taken typically as about 12 dB below the value $10 \log 4\pi/\Omega^2$ in the nominal direction of the first unblocked zone at 6 GHz for large earth station antennae.

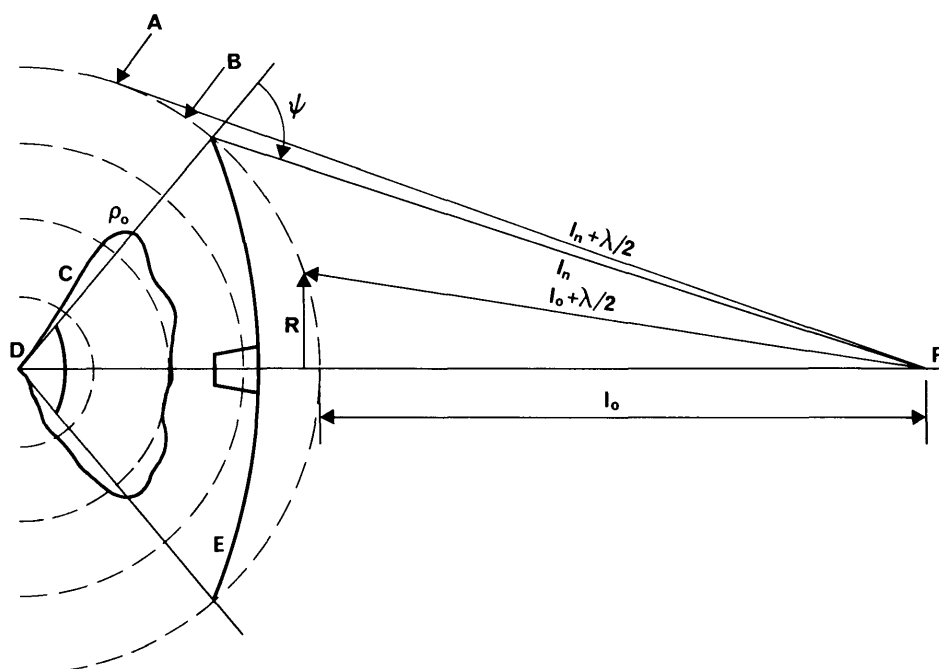


FIGURE 1 — Geometry for calculation of coupling factor between 30 metre earth station antenna and isotropic antenna located in its geometrical shadow

- A: Spherical wavefront of radius ρ_0 originating at focus
- B: First exposed Fresnel zone
- C: Intensity distribution (feed/subreflector) pattern
- D: Prime focus
- E: 30 metre dish
- R: Radius of first Fresnel zone
- P: Isotropic antenna location

Figs. 2a and 2b show the calculated and measured coupling factors between a large antenna and an isotropic antenna, respectively.

To demonstrate more practically the concept of using the same frequency bands for the space and terrestrial links, an additional measurement programme was conducted. Fig. 3 shows the coupling between a standard gain horn and a 30 metre antenna as a function of polarization angle and the distance from the earth station antenna. In addition, a 12 km radio relay link was implemented for operation to demonstrate co-channel interconnect operation. The earth antenna was circularly polarized and the terrestrial radio relay antenna linearly polarized. The collocated 3 m horn reflector antenna transmitting at 4 GHz was located so that its aperture was visible to part of the earth station antenna rim. The resulting geometry produced relatively strong coupling; in practice most alternative configurations could have resulted in less coupling.

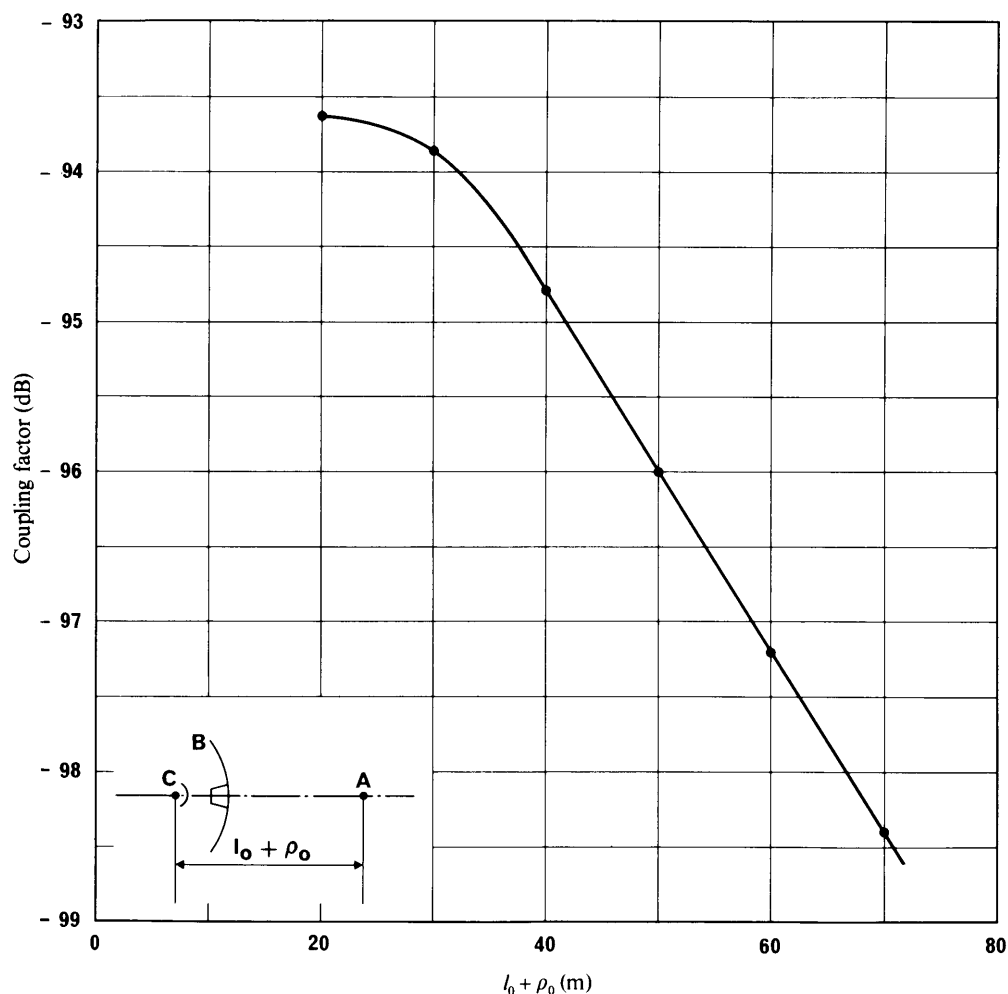


FIGURE 2(a) — Calculated coupling factor between 30 metre antenna and isotropic antenna located behind antenna on rearward projection of focal axis

A: Isotropic antenna
 B: 30 metre dish, $f = 6.4$ GHz
 C: Focus

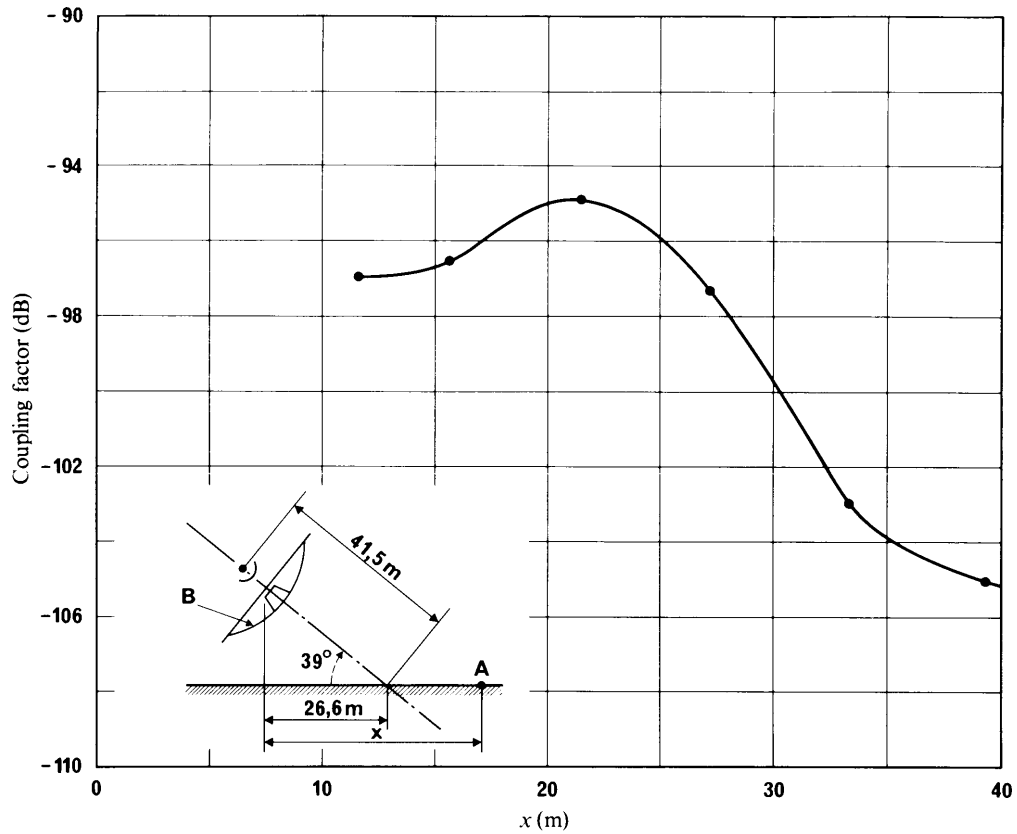


FIGURE 2(b) — Measured coupling factor between 30 metre antenna and isotropic antenna located behind antenna

A : Isotropic antenna
B : 30 metre dish, $f=6.4$ GHz

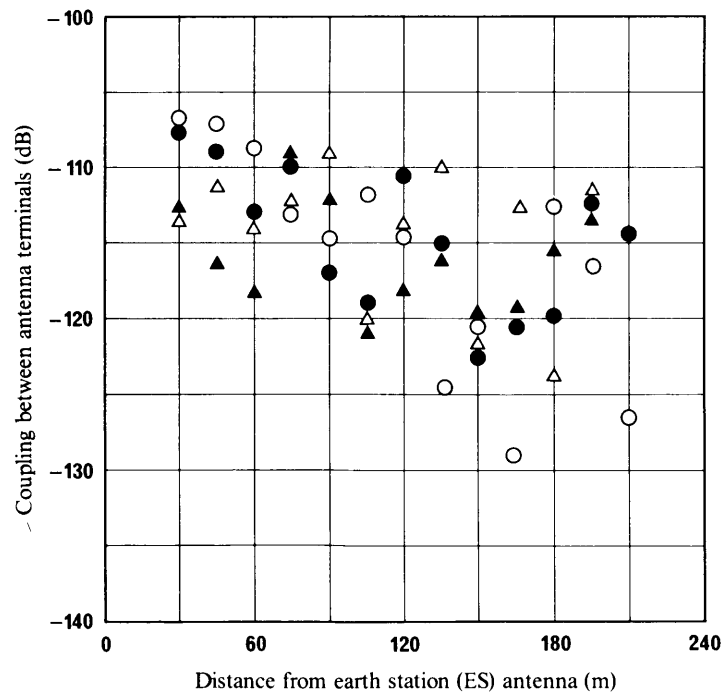


FIGURE 3 — Coupling between the terminal of the earth station antenna and the standard gain horn as a function of distance

- 180° off ES main beam Az., vert. pol.
- 180° off ES main beam Az., horiz. pol.
- ▲ 120° off ES main beam Az., vert. pol.
- △ 120° off ES main beam Az., horiz. pol.

Early during the link demonstration it was established that by far the greatest interference resulted from radiation of the collocated 4 GHz horn reflector antenna into satellite signals received at 4 GHz at the earth station antenna.

After both the radio relay and the satellite links were calibrated, noise power ratio (NPR) measurements were made in the top baseband channel for a wide variety of space and terrestrial link carrier sizes. The satellite link was adjusted for 7500 pWp in the absence of terrestrial link interference. The terrestrial link was designed to conform with INTELSAT-IV transmission parameters and its transmit power was varied in 5 dB steps until a 10 000 pWp noise level was experienced on the space link. The multi-channel modulation index on the terrestrial radio relay link was then reduced by 4 and 10 dB to examine the performance sensitivity to baseband loading. Table I shows the results of these measurements which show good agreement with calculated values.

TABLE I — Summary of space link performance

Number of channels on space link (1)	Multichannel modulation index on space link	Terrestrial transmit power (dBW)	Number of channels on terrestrial link	Multichannel modulation index on terrestrial link	Coupling factor (dB)	Measured C/I (dB)	Calculated (S/N) on space link (dB)	Measured (S/N) on space link (dB)
432	1.50	- 5.0	1800	0.49	142	33.2	51.6	50.2
432	1.50	- 5.0	1800	0.39	142	33.2	51.6	50.2
432	1.50	- 5.0	1800	0.25	142	33.2	51.3	50.2
432	1.50	- 10.0	960	1.10	135	30.8	51.6	50.8
432	1.50	- 10.0	960	0.70	135	30.8	51.5	50.8
432	1.50	- 10.0	960	0.34	135	30.8	51.5	50.8
432	1.50	- 10.0	432	1.50	131	27.0	51.2	50.7
432	1.50	- 10.0	432	0.95	131	27.0	51.1	50.7
432	1.50	- 10.0	432	0.47	131	27.0	51.1	50.7
252	1.54	- 5.0	1800	0.49	132	19.3	51.6	51.1
252	1.54	- 5.0	1800	0.39	132	19.3	50.8	50.6
252	1.54	- 5.0	1800	0.25	132	19.3	50.6	50.1
252	1.54	- 5.0	432	1.50	132	19.2	51.6	52.1
252	1.54	- 5.0	432	0.95	132	19.2	50.8	51.6
252	1.54	- 5.0	432	0.47	132	19.2	50.2	51.6
252	1.54	- 5.0	252	1.54	132	19.2	50.7	50.7
252	1.54	- 5.0	252	0.97	132	19.2	49.9	50.2
252	1.54	- 5.0	252	0.48	132	19.2	49.6	49.7
24	2.55	- 10.0	1800	0.49	127	10.9	50.4	50.9
24	2.55	- 10.0	1800	0.39	127	10.9	50.4	49.9
24	2.55	- 10.0	1800	0.25	127	10.9	49.0	46.9
24	2.55	- 10.0	432	1.50	129	12.2	49.4	49.9
24	2.55	- 10.0	432	0.95	129	12.2	49.3	48.9
24	2.55	- 10.0	432	0.47	129	12.2	46.2	47.6
24	2.55	- 10.0	252	1.54	130	14.0	49.8	49.9
24	2.55	- 10.0	252	0.98	130	14.0	49.6	49.4
24	2.55	- 10.0	252	0.48	130	14.0	47.4	47.9

(1) INTELSAT IV standard baseband parameters were used.

The coupling factor varied with climatic conditions and antenna polarization. If frequency co-ordination between the space and terrestrial links permitted frequency interleaving, an improvement of 15 dB could be realized, allowing a 4 GHz transmitter power of 5 dBW.

The effects of interference on the terrestrial link were also investigated by setting up a worst-case global configuration. In this configuration 972 channels were transmitted over the space link, while 1800 channels were transmitted over the terrestrial link. Interference into the terrestrial link was not a serious problem, even at considerably reduced power on the 6 GHz terrestrial link. For transmission at 6 GHz from the remote site at a reduced power of only -12 dBW (corresponding to -38 dBm received power), the measured carrier-to-interference ratio was about 30 dB. The corresponding baseband interference was only about 1000 pWp, which agrees closely with the calculated value.

For the worst carrier combination, the effect of interference on the terrestrial link was negligible for all 6 GHz power levels (transmitted toward the earth station) from $+13$ dBW to -12 dBW. For transmission at a reduced power of only -12 dBW from the remote site, the measured carrier-to-interference ratio was about 30 dB; the corresponding baseband interference was about 1000 pWp. A wide variety of live and test video signals were transmitted and no impairment was subjectively observed for either link.

3. Conclusion

The test results confirm that collocation of earth station and terrestrial systems using the same frequency band is feasible under controlled conditions.

In the worst case (highest coupling between the two antenna systems), a 10 000 pWp objective on the satellite link could be met if the terrestrial radio relay transmitter power were limited to about -10 dBW and for short links such power is more than adequate.

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- JENKINS and WHITE [1967] *Fundamentals of Optics*, 4th Ed., McGraw-Hill Book Co., New York, USA.
- POTTS, J. B. [1972] Feasibility of collocating a radio-relay station with a sharing earth station, *COMSAT Tech. Rev.*, Vol. 2, 1.

REPORT 385-1

FEASIBILITY OF FREQUENCY SHARING BETWEEN SYSTEMS IN THE FIXED SATELLITE SERVICE AND TERRESTRIAL RADIO SERVICES

Criteria for the selection of sites for earth stations
in the fixed satellite service
(Study Programme (2A-3/4))

(1966 – 1970)

1. Introduction

This Report is intended to provide guidance to Administrations when selecting sites for earth stations in the Fixed Satellite Service. Particular emphasis is placed on making evaluations and recommendations with regard to frequency interference matters.

2. Interference factors

2.1 General

Radio interference involving earth stations can result from:

- terrestrial stations sharing the same frequency band as the satellite system;
- radar systems; the harmonic output of which could fall in the bands used by earth-station receivers [Prescott, 1968];
- terrestrial stations, including trans-horizon radio-relay systems the harmonic output of which fall in the bands used by the earth-station receivers;
- radiolocation or trans-horizon relay systems operating in bands immediately adjacent to the receive bands of the earth station.

2.2 Precipitation scatter

The techniques for avoidance of scatter due to precipitation in the site selection stage are under study and reference should be made to the Sections on Radiometeorology, Space Telecommunications and Propagation Factors in Interference of the work of Study Group 5 for information concerning the effects of precipitation scatter.

2.3 *Considerations of other sources of electrical interference*

High-voltage lines, electric equipment working nearby, ignition, industrial equipment and other disturbances should be noted, although the actual problem is usually not serious.

2.4 *Aircraft interference*

While the problem is difficult to analyse quantitatively, systems with frequency and emission characteristics such as under § 2.1 may cause or suffer interference resulting from re-radiation of energy from aircraft flying through the main beam of the earth station. Siting precautions should include avoidance of airways particularly in the vicinity of large airports.

3. *Analysis of interference*

In making specific analysis of interference problems, the following data on potential interference sources should be obtained.

3.1 Specific locations; frequencies; power levels; antenna sizes, gains and patterns; azimuths of reception and transmission; duty cycles; pulse widths; pulse rates; class of emission; harmonic and spurious characteristics on both transmission and reception. In the cases involving radio-relay stations operating in the shared frequency band, the guidelines given in Report 382-3 for the determination of coordination distance and in Report 448-2 for interference assessment can be applied, making it unnecessary to have the data in the above detail.

3.2 In general, propagation losses need not be measured except for those cases where path characteristics cannot be accurately predicted. The use of Report 569-1 is recommended for computation of the predicted basic transmission losses.

3.3 Instrumentation would appear to be appropriate in those cases where the transmitter characteristics are unknown, particularly in harmonic bands. However, such measurements should be made where these characteristics can be determined without accompanying propagation effects. This implies that test equipment be set up within line-of-sight of a transmitter, not necessarily on the earth-station site.

3.4 After the terrain profile of the great circle path from the earth station to a transmitter has been examined, situations which indicate presence of factors such as off-path reflections, etc., might be resolved by short-term tests.

4. *Siting precautions*

Some basic siting rules which tend to minimize interference problems of any type are:

4.1 Avoid line-of-sight paths between station and the interfering transmitters.

4.2 Avoid locating the earth station with less than a 5° discrimination angle at the transmitter between the great-circle path to the earth station and the direction of the main antenna beam of the transmitter.

4.3 Maintain a minimum distance of about 50 km from transmitters when terrain shielding to approximately 3° to 4° is available. This distance can decrease to about 20 km with shielding at about 10°.

The above considerations apply to any site while the following are intended to apply to siting of stations for use with satellites in the equatorial plane:

- locate on latitudes south of the transmitter's latitude (reverse for southern hemisphere);
- avoid locations which have potential interferers at azimuths at which the earth-station antenna may have to operate at low elevation angles;
- coastal areas which have sea exposure should be avoided if possible and where it appears desirable to consider such areas, some test evaluation of the potential radar interference should be made.

In special cases it may not always be possible to follow all these rules but careful consideration should be given before departing from them.

5. *Interference criteria*

Interference criteria will, in some cases, have to be established by test; however, for line-of-sight radio-relay systems operating in the shared bands, the CCIR Recommendations should be used. For radar and other types of interference, no general guidance is available and will have to be experimentally determined.

6. Geographical factors

6.1 Whilst the earth station must be favourably located to ensure the necessary visibility of all satellites with which it plans to operate, it may be necessary to consider the following additional factors when selecting the most suitable site:

- plans for nearby terrestrial radio systems which may be projected by the home or neighbouring Administrations (Recommendation 359-4, Report 209-3 and the Final Acts of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, refer);
- the proximity of low-flying aircraft, approach lanes, etc.;
- the site should preferably be surrounded by hills for protection against radio interference. However, to ensure maximum satellite availability, angles of elevation of any obstruction should not exceed about 3°;
- the ground should not be liable to subsidence;
- the site may be required to accommodate several large antennae without mutual obscurement;
- obstructions such as trees or man-made structures such as towers or poles should be avoided in the near vicinity of the antennae.

6.2 Atmosphere conditions may significantly affect the residual noise of a system in the fixed satellite service and the ideal climate should be mild and dry, with low wind velocities.

7. Logistic factors

7.1 The site must meet with the approval of the local authorities and it must be possible to enforce building or other restrictions on adjacent land, if required for the interference-free operation of the station.

7.2 Connection to the cable or radio-relay network may be required and the distance to the nearest switching centre should be considered.

7.3 Primary power, adequate water supply and road access should be considered.

7.4 To determine the exact location of an earth station, it may be necessary to choose a site with visible triangulation points.

7.5 A collimation (boresight) tower may be required.

8. Safety factors

8.1 Consideration should be given to the harmful effects of excessive radiation on human beings and the hazards associated with the handling of inflammable and explosive materials. As a guide, in areas where the radiation density exceeds 10 mW/cm², access should be restricted while the station is in operation. At no time should inflammable liquids be handled or explosive devices be stored in such areas. In areas where people are continuously exposed, a smaller radiation density may be appropriate.

8.2 Where low-flying aircraft may be exposed to these dangers, their operators should be advised accordingly.

REFERENCE

PRESCOTT, H. A. [April, 1968] Some aspects of radar interference at earth stations. IEE Conference on interference problems associated with the operation of microwave communication systems. IEE Conf. Publ., 39.

REPORT 554-1

THE USE OF A TRANSPORTABLE EARTH STATION WITH A SMALL ANTENNA FOR RELIEF OPERATION IN THE EVENT OF NATURAL DISASTERS AND SIMILAR EMERGENCIES

(Question 22-1/4)

(1974 – 1978)

1. Introduction

At the World Administrative Radio Conference for Space Telecommunications, held in Geneva in 1971, Recommendation Spa2 – 13 of the Final Acts was put forward to plan and organize the use of satellite telecommunications in natural disaster areas. It is believed that the rapid availability of reliable communications immediately following a natural disaster would prove helpful in saving lives by virtue of improved relief activity co-ordination.

This Report discusses a feasible configuration of an air-transportable earth station in the 4 and 6 GHz bands and its preferred system characteristics, for use with a geostationary satellite system in the Fixed Satellite Service.

The discussion covers some possible types of modulation, required bandwidth, satellite e.i.r.p., earth-station e.i.r.p., low-noise receiver characteristics and high-power amplifier requirements, as well as antenna system parameters.

The parameters given below generally assume that the earth stations may need to operate with a global beam satellite transponder. If a station will only be required to operate within a region covered by a shaped satellite beam, it may be possible to relax these parameters.

2. Basic consideration

In the event of natural disasters, epidemics and famines, etc., the most urgent need is for a reliable communication link for use in relief operations. To set up these communications by the Fixed Satellite Service, it is desirable that a transportable earth station, with access to an existing satellite system, should be available for transportation to, and installation at, the disaster area.

To establish such a communication service, any satellite system compatible with the technical characteristics of the transportable earth station can be used.

2.1 Required channel capacity

The communication link for the relief operation connects the disaster area with designated relief centres, and the required transmission capacity would be at most 6 telephony circuits (including teletype) and an engineering service channel.

2.2 Circuit quality

The quality of circuits for emergency relief operations need not necessarily be of the high quality recommended by the CCIR for the fixed satellite service. An equivalent weighted signal-to-noise ratio of about 30 dB for a voice channel would appear to provide acceptable voice intelligibility for this purpose, but this will need further study.

2.3 Selection of frequency band

Geostationary satellite systems now operate in the 4 and 6 GHz bands, and therefore it is desirable at present to use these bands for the relief operation.

2.4 Associated earth station

The transportable earth terminal could operate with any suitable existing earth station provided it is suitably equipped. Suitable earth stations would need to be identified so that they may be provided, in advance, with the additional equipment.

3. Preferred modulation methods

The choice of the form of modulation best suited to a system using a transportable earth station must take account of the power-limited condition of the down-link together with the need for flexibility of access to the satellite system.

Of the several modulation methods described in Reports 509-2 and 708, a station of this type might employ frequency division multiplex FM, or single-channel-per-carrier (SCPC), FM, PCM/PSK, delta-modulated PSK.

The single-channel-per-carrier PCM/PSK has been in operation already, for example, in the SPADE system; but the other two single-channel-per-carrier systems are not in current use on a global basis. Companded single-channel FM and delta-modulation (DM/PSK) systems, however, are more effective in a power-limited environment. System efficiency may be further improved by use of forward error-correction coding techniques.

Examples of the required satellite e.i.r.p., the earth station e.i.r.p. and the bandwidth required for these modulation methods are shown in Table I. Some of the satellite e.i.r.p.'s shown in Table I may not be available in current satellite systems. It should also be noted that the subjective quality of transmission of each of the systems examined is not necessarily similar. Further studies on this point are necessary.

4. Characteristics of the transportable earth station

4.1 System G/T ratio

In the 4 GHz band, it will be reasonable to consider a system G/T in the range of 17.5 to 23.5 dBK as an objective, but further study is necessary. Assuming an uncooled parametric amplifier of noise temperature of about 50 K and an antenna elevation angle of 10° , these values correspond to antenna diameters in the range 2.5 m to 5 m approximately.

TABLE I — *Examples of transmission system parameters in 6/4 GHz band*

<i>G/T</i> ratio dBK (diameter)	Type of modulation	Bandwidth per carrier	Satellite e.i.r.p. per carrier	Earth station e.i.r.p. per carrier	Earth station transmit power per carrier	Circuit quality (clear sky condition)
17.5 (2.5 m)	FDM-FM (for 6 ch)	250 kHz	14 dBW	57.5 dBW	45 W	<i>S/N</i> 30 dB
	SCPC 64 kbit/s PCM-4 Φ PSK	45 kHz	11 dBW	54.5 dBW	22 W	Bit error-rate: 10^{-4}
	SCPC 32 kbit/s Δ M-2 Φ PSK	45 kHz	5 dBW	48.5 dBW	5.6 W	Bit error-rate: 10^{-3}
	SCPC companded FM	30 kHz	1 dBW	44.5 dBW	2.2 W	<i>S/N</i> 22 dB (without compandor)
23.5 (5 m)	FDM-FM (for 6 ch)	250 kHz	8 dBW	57.5 dBW	11 W	<i>S/N</i> 30 dB
	SCPC 64 kbit/s PCM-4 Φ PSK	45 kHz	5 dBW	54.4 dBW	5.6 W	Bit error-rate: 10^{-4}
	SCPC 32 kbit/s Δ M-2 Φ PSK	45 kHz	- 1 dBW	48.5 dBW	1.4 W	Bit error-rate: 10^{-3}
	SCPC companded FM	30 kHz	- 5 dBW	44.5 dBW	0.6 W	<i>S/N</i> 22 dB (without compandor)

Note 1. — In the FDM-FM and S.C.P.C. companded FM systems, the use of a threshold extension demodulator is assumed.

Note 2. — Value of satellite e.i.r.p. and earth station e.i.r.p. are for a small earth station with antenna elevation of 10° excluding any margin. Earth stations with which the small earth station is communicating have a *G/T* of 40.7 dBK.

Note 3. — Satellite transponder characteristics are similar to those of the INTELSAT IV global beam transponder and the transponder gain is assumed such that the difference between earth station e.i.r.p. and the corresponding satellite e.i.r.p. is 65 dB.

4.2 Earth-station e.i.r.p.

The earth-station e.i.r.p. depends on the type of modulation, the transmitting telephony capacity, and the satellite characteristics. When the transmission telephony capacity is 6 channels, about 70 dBW represents a typical value of the required e.i.r.p.

However, in case of multi-carrier operation, such as the SCPC transmission, the maximum output power of the transmitter must take account of a back-off level to reduce intermodulation noise to an acceptable level. Table I shows typical e.i.r.p. required for the transportable earth station.

5. Configuration of the transportable earth station

The earth station may be divided into the following major sub-systems:

- antenna,
- power amplifier,
- low-noise receiver,
- ground communication equipment,
- control and monitoring equipment,
- terminal equipment, including teleprinters and telephones,
- support facilities.

5.1 Weight and size

All the equipment, including shelters, should be capable of being packaged into units of weight which can be handled by a few persons. Furthermore, the total volume and weight should not be in excess of that which could be accommodated in the luggage compartment of a passenger jet aircraft such as a Boeing B707 (allowable weight 7000 kg) or a Douglas DC8-62 (allowable weight 10 000 kg). This is readily attainable with present-day technology.

5.2 Antenna

The form and dimension of an antenna are determined by the required gain and noise temperature. Other factors such as climatic conditions, the maximum weight and the ease of satellite acquisition and tracking, should also be considered.

One of the major requirements for the antenna is ease of erection and transportation. For this purpose, the antenna reflector could consist of several panels made of light material such as fibre reinforced plastic or aluminium alloy. The use of an antenna of a diameter from 2.5 to 5 m is foreseen, as shown in Table I.

The main antenna reflector may be illuminated by a front-fed horn or a feed which includes a sub-reflector. The latter type may have a slight advantage in G/T performance, since the curvature of both the sub-reflector and main reflector can be optimized, but ease of erection and alignment may take precedence over G/T considerations.

A manual or automatic pointing system may be provided commensurate with weight and power consumption, by monitoring a carrier signal from the satellite, having a steerable range of approximately $\pm 5^\circ$.

5.3 Power amplifier

Air-cooled Klystron and TWT (helix-type) amplifiers are both suitable for this application, but from the point of view of efficiency and ease of maintenance, the former is to be preferred.

Although the instantaneous transmission bandwidth is small, the output amplifier may need to have the capability of being tunable over a wider bandwidth, e.g., 500 MHz, since the available satellite channel may be anywhere within this bandwidth.

The output powers required will be as given in the examples of Table I.

5.4 Low-noise receiver

Because the low-noise receiver must be small, light and be capable of easy handling with little maintenance, an uncooled parametric amplifier is the most desirable.

The noise temperature of this type of receiver is being improved year by year. A temperature of 50 K has been realized and even lower temperatures are expected in the future in the 4 GHz band.

6. An example of transportable earth station

An air-transportable earth station, which may also be carried by an 8-ton truck, has been manufactured using the principles outlined in § 5 above and satisfactory performance has been achieved [Okamoto *et al.*, 1977].

The station has a 3 metre diameter antenna, a peak e.i.r.p. of about 66 dBW and a G/T of about 20 dBK. The total weight is 5.5 tons and the power requirement, including air conditioning, is 7.5 kVA. The reflector is divided into seven sections each weighing about 20 kg, the total setting up time being about 2 hours by three persons. The station uses FDM-FM modulation and can support 6 two-way channels using a transponder similar to an INTELSAT-IVA global beam transponder, or 60 two-way channels using a shaped-beam transponder similar to Japanese CSE (Communication Satellite for Experimental Purpose) transponder, with a channel signal-to-noise ratio of about 43 dB.

7. Conclusion

A transportable earth station used with an existing satellite system can quickly establish a reliable telecommunication service, to assist in relief operations associated with natural disaster and similar emergencies.

The following points should be considered further in the final configuration:

- the determination of acceptable values of signal-to-noise ratios (analogue) or equivalent error-rate (digital) in a telephone channel, and the error-rate in a record channel;
- the technical implications of mutual interference between the transportable earth station on the one hand, and radio-relay and/or other satellite systems, on the other hand;
- the logistic aspects of transportation, installation and operation.

REFERENCE

OKAMOTO, T., EGAMI, S. and OGUCHI, M. [1977] Small transportable earth station for satellite communication. *Japan Telecommunication Review*, Vol. 19, 3, 230.

SECTION 4F: FREQUENCY SHARING BETWEEN NETWORKS OF THE FIXED SATELLITE SERVICE – USE OF THE GEOSTATIONARY SATELLITE ORBIT

Recommendations and Reports

RECOMMENDATION 466-2

MAXIMUM PERMISSIBLE LEVEL OF INTERFERENCE IN A TELEPHONE CHANNEL OF A GEOSTATIONARY SATELLITE NETWORK IN THE FIXED SATELLITE SERVICE EMPLOYING FREQUENCY MODULATION WITH FREQUENCY-DIVISION MULTIPLEX, CAUSED BY OTHER NETWORKS OF THIS SERVICE

(Study Programme 2J-2/4)

(1970 – 1974 – 1978)

The CCIR,

CONSIDERING

- (a) that geostationary satellite networks in the Fixed Satellite Service operate in the same frequency bands;
- (b) that interference between networks in the Fixed Satellite Service contributes to the noise in the network;
- (c) that it is desirable that the interference noise in the telephone channels of networks in the Fixed Satellite Service caused by transmitters of different networks in that service should be such as to give a reasonable orbit utilization efficiency;
- (d) that the overall performance of a network should essentially be under the control of the system designer;
- (e) that it is necessary to protect a network in the Fixed Satellite Service from interference by other such networks;
- (f) that it is necessary to specify the maximum permissible interference power in a telephone channel, to determine space station and earth station characteristics;
- (g) that the value selected for the maximum permissible single entry of interference noise should not result in too wide a minimum orbital spacing;
- (h) that for co-ordination between two satellite networks, it is necessary to know the maximum permissible level of interference in a telephone channel of the wanted network caused by transmitters of the other network;
- (j) that networks in the Fixed Satellite Service may receive interference both into the space station receiver and into the earth station receiver;
- (k) that the mean interference noise power should be an appropriate fraction of the total noise power permitted in the hypothetical reference circuit;
- (l) that in many cases the largest interference contributions to a geostationary satellite network will be from the networks using geostationary satellites in orbit nearby and serving an overlapping coverage area. The value of interference from any other network will generally be less;
- (m) that the accumulation of interference from many entries from other satellite networks and from terrestrial stations is not likely to be equal to the arithmetic sum of the individual interference entries at their maximum value across the band, and the total interference noise level in any single channel may be significantly less;
- n) that the levels of interference between geostationary satellite networks in the Fixed Satellite Service operating in frequency bands below 10 GHz are not expected to undergo a large variation with time,

UNANIMOUSLY RECOMMENDS

1. that different geostationary satellite networks in the Fixed Satellite Service operating in the same frequency bands, below 10 GHz, be designed in such a manner that the interference noise power at a point of zero relative level in any telephone channel of a hypothetical reference circuit of a network in the Fixed Satellite Service, employing frequency modulation, caused by the aggregate of the earth station and space station transmitters of other fixed satellite networks, should not exceed:

1.1 in frequency bands in which the network does not practise frequency re-use; 2000 pW0p, psophometrically weighted one minute mean power for 20% of any month;

1.2 in frequency bands in which the network practises frequency re-use; 1500 pW0p, psophometrically weighted one minute mean power for 20% of any month;

2. that the maximum level of the interference noise power at a point of zero relative level in any telephone channel of the hypothetical reference circuit of a geostationary satellite network in the Fixed Satellite Service employing frequency modulation, caused by the transmitters of another fixed satellite network, should not exceed 400 pW0p, psophometrically weighted one minute mean power, for more than 20% of any month;

3. that the maximum level of interference noise power caused to that network should be calculated on the basis of the following values for the receiving earth station antenna gain, in a direction at an angle θ (in degrees) referred to the main beam direction:

$$G = 32 - 25 \log \theta \text{ dB for } 1^\circ \leq \theta < 48^\circ$$

$$G = -10 \text{ dB for } 48^\circ \leq \theta \leq 180^\circ$$

except when the actual gain is known and is less than the above value, in which case the actual value should be used.

4. that the following Notes should be regarded as part of this Recommendation:

Note 1. — The values quoted in §§ 1.1 and 1.2 are not intended to apply to networks for which a complete advance publication has been submitted to the IFRB by the time of the XIVth Plenary Assembly; for such networks the aggregate interference power in any telephone channel should not exceed 1000 pW0p psophometrically weighted one minute mean power for 20% of any month.

Note 2. — Only a small fraction of the channels of a network will experience the maximum value of interference from any single network and therefore the aggregate level for many channels will be less than the totals contained in § 1. System designers may provide for a lower value in their noise budgets for a large portion of the spectrum. The way in which the aggregate values are to be taken into account in the general noise objectives for networks in the Fixed Satellite Service is defined in Note 7 of Recommendation 353-3.

Note 3. — In some cases it may be necessary to limit the single entry interference value to less than the value quoted in § 2 above in order that the total value recommended in § 1 may not be exceeded. In other cases, particularly in congested arcs of the geostationary satellite orbit, Administrations may agree bilaterally to use higher single entry interference values than those quoted in § 2 above, but any interference noise power in excess of the value recommended in § 2 should be disregarded in calculating whether the total value recommended in § 1 is exceeded.

Note 4. — There is a need for urgent study to be given to means of increasing the single entry interference level quoted in § 2 above without causing the total interference noise level to exceed the values quoted in § 1; this study should include, for example, the feasibility of overcoming problems of interference which result from inhomogeneous network parameters.

Note 5. — There is an urgent need for study of the acceptability of an increase in the maximum total interference noise values recommended in § 1 and more particularly those given in § 1.2 for satellite networks in which frequency re-use is practised.

Note 6. — In segments of the geostationary satellite orbit not likely to be crowded, interference allowances less than those recommended in § 1 above, may be utilized, allowing a corresponding increase in other noise contributions within total acceptable noise limits.

RECOMMENDATION 483-1

MAXIMUM PERMISSIBLE LEVEL OF INTERFERENCE IN A TELEVISION CHANNEL OF A GEOSTATIONARY SATELLITE NETWORK IN THE FIXED SATELLITE SERVICE EMPLOYING FREQUENCY MODULATION, CAUSED BY OTHER NETWORKS OF THIS SERVICE

(Study Programme 2J-2/4)

(1974 - 1978)

The CCIR,

CONSIDERING

- (a) that interference between networks in the Fixed Satellite Service contributes to the noise in the system;
- (b) that it is desirable that the interference noise in television channels of networks in the Fixed Satellite Service caused by transmitters of different networks of this service should be such as to give a reasonable orbit utilization efficiency;

- (c) that the overall performance of a network should essentially be under the control of the system designer;
- (d) that it is necessary to protect a network in the Fixed Satellite Service from interference by other networks of this service;
- (e) that it is necessary to specify the maximum permissible interference power in a television channel, in order to determine space station and earth station characteristics such as required protection ratios and minimum orbital spacing;
- (f) that networks in the Fixed Satellite Service may receive interference both into the space station receiver and into the earth station receiver;
- (g) that the interference noise power should be an appropriate fraction of total noise power permitted in the hypothetical reference circuit;
- (h) that in many cases the largest interference contributions to a geostationary satellite network will be from the networks using the adjacent geostationary satellites and the value of interference from any other network will generally be less,

UNANIMOUSLY RECOMMENDS

1. that different geostationary satellite networks in the Fixed Satellite Service operating in the same frequency bands, be designed in such a manner that the interference noise power in a hypothetical reference circuit for television of a network in the Fixed Satellite Service employing frequency modulation caused by the aggregate of the earth station and space station transmitters of other networks, should not exceed 1/10 of the permissible video noise in the hypothetical reference circuit for more than 1% of any month;
2. that the maximum level of interference noise power caused by any one satellite network into another satellite network should not exceed 4/10 of the interference noise allowance recommended in § 1 but in some cases it may be necessary to limit the single entry value to less than 4/10 of the interference noise allowance quoted above.
3. that the maximum level of interference noise power caused to that network should be calculated on the basis of the following values for the receiving earth station antenna gain in a direction at an angle θ (in degrees) referred to the main beam direction:

$$G = 32 - 25 \log \theta \text{ dB for } 1^\circ \leq \theta < 48^\circ$$

$$G = -10 \text{ dB for } 48^\circ \leq \theta \leq 180^\circ$$

except when the actual gain is known and is less than the above value, in which case the actual value should be used.

4. that the following Notes should be regarded as part of the Recommendation:

Note 1. — The above values of interference noise shall be included in the total noise allowances as defined in Recommendation 354-2.

Note 2. — In segments of the geostationary satellite orbit not likely to be crowded, interference allowances less than those recommended above may be utilized, allowing a corresponding increase in other noise contributions within total acceptable noise limits.

RECOMMENDATION 523

MAXIMUM PERMISSIBLE LEVELS OF INTERFERENCE IN A GEOSTATIONARY SATELLITE NETWORK IN THE FIXED SATELLITE SERVICE USING 8-BIT PCM ENCODED TELEPHONY, CAUSED BY OTHER NETWORKS OF THIS SERVICE

(Study Programme 2J-2/4)

(1978)

The CCIR,

CONSIDERING

- (a) that geostationary satellite networks in the Fixed Satellite Service operate in the same frequency bands;
- (b) that interference between networks in the Fixed Satellite Service degrades the bit error rate performance relative to its value in the absence of frequency sharing;
- (c) that it is desirable that the bit error rate in networks in the Fixed Satellite Service caused by transmitters of different networks in that service should be such, as to give a reasonable orbit utilization efficiency;

- (d) that the overall performance of a network should essentially be under the control of the system designer;
- (e) that it is necessary to protect a network in the Fixed Satellite Service from interference by other such networks;
- (f) that it is necessary to determine the maximum permissible interfering radio frequency power in a satellite system to establish space station and earth station characteristics such as required protection ratios and minimum orbital spacing;
- (g) that networks in the Fixed Satellite Service may receive interference both into the space station receiver and into the earth station receiver;
- (h) that it is desirable that the increase in bit error rate due to interference from other satellite networks should be a controlled fraction of the total bit error rate, as set out in Recommendation 522;
- (j) that where adjacent satellites serve networks with similar characteristics the largest interference contributions to a geostationary satellite network will be from the networks using those adjacent satellites; but this may not be true where network characteristics are inhomogeneous;
- (k) that the levels of interference between geostationary satellite networks in the Fixed Satellite Service below 10 GHz are not expected to exhibit a large variation with time, and under these conditions it is preferable to define the permissible interference limit as a fraction of the pre-demodulator noise power, as this allows multiple interference entries to be superimposed on each other on the basis of RF power addition,

UNANIMOUSLY RECOMMENDS

1. that networks in the Fixed Satellite Service operating in the same frequency bands below 10 GHz, and using geostationary satellites be designed and operated in such a manner that the total interference to an 8-bit PCM telephony system in the Fixed Satellite Service caused by the earth station and space station transmitters of all other networks, should conform provisionally to the following limits:

1.1 in frequency bands in which the network does not practise frequency re-use, the interference power level, averaged over any ten minutes, should not exceed, for more than 20% of any month, 20% of the total noise power level at the input to the demodulator which would give rise to a bit error rate of 1 in 10^6 ;

1.2 in frequency bands in which the network practises frequency re-use, the interference power level, averaged over any ten minutes, should not exceed, for more than 20% of any month, 15% of the total noise power level at the input to the demodulator that would give rise to a bit error rate of 1 in 10^6 ;

2. that the maximum level of interference power in any such 8-bit PCM telephony system caused by the transmitters of another fixed-satellite network, averaged over any ten minutes, should not exceed, for more than 20% of any month, 4% of the total noise power level at the input to the demodulator which would give rise to a bit error rate of 1 in 10^6 ;

3. that the maximum level of interference noise power caused to that network should be calculated on the basis of the following values for the receiving earth station antenna gain, in a direction at an angle θ (in degrees) referred to the main beam direction:

$$G = 32 - 25 \log \theta \text{ dB for } 1^\circ \leq \theta < 48^\circ$$

$$G = -10 \text{ dB for } 48^\circ \leq \theta \leq 180^\circ$$

except when the actual gain is known and is less than the above value, in which case the actual value should be used;

4. that the following notes should be regarded as part of this Recommendation:

Note 1. — It is assumed in this Recommendation that the interference from other satellite networks is of a continuous nature; further study is required with respect to cases where interference is not of a continuous nature.

Note 2. — The values quoted in §§ 1.1 and 1.2 are not intended to apply to networks for which a complete advance publication has been submitted to the IFRB by the time of the XIVth Plenary Assembly; for such networks the aggregate interference power level, averaged over any ten minutes, should not exceed, for more than 20% of any month, 10% of the total noise power level at the input to the demodulator which would give rise to a bit error rate of 1 in 10^6 .

Note 3. — In some cases it may be necessary to limit the single entry interference value to less than the value quoted in § 2 above in order that the total value recommended in § 1 may not be exceeded. In other cases, particularly in congested arcs of the geostationary satellite orbit, Administrations may agree bilaterally to use higher single entry interference values than those quoted in § 2 above, but any interference noise power in excess of the value recommended in § 2 should be disregarded in calculating whether the total value recommended in § 1 is exceeded.

Note 4. — There is a need for urgent study to be given to means of increasing the single entry interference level quoted in § 2 above, without causing the total interference noise level to exceed the values quoted in § 1; this study should include, for example, the feasibility of overcoming problems of interference which result from inhomogeneous network parameters.

Note 5. — There is an urgent need for study of the acceptability of an increase in the maximum total interference noise values recommended in § 1 and more particularly those given in § 1.2 for satellite networks in which frequency re-use is practised.

Note 6. — In segments of the geostationary satellite orbit not likely to be crowded, interference allowances less than those recommended in § 1 above, may be utilized, allowing a corresponding increase in other noise contributions within total acceptable noise limits.

REPORT 710

INTERFERENCE ALLOCATIONS IN DIGITAL SYSTEMS OPERATING AT FREQUENCIES GREATER THAN 10 GHz IN THE FIXED SATELLITE SERVICE

(1978)

1. Introduction

Digital signals are already being transmitted over systems of the Fixed Satellite Service. The most extensive application is likely to be in frequency bands above 10 GHz where rain attenuation begins to contribute significantly to fading.

The way noise and interference are allocated in digital systems may be different from analogue systems. At frequencies above 10 GHz if the error rate performance objective for a small percentage time is met, during non-fading conditions, the error rate is likely to be small.

The relative insensitivity to interference of digital modulation enables the re-use of the same frequencies in any beam employing cross-polarization isolation, assuming that binary or quaternary CPSK modulation is used. However, for 8-phase CPSK modulation (and higher orders) frequencies cannot be re-used because the susceptibility to interference of such systems is much greater. Hence, the utilization of the frequency spectrum may not be greater for these higher level systems in comparison to the lower level systems.

2. Sources of interference

Interference may arise from a number of sources. For the purpose of this document, these are identified as:

- cross-polarized co-channel interference;
- other interference sources within the same satellite system (intrasatellite interference);
- interference from other satellite systems and services (external interference).

Where cross-polarization isolation is employed, under conditions of fading, co-channel interference is likely to be dominant.

Interference entries which are small may be treated as thermal noise, but it would be pessimistic to assume this for higher levels of interference.

In the following section an example is given of the way in which interference may be allocated.

3. Example of the allocation of interference in a 4-phase CPSK system

In deriving this example, the following assumptions are made:

- There are two intrasatellite interference entries on both the up- and down-links.
- Under non-fading conditions, the wanted carrier-to-intrasatellite interference ratio is taken to be 35 dB for both up- and down-links.
- Under non-fading conditions the cross-polarization isolation is taken to be 25 dB for both up- and down-links.

- There are two external interference entries on the down-link; these are assumed to be equivalent to intrasatellite interference.
- External interference on the up-link is assumed to increase the satellite thermal noise by 3 dB.
- Under conditions of fading the system performance becomes unacceptable when the error rate reaches 1 in 10^3 .
- The probability that both the up- and down-links fade at the same time is sufficiently small to be ignored.

Under normal conditions of propagation, a higher degree of cross-polarization isolation can be expected. However, precipitation not only causes attenuation of the signal, but can degrade the polarization isolation between re-used frequencies, so that this becomes the dominant source of degradation. In this example it has been assumed that when the polarization isolation is reduced to 10 dB, the system is no longer acceptable (since the error rate at this point will have reached 1 in 10^3).

The required signal to interference plus noise ratio for an error rate of 1 in 10^3 with a 15 dB signal to co-channel interference ratio is 14.8 dB, and with a 10 dB co-channel interference ratio it is 17 dB. These figures assume an implementation margin of 3 dB.

It is assumed that depolarization on the up-link will be somewhat greater than on the down-link (i.e. because higher up-link frequency is used); on the up-link it is assumed that when the signal fades by 10 dB, the cross-polarization isolation between co-channel signals reduces from 25 dB to 10 dB. It is also assumed that external and intrasatellite interferences are uncorrelated.

Fading on the down-link is assumed to be less than on the up-link, and under conditions of fading, depolarization is also assumed to be less, and the wanted to unwanted signal ratio is taken as 15 dB.

An example of the allocation of noise and interference under unfaded and faded conditions is set out in Tables I and II which follow.

TABLE I — *Example of possible up-link noise and interference allocations*

	dB below signal	
	Faded	Unfaded
1. Cross-polarized co-channel interference	10	25
2. Thermal noise plus other interferences	17	27
2.1 Intrasatellite interference (2 entries)	25	35
2.2 External system interference (equal to thermal noise)	21.7	31.7
2.3 Thermal noise	21.7	31.7

TABLE II — *Example of possible down-link noise plus interference allocations*

	dB below signal	
	Faded	Unfaded
1. Cross-polarized co-channel interference	15	25
2. Thermal noise plus other interferences	14.8	24.8
2.1 Intrasatellite interference (2 entries)	35	35
2.2 External system interference (2 entries)	25	35
2.3 Thermal noise	15.8	25.8

In the example it is apparent that the up-link has a better signal-to-thermal noise ratio than the down-link by about 6 dB. Moreover, for the degree of depolarization assumed under fading conditions it might seem that the use of 8-phase CPSK without frequency re-use could be more efficient. In fact this is not the case since 8-phase CPSK would require a signal-to-noise plus interference ratio of 18.8 dB and the total relative capacity of the system would be 25% less.

4. Summary

An attempt has been made to identify certain possible sources of interference in a digital system in the Fixed Satellite Service.

A possible link budget has been calculated based on the assumptions identified.

RECOMMENDATION 524

MAXIMUM PERMISSIBLE LEVELS OF OFF-AXIS e.i.r.p. DENSITY FROM EARTH STATIONS IN THE FIXED SATELLITE SERVICE TRANSMITTING IN THE 6 GHz FREQUENCY BAND

(Study Programme 2J-2/4)

(1978)

The CCIR,

CONSIDERING

- (a) that geostationary satellite networks in the Fixed Satellite Service operate in the same frequency bands;
- (b) that interference between networks in the Fixed Satellite Service contributes to noise in the network;
- (c) that it is necessary to protect a network in the Fixed Satellite Service from interference by other such networks;
- (d) that it is necessary to specify the maximum permissible levels of off-axis e.i.r.p. density from earth stations, to determine space station and earth station characteristics such as required protection ratios and minimum orbital spacing;
- (e) that networks in the Fixed Satellite Service may receive interference into the space station receiver;
- (f) that in many cases the largest interference contributions to a geostationary satellite network will be from the networks using the adjacent geostationary satellites and the value of interference from any other network will generally be less;
- (g) that the level of interference from an earth station into a space station in the Fixed Satellite Service operating in a frequency band below 10 GHz is not expected to undergo a large variation with time;
- (h) that the use of antennae with the best achievable radiation patterns will lead to the most efficient use of the radio-frequency spectrum and the geostationary satellite orbit,

UNANIMOUSLY RECOMMENDS

1. that future earth stations of networks in the Fixed Satellite Service transmitting in the 6 GHz frequency band be designed in such a manner that at any angle, φ , 2.5 degrees or more off the main-lobe axis of an earth station antenna, the e.i.r.p. per 4 kHz in any direction within 3 degrees of the geostationary satellite orbit should not exceed the following values:

<i>Angle off-axis</i>	<i>Maximum e.i.r.p. per 4 kHz</i>
$2.5^\circ \leq \varphi < 48^\circ$	$(35 - 25 \log \varphi) \text{ dB(W/4 kHz)}$
$48^\circ \leq \varphi \leq 180^\circ$	-7 dB(W/4 kHz)

2. that the following notes should be regarded as part of this Recommendation.

Note 1. — Enhanced orbit utilization and easier co-ordination would be attained with lower sidelobe e.i.r.p. values, and therefore, Administrations are encouraged to achieve lower values where practicable.

Note 2. — The values contained in § 1 above, have been derived mainly from an analysis of FM systems used for analogue television or multi-channel telephony and it is not known at the present time whether some types of single-channel-per-carrier (SCPC) systems comply with these provisions. Studies should be undertaken in order to determine how SCPC systems could comply with the values of § 1.

Note 3. — Wherever practicable, existing earth stations should comply with the values of § 1.

RECOMMENDATION 484-1 *

STATION-KEEPING OF GEOSTATIONARY SATELLITES USING FREQUENCY
BANDS ALLOCATED TO THE FIXED SATELLITE SERVICE

(Study Programme 2J-2/4)

(1974 - 1978)

The CCIR,

CONSIDERING

- (a) that the geostationary satellite orbit is of unique usefulness to telecommunications services;
- (b) that the interference imposes a limit on the number of satellites which may operate in the same frequency band on the same part of the orbit but the number will tend to increase as the degree of accuracy of station-keeping is improved;
- (c) that the number of satellites using this orbit for operational purposes is likely to grow significantly in the next decade;
- (d) that it is technically feasible to maintain satellite position to $\pm 0.1^\circ$; this applies primarily at present to satellites located at, or near, the stable points of the geostationary satellite orbit,

RECOMMENDS

that space stations on geostationary satellites using frequency bands allocated to the fixed satellite service:

1. should maintain their positions within $\pm 0.5^\circ$ of longitude of their nominal positions irrespective of the cause of variation; but
2. need not comply with § 1 as long as the satellite network to which the space station belongs does not produce an unacceptable level of interference into any other satellite network whose space station complies with the limits of § 1;
3. that the following Note will be considered part of this Recommendation.

Note. — In the more congested arcs of the geostationary-satellite orbit enhanced orbit utilization would be attained with smaller station-keeping tolerances, and therefore, Administrations are encouraged to maintain smaller tolerances where applicable.

REPORT 556-1

FACTORS AFFECTING STATION-KEEPING OF GEOSTATIONARY
SATELLITES OF THE FIXED SATELLITE SERVICE

(Study Programme 2J-2/4)

(1974 - 1978)

1. Introduction

On certain portions of the geostationary-satellite orbit, where satellite density is relatively light, station-keeping accuracy is not a prime requisite in limiting interference between systems. The introduction of new satellite systems will, however, increase the satellite density; therefore, in order not to restrict the development of new systems, it would be desirable to keep all satellites on station within a reasonable tolerance.

Report 453-2, considering some of the technical factors which affect the efficient utilization of the geostationary-satellite orbit, has drawn attention to the fact that the efficiency could be increased if the position of the satellites could be more closely controlled. The orbit capacity is only slightly impaired by moderate orbit inclinations, but the reduction in capacity could become substantial when longitudinal drift approaches a significant fraction of the satellite spacing. (See also Nos. 470VC, 470VD and 470VE of the Radio Regulations.)

2. Factors affecting the satellite position

When the longitudinal positions of satellites are subject to some uncertainty due, for example, to orbit drift or orbit inclination, a reduction in the potential geostationary-satellite orbit capacity will result. The extent of this reduction is related to the magnitude of the longitudinal variation and the nominal spacing between satellites. It can be shown, for example [CCIR, 1970-74], that a longitudinal variation of 1° for satellites which would need a separation of 5° if station-keeping were perfect, will reduce the efficiency of orbit utilization to 79% of the theoretical maximum, and that this efficiency would fall to 62% if the required spacing were reduced to 2.5° .

* The Administration of the People's Republic of China reserves its position with respect to this Recommendation.

Movement of geostationary satellites in longitude arises mainly from the following causes:

- orbital inclination;
- orbital period variations;
- orbital eccentricity;
- errors in determination of orbital elements.

These sources are considered separately in the following paragraphs.

2.1 *Orbital inclination*

The principal effect of the gravitational fields of the Sun and the Moon on a quasi-geostationary satellite is to change the angle of inclination of the orbital plane. For satellites in the equatorial plane, the initial rate of change of inclination is currently about 0.86° per year, but this value varies from year to year between 0.75° and 0.95° for astronomical reasons. The rate of change tends to decline as inclination increases. Seen from the Earth, orbital inclination causes a daily excursion of the satellite north and south of the equatorial plane. There is also a longitudinal component in this motion, the satellite moving in a figure-of-eight path. Fig. 1 shows the magnitude of this longitudinal motion; it is $\pm 0.12^\circ$ for an angle of inclination of 5° , and becomes increasingly significant for larger angles of inclination. The elimination of orbital inclination by the use of secondary propulsion systems places substantial demands upon the satellite propulsion unit at the present stage of technical developments.

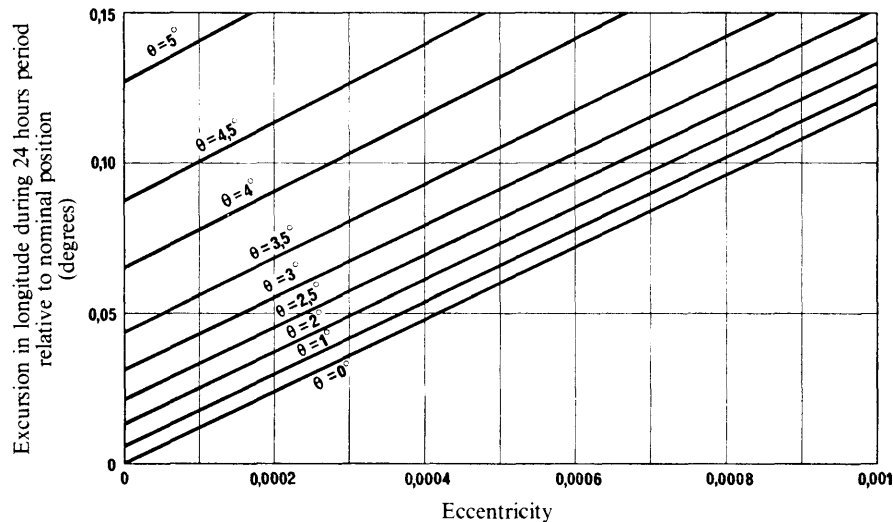


FIGURE 1 — *Maximum daily variation of longitude due to eccentricity and inclination of orbit*

θ: Inclination

Note. — The peak-to-peak daily deviation in longitude is twice the value indicated in the above figure.

2.2 *Orbital period variations*

At about 76.8° east and 108.1° west longitude, a satellite in the geostationary-satellite orbit which has been given an accurate initial orbital period will not drift either to the east or to the west. The Earth's gravitational field decreases around the geostationary-satellite orbit in both directions from these stable points. There are two points of unstable equilibrium located at approximately 161.8° east and 12.2° west longitude. At other points in the orbit, forces due to non-uniformities in the Earth's gravitational field will act upon a satellite so as to increase or reduce its period, causing the satellite to drift slowly to the east or west. The consequential error in longitude must be reduced to an acceptable value from time to time, and an accuracy of perhaps a few hundredths of a degree could be achieved given daily corrections. However, correction at this frequency raises technical difficulties, since it is necessary to establish orbital elements after each correction to measure the effect achieved. An accuracy of 0.1° involving corrections perhaps every few weeks, should be readily achievable.

To change the longitudinal position of a geostationary satellite requires at least two operations of the east/west station-keeping thrusters – one to start the drift and the second to stop it. Drift rates of 1° per day or 10° per day are realized by changes in the orbital velocity (ΔV) of about 2.8 m/s or 28.5 m/s, respectively. These velocity changes may be compared with those required for the normal station-keeping operation of a geostationary satellite. Satellite specifications have typically required a total ΔV capability of about 53.5 m/s per year of which north/south station-keeping accounts for about 50 m/s per year, east/west station-keeping accounts for 2.5 m/s per year and attitude control requirements account for an equivalent of about 1 m/s per year. Therefore, a single repositioning manoeuvre at the rate of 10° per day (total ΔV required is 57 m/s) is equivalent to about 13 months of normal east/west and north/south station-keeping. If the propellant were hydrazine, with a specific impulse of about 220 s, and the satellite had a mass of 1000 kg, then 26 kg of hydrazine would have been expelled to reposition at a rate of 10° per day irrespective of the total longitudinal change.

2.3 *Orbit eccentricity*

Eccentricity of the satellite orbit causes a daily longitudinal excursion of apparent position. Thus can eccentricity of 0.001 cause an excursion of $\pm 0.12^\circ$ about the mean position (see Fig. 1). Although eccentricity can be reduced to any desired extent upon initial injection into a geostationary orbit, it will change with time. The main cause of the change in eccentricity is solar radiation pressure which causes the eccentricity to vary cyclically over the year. The extent of this annual variation is likely to be in the range 0.0002 to 0.002 for current and foreseen satellite configurations, depending upon the ratio of the projected area to the mass of the satellite. If uncorrected, it has been shown in some studies that this will cause a maximum daily longitudinal excursion in the range $\pm 0.02^\circ$ to $\pm 0.25^\circ$ at the peak of the cycle. However, it should be possible to reduce this considerably by suitable correction every few months.

2.4 *Errors in determination of orbital elements*

The precision with which a satellite can be maintained in its designated longitudinal position depends to some extent upon the accuracy with which its orbital element can be determined. However, given suitably located measuring stations and appropriate measuring techniques it is certainly possible to determine satellite angular positions to better than 0.005° . Thus, the uncertainty in longitude due to errors of measurement could be made negligible.

3. *Present capability*

The INTELSAT and the Canadian ANIK-I spacecraft have successfully demonstrated that a station-keeping capability of $\pm 0.1^\circ$ can be achieved with little or no propellant penalty. Station-keeping of this order does not seriously affect the life of the spacecraft. It should be noted, however, that an increase in the precision of station-keeping entails an increase in the computing capability and associated costs.

This applies primarily at present to satellites located at or near the stable points of the orbit.

4. *Conclusions*

To sum up, it is an important objective for geostationary satellites to be maintained with high standards of station-keeping, taking into account all possible kinds of apparent satellite movement (longitudinal residual movement, residual orbit eccentricity and orbit inclination) as well as the accuracy with which the actual position of the satellite can be determined.

As the minimum required satellite spacing can be decreased by improved communication techniques, the ultimate orbit capacity will become more and more a function of the achievable satellite station-keeping tolerance and all possible technological means of attaining reduced station-keeping tolerances should be explored.

REFERENCE

CCIR Document

[1970-74]; 4/15, (United Kingdom).

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REPORT 453-2

**TECHNICAL FACTORS INFLUENCING THE EFFICIENCY OF USE OF THE
GEOSTATIONARY SATELLITE ORBIT BY RADIOCOMMUNICATION SATELLITES
SHARING THE SAME FREQUENCY BANDS**

General summary

(Study Programme 2J-2/4)

(1970 - 1974 - 1978)

1. Introduction

This Report responds to Study Programme 2J-2/4 and has made extensive use of the reports of Interim Working Party 4/1, which was set up in Geneva, September, 1968. Its current terms of reference are in Decision 2-2.

The first meeting of the Interim Working Party was in Ottawa, from 10 to 13 June, 1969, and the report is given in [CCIR, 1969] of the Geneva meeting, September, 1969. There was a second meeting of the Interim Working Party in London from 19 to 23 October, 1970 and the report is given in [CCIR, 1970-74a]. The reports of the third meeting (Melbourne, 1 to 5 October, 1973) and of the short fourth meeting (Geneva, 5 to 6 March, 1974) are [CCIR, 1970-74b], respectively. The report of the fifth meeting (Munich, 3 to 6 June 1975) is [CCIR, 1974-78a]. The report of the sixth meeting (Washington, 25-29 April 1977) is referenced [CCIR, 1974-78b]. Many other contributions, however, have been drawn upon for the revision of the present Report.

Some remarks of a fairly general character should be made before discussion of the more complex technical factors. First, it must be recognized that the maximum coverage of the surface of the Earth from any one satellite in the geostationary orbit, despite the undoubted advantages of this orbit, is limited by geometrical considerations, especially in regard to the coverage of high-latitude regions of the Earth. Because of these considerations, there could arise multiple and perhaps competing demands upon certain parts of the orbit which might then become congested at an early date. This depends upon geographical factors, distribution of population, demand for telecommunication services, etc. On the other hand, other parts of the geostationary-satellite orbit might be little used for a number of years to come.

The difficulties which could arise in congested parts of the orbit must, therefore, be met in advance by considering all the major technical factors which govern the minimum separation needed to avoid interference between satellites employing common frequencies. The present Report provides a summary of the technical factors involved and makes reference to other Recommendations and Reports of Study Group 4 where these are relevant. Overall treatments of the subject are also given in [Jowett and Jefferis, 1969; Fuenzalida, 1969].

This Report is concerned primarily with technical factors, although some reference is made in it to other factors, mostly operational. It should, however, be emphasized that other factors are also of the greatest importance in achieving efficient use of the geostationary-satellite orbit and the frequency spectrum. Most important of all, perhaps, is the effective use of the procedures established by the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, for the co-ordination of frequencies assigned to space and earth stations. Articles 7 and 9A of the Radio Regulations refer. See also Report 454-2.

Finally it should be noted that this Report is concerned with general principles. Reference should be made to other Reports for information on the specific technical problems of orbit and spectrum sharing, and in particular to Reports 388-3, 390-3 and 455-2 as well as Reports 555-1, 556-1, 557, 558-1, 559 and 561-1.

The contents of this Report are as follows:

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 - 2.2 Polarization discrimination advantage
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2. Factors affecting the relationship between the nominal angle of separation and carrier-to-interference ratio

2.1 *Radiation diagrams of earth-station antennae*

The radiation pattern of the earth-station antenna, more particularly in the first 10° from the principal axis and in the direction of the geostationary-satellite orbit, is one of the most important factors in determining the interference between systems using geostationary satellites. A reduction in side-lobe levels would increase the efficiency of utilization of the geostationary-satellite orbit significantly.

It should be recognized that antenna patterns considerably better than the reference radiation pattern given in Recommendation 465-1 may be achieved by careful control of the side-lobe levels. High side-lobe response is caused mainly by scattering from blockage in the aperture of the antenna. There are antenna configurations which have no such blockage and their use desirable. Some ways in which the constructional features of Cassegrain-type earth-station antennae may be designed so as to reduce side-lobe radiation are discussed in Report 390-3.

For example, a study has been made [CCIR 1974-78c] that indicates an orbit utilization efficiency improvement of about 200% could be obtained by either of the following improvements in the side-lobe envelope of the earth station antennae, assuming an initial satellite spacing of 5° :

- change of the angular gain decay exponent from an assumed value of -2.5 to a new value of -3 (Fig. 1a);
- reduction of the level of all side-lobes by 7 dB. This applies to any value of satellite spacing (Fig. 1b).

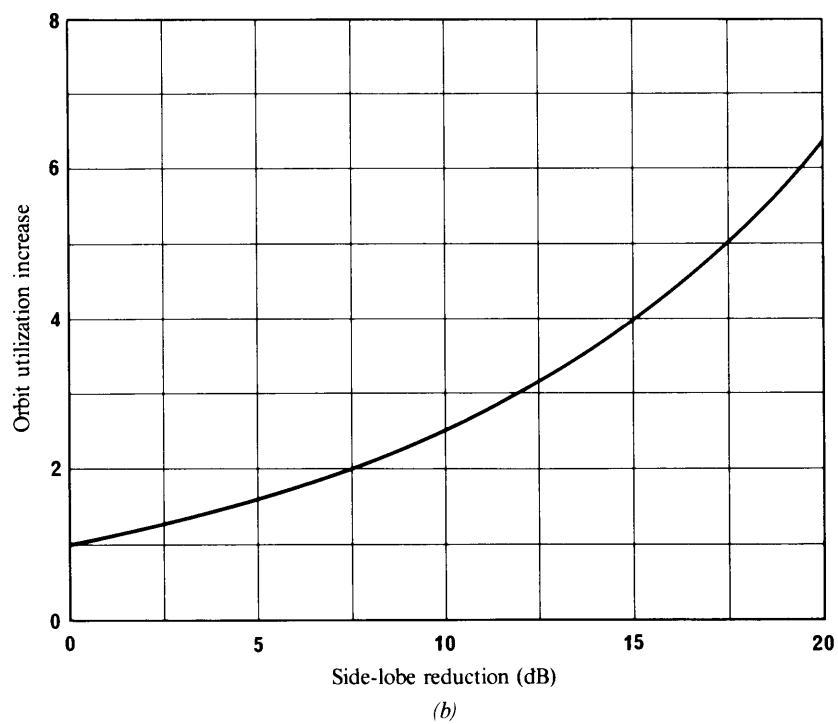
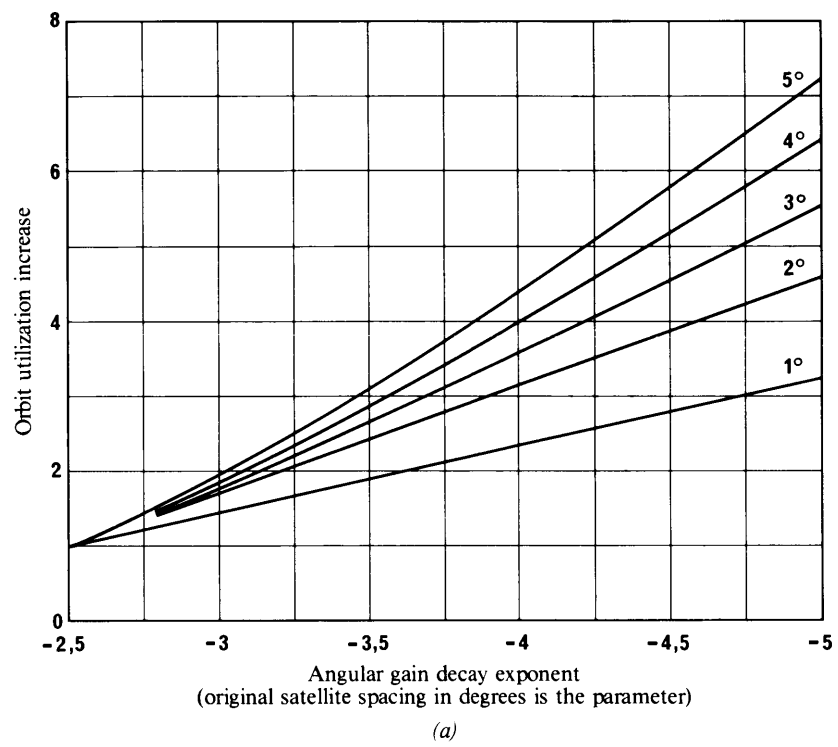


FIGURE 1 — Effect of side-lobe reduction of earth station antenna in global beam system

It is thought that the use of off-set feed geometry for small and medium-sized antennae is becoming feasible but it is not yet clear whether the use of such techniques for large antennae would involve undue economic penalties. Nevertheless it would be desirable for a recommendation to be made soon on the maximum side-lobe levels of earth-station antennae. For large antennae operating in the 4 and 6 GHz frequency bands, it might be appropriate to use the pattern given in Recommendation 465-1.

It would be desirable to establish a design objective for the side-lobe level of new antennae. This would be somewhat more stringent than the performance recommendation proposed in the previous paragraph. One law suggested for antennae with $D/\lambda > 100$ is as follows:

- for side-lobes directed within 3° of the geostationary satellite orbit,
 $G(\varphi) \leq 28 - 25 \log \varphi$ (dB) for $1^\circ \leq \varphi \leq 83^\circ$
 $G(\varphi) \leq -20$ (dB) for $\varphi > 83^\circ$
- for other directions, the envelope in Recommendation 465-1 would apply.

However, further consideration needs to be given to the values to be specified for the design objective.

It is evident that orbit utilization efficiency is enhanced when systems using earth stations with both high gain and a high figure-of-merit (G/T) are involved.

2.2 Polarization discrimination advantage

The use of orthogonal linear or circular polarizations should permit discrimination to be obtained between two emissions in the same frequency band from the same satellite or from closely adjacent satellites. This will augment discrimination provided by the directional properties of satellite and earth-station antennae. A detailed discussion of this topic is to be found in Report 555-1.

Until more general information is obtained on the polarization discrimination achievable in the main beam of a variety of types of satellite and earth-station antennae, and until a better understanding is obtained of the extent of irremovable propagation degradations of wave polarization, some doubt remains as to whether it will be possible to achieve the 20 to 30 dB of discrimination that is required for in-beam frequency re-use.

If adjacent single-polarization satellites use orthogonal linear or circular polarizations, it may be possible to use the polarization discrimination in the side-lobes of the earth-station antennae to reduce interference between the satellite networks, and to allow satellite spacing to be reduced. It is already clear that the side-lobe polarization discrimination obtainable in this way will be small, although even a few decibels of discrimination would permit a significant reduction in satellite spacing. However, it would not be possible to realize even this benefit in a systematic way unless and until preferred polarization characteristics have been adopted. This would need to involve a choice between linear and circular polarization and, where linear polarization is adopted, a choice of the preferred planes of polarization. There is not, at present, sufficient information to allow these choices to be made.

Further study of these matters is proposed in Study Programme 2J-2/4. A new Recommendation may be desirable to give preferred types of polarization, linear or circular, under specified conditions of frequency, beamwidth, etc., and recommending high standards of cross-polar discrimination, even in networks which do not employ both modes of polarization.

The use of polarization discrimination, whichever form of polarization is used, may permit the re-use of frequency within the same satellite beam. The channel capacity increases that can be achieved, given the necessary wanted-to-unwanted carrier ratios for the overall links, have been studied [CCIR, 1970-74c] and the following main conclusions have been reached:

- for similar co-channel FDM/FM emissions, wanted-to-unwanted carrier ratios in the range 23–31 dB would be sufficient to limit mutual interference to 1000 pWp. Given that ratio, the total channel capacity for a bandwidth-limited system would be increased by 60% for no increase in the total down-path power, and by 100% given twice the total down-path power. There would be no increase in capacity if the satellite system were power-limited;
- for similar co-channel 4-phase PCM/PSK emissions, and for a bit error rate of 10^{-4} , a wanted-to-unwanted carrier ratio of about 20 dB and an increase in the total down-path power of 4 dB would permit the total channel capacity to be doubled. For 8-phase PCM/PSK emissions, the corresponding carrier ratio would be about 25 dB;
- by interleaving the carrier frequencies, the required wanted-to-unwanted carrier ratios for FDM/FM emissions would be reduced. No corresponding advantage is foreseen with digital transmission. See § 3 below.

In another study [CCIR, 1974-78d], two possible applications are considered:

Model I: use of orthogonal polarizations on adjacent satellites to permit closer satellite spacing;

Model II: frequency re-use on a single satellite by means of orthogonal polarization within the main beams.

Calculations made for a homogeneous case by the method given in Annex II of Report 711 gave the following results:

For Model I, values of 10-15 dB of cross-polarization discrimination of the earth-station antenna side-lobe and the satellite antenna main-lobe lead to a significant improvement in bandwidth and orbital arc utilization. For Model II, 25 dB of cross-polarization discrimination of the earth-station antenna main-lobe and the satellite antenna main-lobe and about 10 dB of earth station side-lobe polarization discrimination is sufficient to improve the bandwidth and orbital arc utilization.

Further, a comparison of the improvements achieved by the two models, for a wide range of polarization discriminations, shows that Model II always achieves the larger improvement in bandwidth and orbital arc utilization.

2.3 *Frequency re-use by means of narrow-beam satellite antennae*

The use of the same carrier frequencies to serve different areas on the surface of the Earth by adjacent geostationary satellites can be greatly facilitated by the use of satellite antennae having an effective beamwidth much less than the angle which the Earth subtends at the geostationary orbit. This means that the angular separation between the earthward beams is less than 17° and that, to obtain the necessary discrimination between the wanted signal and the unwanted signal, the main-lobe patterns of satellite antennae should conform to the coverage areas as closely as possible, this being attainable by beam shaping in the plane normal to the direction of propagation. It should, however, be noted that it will be necessary to study ways in which the concept of coverage area should be defined. In addition, beam shaping within the coverage area is desirable in order to maximize the satellite e.i.r.p., particularly towards the earth stations in the coverage area. Also, shaped beams can contribute to efficient orbit utilization through spectrum re-use and reduction of interference through the generation of a variable pattern. The status of shaped beams developed as reported by various organizations is indicated in Table I. However, unless the capability exists for re-shaping the beam on board the satellite, efficiency may be reduced through the lack of orbital position flexibility. The discrimination offered by the use of cross-polarization can generally be used to increase the effective side-lobe discrimination and can thus be employed to decrease the angular separation required between beams or to increase the possible beamwidths. Under certain circumstances, the same satellites may also transmit separate information on the same frequencies twice over or even a greater number of times using antennae serving different parts of the world.

The radiation outside the coverage area of satellite antennae should be controlled. The utilization of techniques to reduce the first side-lobe level, and to increase the attenuation of further side-lobes, which illuminate the Earth, is to be encouraged. In this respect studies of satellite antenna types have shown lower side-lobe levels for those configurations which do not have blockage in the aperture. However, the design of complex systems without aperture blockage presents problems which are not yet fully understood. The radiation levels outside the desired coverage area can also be reduced by the use of large apertures with tapered illumination. It should, however, be recognized that the use of a large aperture raises spacecraft size and mass problems; furthermore, the use of tapered illumination shapes the main beam, causing a rapid fall in gain at its edge, and so makes more stringent the requirements for satellite attitude and orbital control when area coverage is required. (It should, however, be noted that beam shaping may reduce the required precision of attitude and orbital control in some cases, e.g., when the coverage area is unavoidably greater than the service area.) For further discussion of these matters, see Report 558-1.

In order to facilitate studies on the re-use of spectrum by narrow satellite antenna beams, the adoption of a reference satellite antenna pattern may be desirable. However, the design of a satellite antenna is influenced by various system parameters, such as size and shape of the coverage area, required minimum gain, limitation of aperture size and flux-density, etc. Thus, it is rather difficult to define a satellite antenna reference pattern which will be applicable to the large variety of complex patterns which may be utilized.

The advantages of frequency re-use may not be fully realized if the control of the satellite beam position is inadequate. However, no substantial reduction of these advantages is likely so long as the spacecraft antenna beam position can be held to within a small fraction, 0.2 or less, of its beamwidth. For example, the 0.5° beamwidth achievable today can utilize this technique if the beam position is held to within $\pm 0.1^\circ$, which is feasible. In the case of narrow satellite antenna beams the following benefits of improved beam pointing accuracy are noted:

- Firstly, there is a reduced potential for interference between satellite networks with coverage to neighbouring service areas.
- In addition, there is the possibility of designing for a closer relationship between the coverage area of the beam and its required service area. This would result in a consequent increase in antenna gain and off-beam discrimination to further reduce the potential for interference between satellite networks.

Satellite antennae should be designed so that the satellite may be re-positioned in the geostationary-satellite orbit and still provide the required service in its coverage areas.

TABLE I — *Summary of shaped beam antenna development*

	LENS				REFLECTOR				
	Lincoln Labs	Raytheon	Hughes	GE	Lockheed	Fairchild	Ford Aerospace	JPL	Std. Circular Aperture
HPBW (spotbeam) ⁽¹⁾	3°	4°	2°	2°-3°	1.5°	2.5°	2°		2.7°
Spotbeam Gain	30 dB	28 dB	40 dB	≈ 40 dB (est.)	36 dB				37.5 dB
Widebeam Coverage	EC 17.3°	EC ⁽²⁾	5° with 3 feeds	EC 18°	Hemisphere	CONUS & ETZ ⁽³⁾	CONUS or Zone	ETZ	—
Widebeam Gain	20 dB	28 dB	≈ 35 dB	probably 30 dB, est.	29 dB				—
No. of feeds/beams	19	500	7	19 + 61	16	8 for ETZ	48	7 × 9 elements	1
Bandwidth	5-10%	Octave	250 MHz	8%	8%	waveguide feed	waveguide feed		waveguide feed
Frequency Band	X-Band	X-Band K-Band	X-Band	X-Band	4/6 K-Band	K-Band	X-Band		X-Band
Power Handling	high	limited by stripline	high	high	high	high	high		high
Calculated Aperture Efficiency (spotbeam)	≈ 50%		50% measured	50% measured	55%				56%
Form factor/Complexity	moderate	moderate	moderate	moderate to high	simple	brassboard	simple		—
Sidelobe level-Secondary beam	20 dB	22 dB	30 dB	15-20 dB for 19 beams	30 dB	16-25 dB	30 dB		30 dB
Feed type	circular horn	Rotman lens stripline	circular horn	circular horn	dielectric loaded sq. waveguide	dielectric loaded sq. waveguide	square horn		
Antenna type	waveguide lens	annular slot array	waveguide lens	waveguide lens	offset-fed reflector	offset-fed reflector	offset-fed reflector		centre-fed parabolic reflector
Aperture diameter	76.2 cm	1.22 to 1.52 m	2.13 m	71.1 cm to 114.3 cm	1.83 m		1.05 m		
F/D ratio					0.6	0.6	0.4		
Off-axis scan	± 8°	± 25°	± 9°		± 9°				

⁽¹⁾ High power beamwidth.⁽²⁾ Earth coverage.⁽³⁾ "Continental" and "East Time Zone".

2.4 *Satellite station-keeping*

When the longitudinal position of geostationary satellites is subject to some uncertainty due to orbital drift or orbital inclination, a reduction in the potential geostationary orbit capacity will result. Capacity is only slightly impaired by moderate orbital inclinations, but is greatly reduced when longitudinal positional drifts approach values comparable with the minimum permissible satellite spacing. The factors affecting the positioning of satellites and the accuracy of station-keeping that is technically feasible at present are considered in Report 556-1.

The Radio Regulations require all satellites to be maintained within $\pm 1^\circ$ of the longitude of their nominal position if this is necessary to prevent unacceptable interference in any other satellite network, and urges that efforts should be made to develop spacecraft and control facilities to achieve a capability of maintaining their positions at least within $\pm 0.5^\circ$ of the longitude of their nominal position. *

As the various available means are taken into use to reduce the minimum necessary spacing between satellites, the impact of errors in station-keeping will become increasingly serious. A study of homogeneous orbit occupation by systems used for FDM/FM transmissions has been made [CCIR, 1970-74d]. Some of the results are shown in Fig. 2. There it will be seen that large improvement in total orbit capacity may be obtained both by increasing the interference noise allowance and by increasing the modulation index, if it may be assumed that satellites will remain on their assigned positions within say $\pm 0.2^\circ$. However, not only is the capacity of the orbit reduced, with transmission parameters unchanged, but the advantage of increasing the interference noise allowance is greatly reduced if satellites drift $\pm 0.5^\circ$ from their nominal positions, and the trend in favour of a larger modulation index may even be reversed.

2.5 *The use of frequency bands allocated for the Fixed Satellite Service for both up-paths and down-paths*

It may be feasible to increase the number of satellites using a pair of frequency bands in a given arc of the geostationary-satellite orbit if the frequency assignments are reversed between adjacent satellites, the up-path band assigned for one satellite being the down-path band for the next. This technique may, to some extent, compete with other methods of increasing the capacity of the orbit such as the use of high-gain satellite antennae or polarization discrimination to reduce interference between alternate satellites and it may make necessary some worsening of the sharing criteria in frequency bands shared with terrestrial services. Nevertheless, it is of interest and should be studied further. See Reports 557 and 561-1.

If, in the future, it should be found that this technique is of value, it will be desirable for Administrations to determine which shall be the preferred direction of transmission for each frequency band. A responsibility might then be placed upon systems using bands in the mode which is not preferred to be particularly attentive to site screening at earth stations where this will reduce interference to earth stations using the same frequency bands in the preferred mode.

A method has been identified for employing frequency bands in the reverse direction which could significantly reduce earth station costs. Given two band pairs, each pair representing an up- and a down-path allocation under the present "direction" constraint, it might appear beneficial to a systems designer to utilize a reversal mix between the two band pairs such that one band pair in its entirety is utilized in one direction, the other in the other direction. Since band pairs, as conventionally used, are close to each other in the frequency domain, one could establish a network with twice the bandwidth of the narrower band-pair, as conventionally used. In addition, propagation conditions would be approximately uniform at all up-path frequencies and approximately uniform at all down-path frequencies.

A demonstrative example would be the band pairs 6/4 and 14/11 GHz allocated to the Fixed Satellite Service. If both the 14 and the 11 GHz bands were used as up-path bands, and both the 6 and 4 GHz bands as down-path bands, down-path margin requirements (similar and moderate at both 6 and 4 GHz) would be substantially relieved, with the burden placed on the up-path. Total bandwidth would be 1 GHz, and the 6 and 11 GHz bands would be used in a direction opposite to that of the present allocations.

However it should be noted that the earth stations of such a network might have to be separated geographically from the earth stations of other networks using these same bands, either conventionally or in the reverse of the conventional mode, to reduce frequency co-ordination problems. Furthermore, this arrangement does not provide the prospective improvement in orbit and spectrum utilization referred to in the first paragraph of this section.

* See Nos. 470VC, 470VD and 470VE of the Radio Regulations.

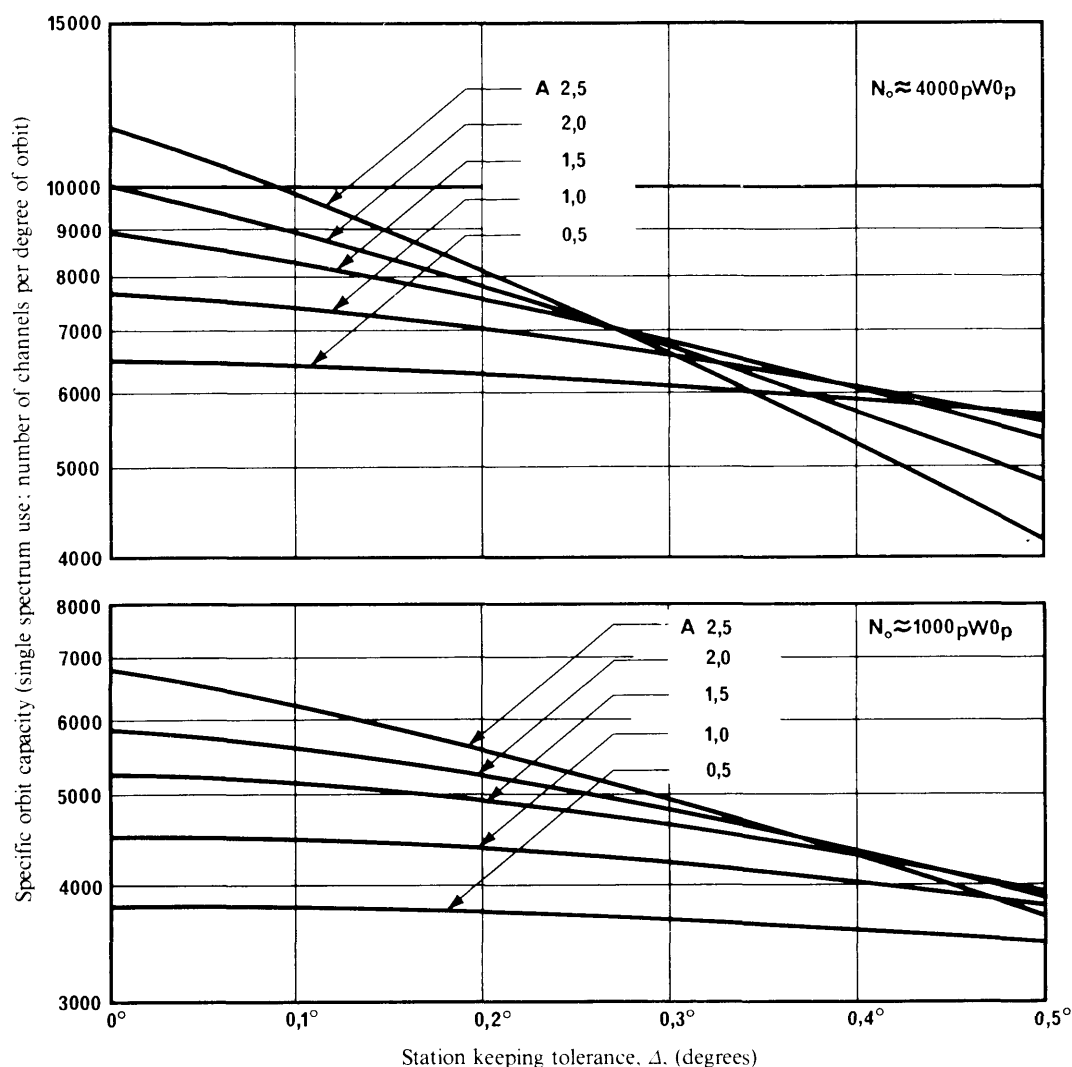


FIGURE 2 — Specific orbit capacity vs. station-keeping tolerance for two values of interference noise allowance, with r.m.s. modulation index as a parameter

Homogeneous system
Global satellite antenna beams
Earth-station antenna diameter 85 feet (26 m)
CCIR earth-station reference antenna pattern
Bandwidth = 500 MHz

A : r.m.s. Modulation index

2.6 Modulation conversion transponders

The examination of technical factors affecting the utilization of the geostationary satellite orbit has been made in most cases for systems providing communications in the Fixed Satellite Service only. However, the Fixed Satellite Service is also used specifically to provide up-links to satellites (e.g. broadcasting-satellites) in other Services and therefore may involve technical characteristics not necessarily optimum from the standpoint of bandwidth/orbital arc utilization. In these cases, other criteria may be more important in achieving system designs. In a particular case the available frequency spectrum could be used economically by means of special techniques, e.g. modulation conversion in the satellite. This technique may lead to a more efficient utilization of up-link fixed-satellite frequency bands used for other services and may also simplify the co-ordination between systems in congested regions of the orbit.

One means of efficient utilization of the up-link frequency spectrum is the application of narrow band FM, which can be accomplished relatively simply. With more advanced digital modulation techniques the available frequency band may be utilized more efficiently than with FM, although at the cost of an increased complexity of the transponders, due to the digital to analogue conversion.

3. Relationship between input carrier-to-interference ratio and baseband performance

3.1 *Co-channel carriers*

Quantitative studies of orbit and spectrum use require that the relationships between input carrier-to-interference ratio and baseband performance for various modulation systems be known. This is a specific technical problem which need not be considered in detail in this Report. Report 388-3 and its bibliography provide a good summary of the conclusions on this subject. Report 449-1 gives the results of subjective and objective measurements of the effect of interference between frequency-modulated television signals.

3.2 *Interleaved carriers*

In certain cases interference between two networks may be reduced by interleaving the carrier frequencies. The advantage that may be obtained in this way is discussed in Report 455-2 § 4.

Use of energy dispersal with FM carriers is of primary interest when interference between the Fixed Satellite Service and terrestrial service is considered. Energy dispersal also reduces interference between satellite networks when the interfering carriers are close in frequency. However, the same situation does not always exist when interference between networks within the Fixed-Satellite Service is considered because of the large modulation index used. When considering the possibilities of increasing the efficiency of utilization of the geostationary satellite orbit by separation of carrier frequencies, account should be taken of the fact that the advantage of that technique is smaller when energy dispersal is used as compared with the use of no energy dispersal.

For 4-phase PCM/PSK systems, no advantage is generally obtainable by interleaving the carrier frequencies.

When a satellite network employs frequency re-use by polarization or spot-beam discrimination and FDM/FM, frequency interleaving may provide a useful reduction in the discrimination required. However, for networks which do not have frequency re-use within the network, the sacrifice of the bandwidth of half a broadband channel which frequency interleaving requires is objectionable. Furthermore, where a particular system has more than one satellite in operation and where earth stations are required on occasion to operate with one or the other of these satellites, then the application of frequency interleaving between the two satellites would result in increased earth-station complexity and cost. Furthermore, in the space segment, the advantages of a standard satellite design would be lost.

In view of the above considerations and the discussion in Report 455-2 § 4, the advantages of frequency interleaving between satellites may, in practice, be restricted to relatively few applications.

4. Allowance for inter-system interference noise

Theoretical studies show that greater capacity can be obtained from the geostationary-satellite orbit if a large part of the noise budget is allocated to interference between satellite systems. For example, below 10 GHz and in the absence of frequency re-use within individual satellite networks, it is estimated that the total capacity of a busy arc of the orbit might be increased by at least 75% if the inter-network interference noise component were raised from 10% of total noise to about 50% of total noise; an increase in the permissible single entry interference allowance for FDM/FM telephony from 400 pWp to 1000 pWp is estimated to increase the capacity of the orbit by approximately 20%.

This matter is considered in some detail in Report 455-2 § 3.

5. The effect of modulation characteristics on orbit/spectrum utilization

Studies have been made [CCIR, 1970-74e, f, g] of the effect of modulation characteristics on orbit/spectrum utilization.

For FM systems, as the modulation index is increased, the capacity per satellite is reduced but the baseband noise density due to interference at a given carrier-to-interference ratio falls, permitting closer satellite spacing and generally resulting in an increase in the efficiency of use of the geostationary-satellite orbit. For digital transmissions using PSK, similar conditions exist, that is, the interference immunity of a signal is increased as the number of phases is reduced, again allowing closer satellite spacing. However, in this case, the utilization of the geostationary-satellite orbit tends to be optimized when the number of phases is in the range of four to eight, the orbit utilization tending to be decreased as either a higher or a lower number of phases is utilized.

In the case of angle modulated interference from a number of equi-distantly spaced satellites into a PSK transmission, the interference effect shows a pronounced threshold characteristic in terms of the distance between the satellites. A reduction of the satellite spacing below the threshold results in a rapid increase of the interference

effect. CCIR studies [CCIR, 1974-78e and f] indicate the dependency of this threshold characteristic on various parameters such as permissible error rates, number of carrier phases, earth station antenna radiation pattern and number of interfering satellites.

The relationship between modulation characteristics and other factors that affect orbit utilization is considered in more detail in Report 559. See also § 8.

6. Off-axis radiation level from earth station antennae

The following information, which relates in particular to the 6 GHz band, is provided as a basis for the development of a Recommendation which would increase the efficiency of orbit utilization while permitting reasonable conditions of utilization for many newly developing applications.

The establishment of a recommended limit for off-axis spectral e.i.r.p. density can be approached from two viewpoints:

- limitation of the interference level entering another satellite taking particular account of interference to networks employing large earth-station antennae,
- determination of the on-axis e.i.r.p. requirements for earth stations, particularly those employing relatively small antennae and consideration of the on-axis and off-axis gain that such antennae could be expected to provide.

An examination from both viewpoints has led to a tentative conclusion that the recommended limit should take the following form for up-path emission at about 6 GHz.

At any angle, ϕ , 2.5 degrees or more off the main-lobe axis of an earth station antenna, the e.i.r.p. per 4 kHz in the direction of the geostationary satellite orbit should not exceed the following values:

<i>Angle off-axis</i>	<i>Maximum e.i.r.p./4 kHz</i>
$2.5^\circ \leq \phi \leq 25^\circ$	$(E - 25 \log \phi) \quad \text{dB(W/4 kHz)}$
$25^\circ < \phi \leq 180^\circ$	$(E - 35) \quad \text{dB(W/4 kHz)}$

where the value of E would be within the range 32.0 to 38.5. The value of E should be as small as practicable, and will vary from one frequency band to another.

From the viewpoint of tolerable interference into a satellite network with large station antennae, it may be noted that a value of 38.5 for E would permit a maximum e.i.r.p. density of 21.0 dB(W/4 kHz) to be radiated from an earth station at 5° off-axis.

From the viewpoint of the reasonable requirements of earth stations with small antennae, four Cases that might be considered are:

- high density FM carrier – large station.
- FM-TV – small station (global satellite antenna).
- FM-TV – broadcast satellite up-link.
- single-channel-per-carrier (SCPC) – narrow band.

Assuming the following,

- the satellite noise temperature ≤ 3000 K;
- the satellite antenna gain ≥ 16 dB;
- the earth station antenna conforms to Recommendation 465-1 for off-axis angles less than 25° , but the side-lobe envelope has a constant level of -3 dBi beyond 25° ;
- $10 \log_{10}$ (earth station noise temperature) ≥ 19 .

(Values for the minimum power density at an off-axis angle of 5° are shown in Table II).

The worst interference would be from Case 2 where a 53 dB gain corresponds to a 10 metre diameter antenna. The required transmitter power would be about 500 watts. With 27 dB (2 MHz) of spreading advantage, the nominal transmit power density would be 0 dB(W/4 kHz) resulting in an off-axis radiation of 14.5 dB(W/4 kHz) at 5° .

TABLE II — Minimum off-axis power density for typical carriers

	FDM-FM 1332 channels 36 MHz RF bandwidth	FM-TV	FM-TV broadcasting satellite up-link	SCPC global
Satellite G/T (dB)	- 7	- 17	0	- 17
Up-link C/T (dB(W/K))	- 125	- 137	- 134	- 154
e.i.r.p. (dBW)	82	80	66	63
Earth station antenna transmit gain (dB)	60	53	46	53
RF power input to earth station antenna (dBW)	22	27	20	10
RF spectral power density input to earth station antenna (dB(W/4 kHz))	- 8	0	- 4	0
E_{5° (dB(W/4 kHz)) ⁽¹⁾	6.5	14.5	10.5	14.5

⁽¹⁾ Radiation at 5° assuming $32 - 25 \log \varphi$ relationship.

While Case 4 indicates a similar value for off-axis power density radiations, other factors must be considered. Single-channel-per-carrier (SCPC) are low level carriers with a nominal earth station transmit level of 63.5 dB(W/channel). Since TV normally only has spreading at a slow rate (25 or 30 Hz), it is considered that the total carrier power must be considered as pulsed interference. In this case, at 5° the C/I would be 22 dB on the up-link and 13 dB on the down-link. While criteria for interference in these cases do not exist, an overall C/I of 20 dB has been adopted in some analyses for such pulsed interference. Recognizing the severe incompatibility of this situation, the conclusion is reached that adequate protection is not reasonably attainable by satellite separation nor by more severe e.i.r.p. restrictions since the down-link is dominant. One solution is to restrict the uses of the two types of signals such that they would also be separated in frequency where the Fixed Satellite Service is involved on both up- and down-links. A second solution which might considerably relieve the problem noted above is a different method of carrier energy dispersal for television by transformation of the video signal as described in § 5 of Annex II of Report 384-3.

Two examples from the Canadian Telesat system [CCIR, 1974-78g] show that at 6 GHz and an off-beam angle of 5° , a level of unwanted e.i.r.p. density in the approximate range 17-18 dB(W/4 kHz) is associated with single-channel-per-carrier transmissions from a 4-5 metre diameter antenna and with TV transmissions from a 10 metre diameter antenna.

Based on the foregoing, it is tentatively concluded that the utilization of the geostationary satellite orbit at about 6 GHz could be protected, while permitting earth stations with antennae as small as 4 or 5 metres in diameter to be used, by applying the following guidelines:

- care should be exercised in frequency planning to ensure that television transmissions in one network do not use the same frequencies as single-channel-per-carrier telephony transmissions in a network using a nearby satellite;
- in all other cases, earth stations should conform to the off-axis e.i.r.p. spectral density limits in the direction of the geostationary satellite orbit indicated in the third paragraph of this section, the value of E probably lying within the range 32.0 to 38.5;
- earth-station antennae should be designed for minimum side-lobe gain in the range 2° to 30° off-axis, particularly in the direction of the geostationary satellite orbit.

The value to be assigned to E for application in frequency bands other than 6 GHz requires further study.

7. Frequency-band pairing

7.1 *Pairing of frequency bands allocated to the Fixed Satellite Service*

The Table of Frequency Allocations of the Radio Regulations designates frequency bands in the Fixed Satellite Service for Earth-to-space use and for space-to-Earth use. However, the Radio Regulations do not require a satellite to use a specific pairing of bands in this regard. Utilization of the geostationary satellite orbit and the frequency spectrum would be made more efficient, and co-ordination of satellite networks would be facilitated if certain frequency bands were paired.

For historical reasons, the 6 and 4 GHz frequency bands are commonly used in existing and planned fixed-satellite systems, and the 14 to 11 GHz bands are likely to be used together soon. The studies made so far (Study Programme 2J-2/4 Decides 5 refers) have not yet identified any particular pairings as the best technical arrangement. Indeed, the results obtained so far indicate that there are no very strong technical reasons for preferring one pairing to another. Nevertheless, it is considered that the following technical factors should be taken into account in pairing frequency bands for satellites of the Fixed Satellite Service:

- Current practice. It is desirable to retain the up-path and down-path frequency band pairing that is commonly used in existing networks and new networks now at the planning stage.
- Antenna feed design. At many space stations and most earth stations, a common antenna system serves for transmitting and receiving. The design of the feed system would be simplified if the ratio of up-path to down-path frequencies lay between 1 : 1.25 and 1 : 2.
- Propagation conditions. It will usually be economically desirable for a down-path frequency band in which earth terminal diversity is not required, to be paired with an up-path frequency band where similar propagation conditions are found. Differences in the relative suitability of circular and linear polarization at different frequencies may also lead to a preference for pairing frequency bands which are not greatly different in frequency.
- Allocated bandwidth. The up-path and down-path should have equal bandwidth.

It can be foreseen that difficulties will arise in implementing the principle of pairing frequency bands, and these difficulties include the following:

- Only a few of the frequency bands allocated to the Fixed Satellite Service have been taken into extensive use, and the best ways of using the others have yet to be studied widely and in detail.
- Experimental satellites operating in more than one pair of frequency bands are already in orbit, and similar operational Fixed-Service Satellites may be launched soon. In such satellites it may be desirable for the frequency bands to be cross-patched, in whole or in part.
- There are significant differences between the Fixed-Satellite Service frequency allocations in the three ITU Regions.
- The Fixed Satellite Service frequency bands may be used for connections with satellites in other Services, such as the Broadcasting-Satellite Service and the various Mobile-Satellite Services. In these cases, a carrier will be transmitted up to a satellite in a Fixed-Satellite band but it will be retransmitted in a band allocated to a quite different service, or vice versa.

Having regard to these difficulties, it may be doubted whether a future Administrative Radio Conference would require that specific pairs of bands be used in future systems. Nevertheless, guidelines might be laid down, although such guidelines could not be applied rigidly in all cases.

7.2 *Translation frequency for narrow-band satellites*

Some satellites need to occupy only a part of the bandwidth of the frequency band allocated. In such cases the co-ordination of several narrow-band satellites occupying the same part of the geostationary satellite orbit would be facilitated if all the satellites used the same effective translation frequency between up-path and down-path.

7.3 *Use of multiple frequency-band-pairs in satellites*

In some satellite networks it may be economically and operationally advantageous to use more than one pair of frequency bands, because this will enable the effective bandwidth of the network to be increased. This is usually the most economical way of increasing the communication capacity of a network. Use of multiple-frequency bands has no significant impact on economy in the use of the frequency spectrum or the geostationary-satellite orbit while only one pair of frequency bands is heavily loaded in the relevant part of the orbit, but it has several disadvantages when the second pair of frequency bands is also intensively used, as follows:

- the process of co-ordination of frequency assignments will be made more complex and the optimization of the orbital location of satellites operating in the various frequency bands will no longer be independent, so that the efficiency of these processes will be reduced;

- the angular separations required in the different pairs of frequency bands will probably be different, raising the possibility that full use will be made of the orbit in only one pair of frequency bands.

The use of multiple band pairs on a single satellite in the Fixed Satellite Service may cause little loss in the utilization of the bandwidth and orbital arc if:

- networks using adjacent satellites have similar characteristics;
- the antenna gains and G/T_s of the earth stations are generally in the order of the largest practically attainable in all the bands used;
- certain parameters (including type of modulation, up-path and down-path noise allocations, and the interference noise allowance) of the systems within one band pair are designed and adjusted to maximize the utilization of bandwidth and the orbit.

In a non-homogeneous orbit utilization situation the loss of capacity would probably be greater, but no serious loss of effectiveness of orbit utilization seems likely to arise unless a substantial proportion of the satellites occupying an arc of the orbit uses multiple frequency band pairs. However, this matter requires further study.

Two strategies for reducing the impact of this problem in orbital situations where it could lead to inefficient usage have been suggested, namely:

- for certain multiple-band configurations it is possible to adjust system parameters to minimize the overall orbit/spectrum capacity losses. This generally corresponds to equalizing the required separation angles in the various bands;
- it may be feasible to make room in between two multi-band satellites for an additional satellite operating in only one pair of the frequency bands used on the multi-band satellites. This, however, may involve adjustment of the characteristics and parameters of the satellite networks.

It is recommended that these two possible strategies should be taken into account in determining the characteristics and parameters of satellite networks using more than one pair of frequency bands.

7.4 *Use of frequency bands of the Fixed Satellite Service for connections to satellites dedicated to other services*

Consideration needs to be given to the technically preferred frequency bands for connecting to satellites in services such as the Maritime Mobile Satellite Service, the Aeronautical Mobile Satellite Service and the Broadcasting-Satellite Service. In the first and second cases the total bandwidth requirements for both up-links and down-links are relatively small. The total bandwidth likely to be required for connecting to broadcasting satellites would be much greater than the foreseen needs of these Mobile Satellite Services.

The desirable choice of frequency bands is under study under Study Programmes 2K-2/4 and 2M/4 and in this Report it is sufficient to indicate the principles which should be followed in order that optimum use of the geostationary satellite orbit and the spectrum may be achieved.

Regarding the connections to broadcasting satellites, the main problem is as follows: The WARC on Satellite Broadcasting (1977) agreed to a frequency assignment plan for Regions 1 and 3 for the down-paths at 12 GHz. If a corresponding bandwidth in fixed-satellite up-path bands were to be identified for use for the up-path to the broadcasting satellites, the up-paths for satellites of the Fixed Satellite Service would be largely or wholly excluded from that bandwidth and the corresponding down-path bandwidth would not be usable as intended. On the other hand, if bandwidth was not identified in this way, other fixed satellite services might become established in up-path bands before satellite broadcasting systems were set up, and difficulties would arise in the implementation of the satellite broadcasting plan.

Various suggestions were made with respect to up-paths to broadcasting satellites:

- It might be possible to identify a suitable up-path frequency band already allocated to the Fixed Satellite Service which does not have a corresponding down-path band; this situation may vary from Region to Region. Alternatively the WARC in 1979 might allocate new bandwidth for this purpose.
- The frequency bands allocated for the down-paths of satellites of the Fixed Satellite Service might be used for the up-paths to broadcasting satellites with little constraint upon the former satellites although there may be constraints on the latter from this mode of operation. As an example, bands around 11, 12 or 18 GHz might be used in this way.

It would be very desirable to identify up-path bands for broadcasting satellites equal in bandwidth to the down-path band used for broadcasting. If this were not feasible the use of bandwidth reduction techniques such as high-density modulation techniques in the up-path, with a processing transponder, should be considered.

It will, no doubt, be necessary to identify frequency bands which would be available for connections between shore earth stations and satellites of Mobile Satellite Service at any location in orbit. To enable efficient use to be made of those frequency bands elsewhere in the orbit, it is desirable that they should also be available for networks of the Fixed Satellite Service. An effort should be made to avoid too great an incompatibility between the characteristics of the emissions used for the Mobile and Fixed Satellite Services in order that the necessary orbital separation distance should not be large.

8. Homogeneous and inhomogeneous orbit and spectrum utilization

8.1 *Homogeneous orbit utilization*

8.1.1 *System homogeneity*

The most efficient orbit utilization would be obtained if all satellites utilizing the geostationary-satellite orbit, illuminating the same geographical area and using the same frequency bands had the same characteristics, i.e., if they formed an homogeneous ensemble. However, in practice, satellite systems will have differences.

Consider two satellite systems A and B, using satellites having adjacent orbital positions. If A and B have widely differing characteristics, e.g., as regards satellite receiver sensitivity and down-path e.i.r.p. or as regards their associated earth-station characteristics, then the angular spacing necessary to protect A against interference from B may differ from that necessary to protect B from A. In practice, the greater of the two angles must be selected. The extent to which this may represent an inefficient utilization of the geostationary-satellite orbit is dependent on many factors in the design of the satellite systems using orbital positions near those of A and B. It is possible for the orbit to be more effectively utilized if inhomogeneity is taken into account during the satellite system design. The system parameters in particular, which should be given consideration are satellite e.i.r.p., earth station figure of merit (G/T) and the relative immunity of the modulation system to interference.

The growing tendency to use spot-beam satellite antennae adds to the complexity of the problem of orbital capacity and must also be taken into account.

8.1.2 *An homogeneous parametric study*

An homogeneous inter-system interference model was constructed as follows:

- a full ring of equally spaced satellites in the geostationary-satellite orbit;
- frequency modulation is used, with FDM telephony basebands of capacity not less than 240 channels;
- all satellites have earth coverage antennae, possess identical transmission and modulation parameters, and transmit the same type of signal on the same nominal carrier frequency (co-channel sharing);
- all earth stations are identical, with antenna side-lobe characteristics conforming to Recommendation 465-1;
- propagation conditions are clear weather;
- the down-link only is considered.

Apart from the above restrictions, some of which may be relaxed, all parameters are allowed to vary freely and, to this extent, the homogeneous model provides much intuitive direction for the various trade-offs involved.

Fig. 3 shows the effect of the interference noise budget N_i on the minimum inter-satellite spacing. The satellite spacing has been normalized to unity at $N_i = 1000 \text{ pW0p}$, which is the value currently stipulated in Recommendation 466-2. Similarly, Fig. 4 shows the sensitivity of the minimum inter-satellite spacing to changes in the earth-station antenna size. Here, the spacing is normalized to unity at $D/\lambda = 100$, where D is the antenna diameter and λ is the operating wavelength.

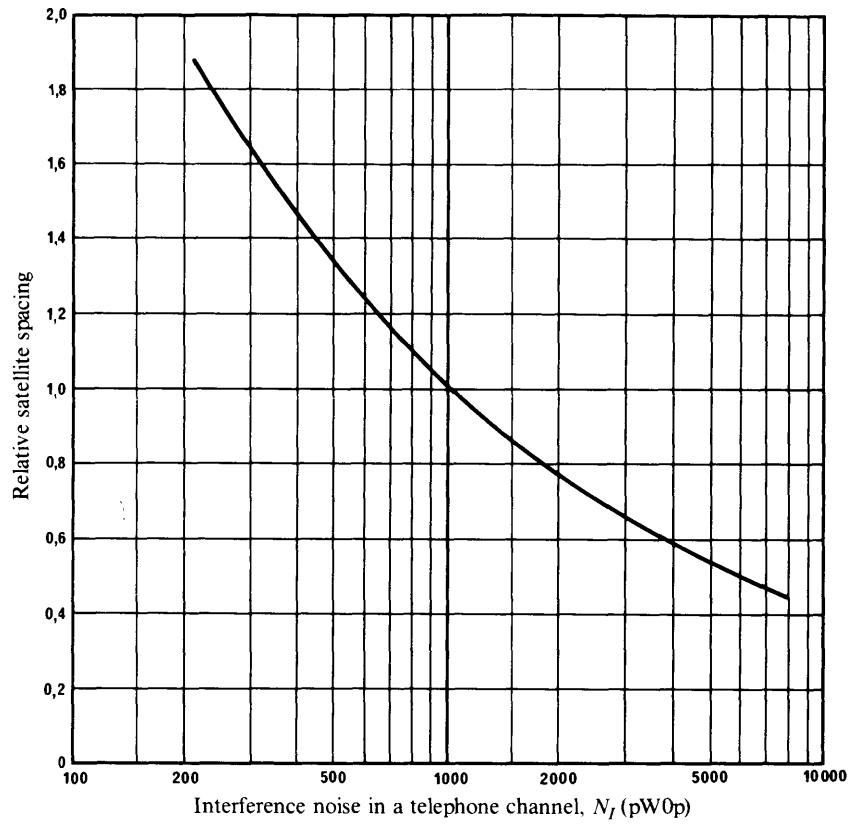


FIGURE 3 — Satellite spacing as a function of interference noise

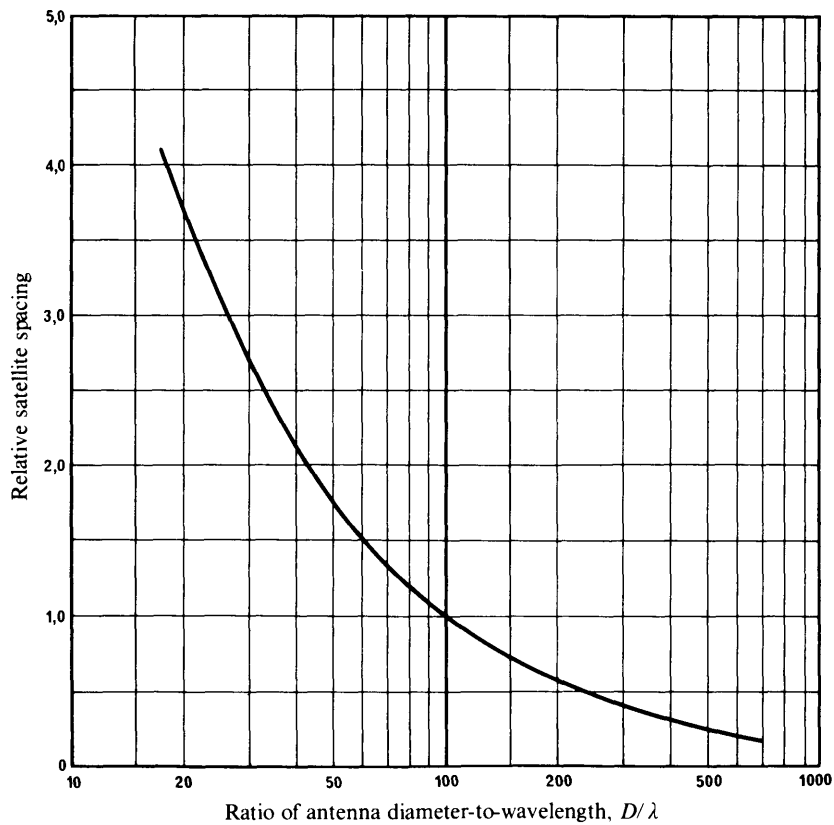


FIGURE 4 — Satellite spacing as a function of earth-station antenna size

The impact of the modulation parameters can be observed in Fig. 5. The abscissa is given in terms of $\bar{n}$, the number of telephone channels per MHz, which is a function of the modulation index. As in previous curves, the ordinate shows the corresponding change in spacing, relative to the case with an r.m.s. modulation index = 1.0. Fig. 5 further indicates that a substantial improvement in spacing can result from an interleaved frequency plan. It should be noted, however, that for small modulation indices, the co-channel condition is no longer the worst case of a frequency plan; in fact for relatively small departures from the true co-channel condition, and in particular when the difference between the carrier frequencies is less than the width of the baseband, the interference can increase markedly.

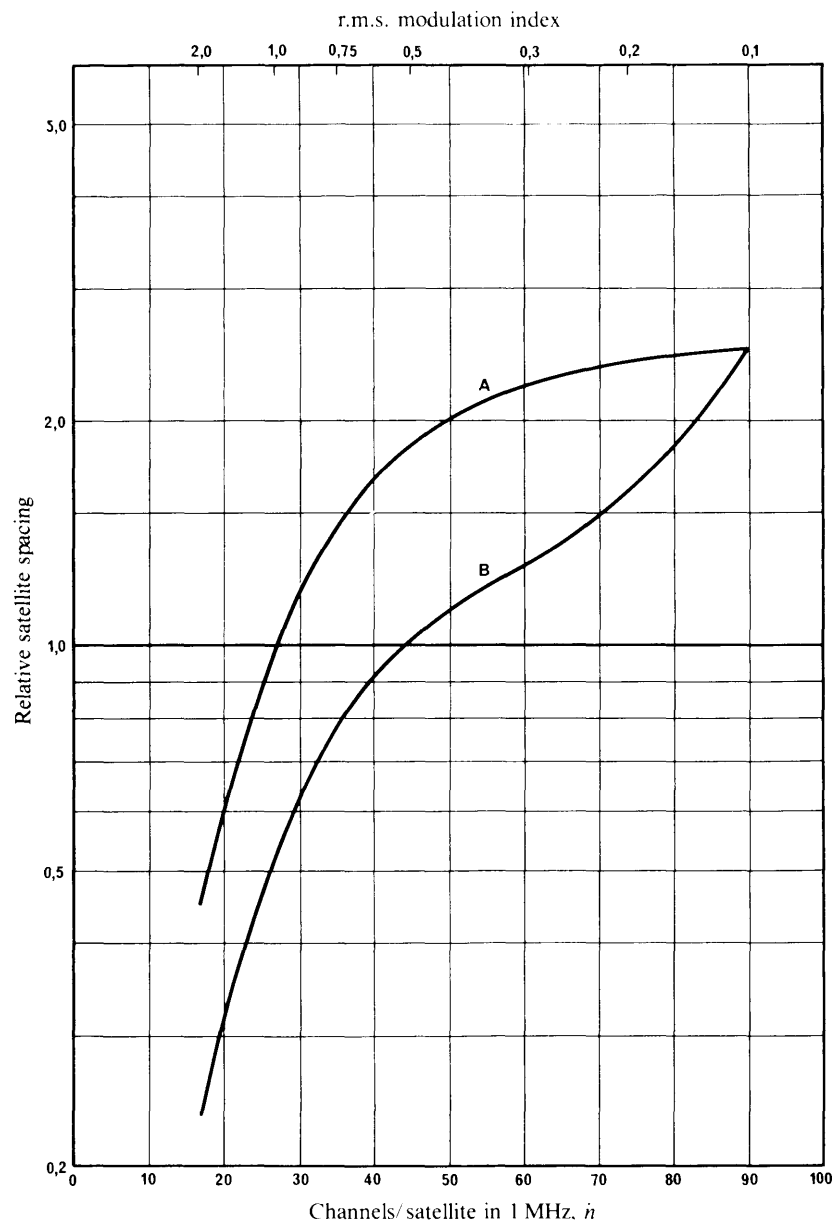


FIGURE 5 — Satellite spacing as a function of modulation index

A: Co-channel
B: Interleaved

Fig. 3 displays a variation in interference noise without, however, specifying the corresponding variation in e.i.r.p. which must occur to maintain the total noise budget, interference noise plus thermal noise, at some specified value. An equitable basis for comparison would seem to require maintaining fixed values of e.i.r.p. while varying the spacing. These interactions are displayed in Fig. 6 where $\tilde{n}$, the number of telephone channels per orbit degree and per MHz, has been used as a meaningful measure of orbit/spectrum utilization. The parameter chosen is carrier-to-thermal noise ratio (CNR), since it is more convenient to use than e.i.r.p. but is related to the latter in an obvious fashion. Finally, the figure also shows loci of constant ratio of thermal-to-interference noise when their sum totals 7500 pW.

Some conclusions may be drawn from Figs. 3 to 6. Some of these conclusions, of course, apply to the FDM/FM homogeneous system model only, but may be extended, with proper care, to more general contexts.

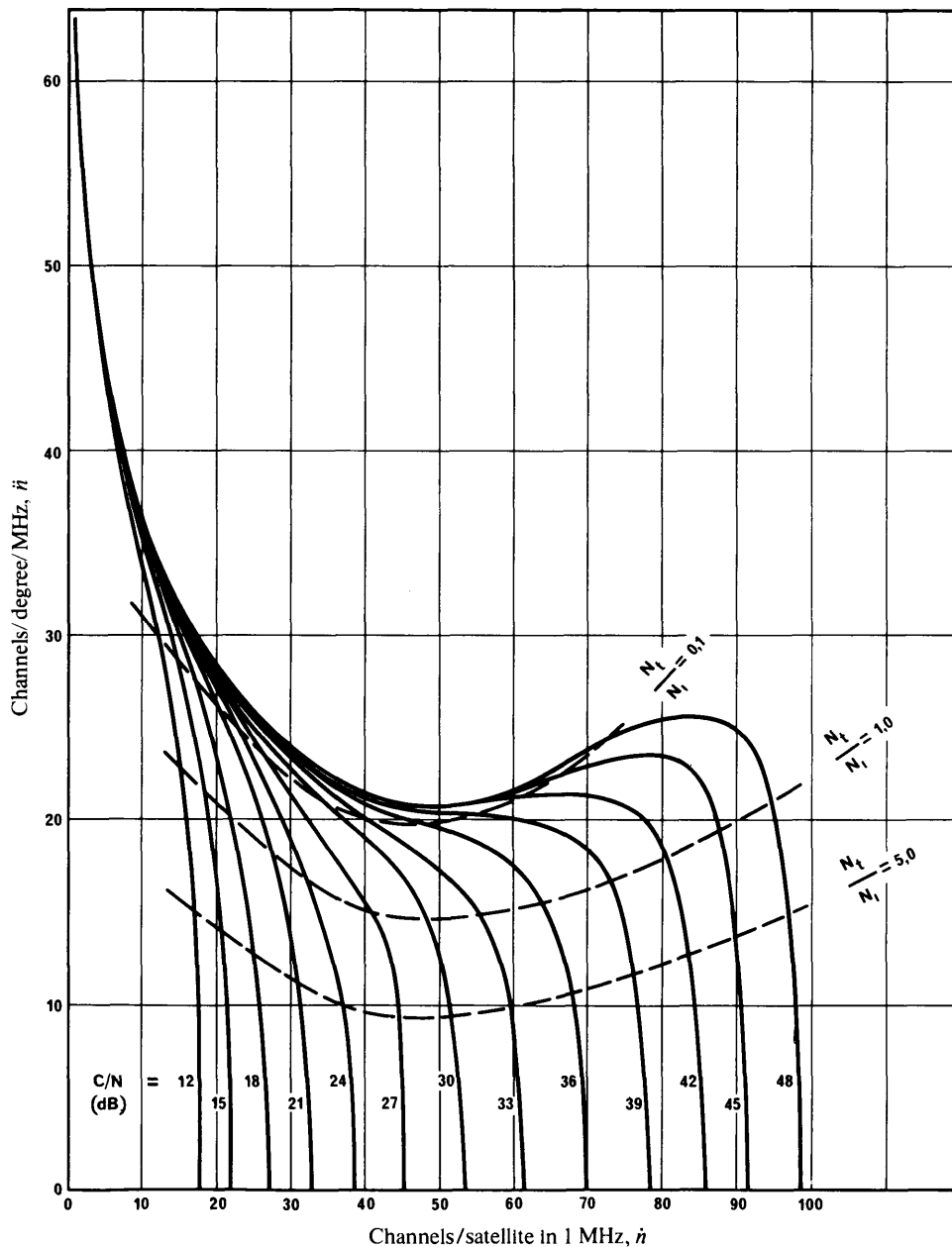


FIGURE 6 — Orbit/spectrum utilization as a function of channels per satellite

$$(D/\lambda = 300, N_t + N_i = 7500)$$

(Interfering carriers are assumed to be co-channel)

First, it may be seen from Fig. 3 that, all other things being equal, satellite spacing varies inversely with interference noise allowance. Furthermore, the latter varies rapidly with the former; for example, as N_i varies from 250 pW to 7500 pW, a 1 : 30 change, $\Delta\theta$ varies by about a factor of 4. Thus, as N_i approaches the total noise budget, there will be diminishing returns in $\Delta\theta$ for allowing progressively more interference noise.

Next, Fig. 4 also indicates that satellite spacing varies inversely with earth-station antenna size, the relative rate of change being fairly small when antennae are relatively large (D/λ greater than 100) but more rapid for small antennae.

The relationship plotted in Fig. 5 shows again that, all other things being fixed, satellite spacing varies inversely with modulation index, these being roughly in a one-to-one correspondence for a high modulation index. The capacity of each satellite is reduced rather substantially as the modulation index is increased, but there is a gain in total orbit capacity because more satellites can be used in the orbit. Thus, increasing modulation index is potentially an effective means of increasing orbit utilization in FM/FDM systems.

For the adopted measure of orbit/spectrum utilization, namely channels/degree/MHz, it can be seen from Fig. 6 that efficiency generally increases with modulation index, in agreement with the foregoing observation. It may be pointed out, however, that a high modulation index implies low capacity satellites for a fixed bandwidth. Hence, for a total traffic capacity more satellites are required, and this may result in an economic burden. It may be further observed that for some range of modulation index and relatively high carrier-to-noise ratio, there is relatively little variation in $\bar{n}$ and therefore, within this range, it is possible to choose satellite capacity as desired without compromising orbit utilization.

It is also worth noting that as the carrier-to-noise ratio decreases, so the possible range for $\bar{n}$ decreases. This is explained by the fact that, for each carrier-to-noise ratio, there is an $\bar{n}$ for which the thermal noise (N_t) approaches the total noise allowance (N_T), at which point no interference noise is permitted, which, in turn, requires "infinite" spacing. This accounts for the downward bend and asymptotic appearance of the curves. Finally, it can also be seen, as expected from Fig. 3, that greater total orbital capacity is potentially available if a successively larger fraction of the noise budget is allocated to interference.

8.2 *Inhomogeneous orbit utilization*

8.2.1 *Orbital spacing studies using specific system characteristics*

Studies have been made in which the satellite spacing required and the network capacities achievable have been calculated for systems with various arbitrarily chosen characteristics, earth station antennae being assumed to conform to Recommendation 465-1. Other studies are reported in Report 559. Some of the results may be summarized as follows:

- with earth station G/T about 40 dBK using PSK or wide-deviation FDM/FM, required satellite spacings in an homogeneously occupied arc of the orbit are typically between 1.5 and 3.0 degrees;
- with earth station G/T about 28 dBK the corresponding satellite spacing required for wide-deviation FM is 3 or 4 degrees, but only about 1.5 degree would be required for PSK;
- with low-deviation FM, spacings may be two or three times as great as for wide-deviation FM;
- when a satellite serving earth stations with $G/T = 40$ dBK is adjacent to one serving earth stations with $G/T = 28$ dBK, the required spacing may be two or three times as great as either network would need in an homogeneously used arc of the orbit.

8.2.2 *Optimization of heterogeneous orbit utilization*

In general, the satellite networks operating in the same band and making use of adjacent positions on the geostationary-satellite orbit will have dissimilar characteristics. This situation will occur within fixed satellite bands, and where the fixed satellite bands are shared with other services, as for example the broadcasting satellite service. It seems probable that this situation will not prove to be tractable to analytical methods which will apply to arbitrary collections of satellites. Such situations seem best suited to solutions on a case-by-case basis, whereby different combinations of satellites are analysed to determine the optimum arrangement, and hence are very amenable to treatment by computer. Some specific example results generated by such computer programmes are given in [CCIR, 1970-74h, i, j].

This analytical technique has been applied to some of the preliminary characteristics of several proposed United States domestic satellite systems. Certain characteristics of the Canadian domestic system were also considered, although the characteristics assumed do not take into account all present operational parameters of the Canadian domestic system (including the critical FDMA case). With the stated assumptions it was demonstrated that despite appropriate positioning of satellites, this heterogeneous set of satellites cannot achieve acceptable interference levels at a uniform spacing of 3° , even with polarization discrimination. However, these same systems could use an average spacing of about 3° with careful co-ordination. To the extent that the actual system parameters differ from those assumed, the results would have to be re-examined on a case-by-case basis. This result can be compared with an ideal situation where a homogeneous set of FDM/FM networks, having earth-station antennae not less than 10 m in diameter, can achieve 2° to 3° orbital spacing.

[CCIR, 1970-74j] describes how an analytical technique might be applied to the sharing of the 11.7-12.2 GHz part of the spectrum by both fixed service satellites and broadcasting satellites. The analysis hypothesizes characteristics of possible systems in the indicated services. It concludes that even such different systems as fixed and broadcasting satellites can effectively utilize adjacent parts of the geostationary-satellite orbit in this frequency band. See also Report 561-1.

Analytical methods such as those described in these papers provide a viable means for optimizing the positioning of satellites in networks having dissimilar characteristics in congested areas of the geostationary-satellite orbit whether of the same or different services, and the use of these methods is recommended. It should, however, be noted that the orbital plan can most easily be optimized when all systems are at the planning stage; it will be more difficult to find a good arrangement when new requirements, unforeseen at the initial planning stage, have to be accommodated at a later time.

8.3 *Studies of practical strategies for effective orbit and spectrum utilization*

Studies made for the purpose of developing practical strategies for using effectively the geostationary satellite orbit and the spectrum with very dissimilar networks have produced the results reported below.

8.3.1 *Fixed-satellite networks using high- and low-gain earth station antennae*

The bandwidth and orbital arc utilization of a set of satellite networks is a function of both the bandwidth utilization and the minimum angular spacing required between the satellites in order to meet a given interference criterion. Assuming that the bandwidth utilization is not a variable, then a measure of the effectiveness of bandwidth and orbital arc utilization may be obtained from the angular spacing required between the various satellites and the orbital arc occupied by the set of satellites as a whole.

The angular spacing required between satellites is a function of many network parameters, e.g. antenna radiation patterns, multiple access modes, satellite transponder gains, energy dispersal and others.

In one study [CCIR, 1974-78h] it was assumed that:

- some satellites serve earth stations with large antennae only, and others serve earth stations with small antennae only,
- satellite transponder gains can be adjusted to vary down-link to up-link noise ratios to minimize overall system interference, and
- satellite transponders are operated in a quasi-linear mode.

Conclusions may then be derived as follows:

- (a) Earth station antenna gain tends to be a dominant factor in determining orbit spacing requirements. A gain difference of 20 dB can result in an orbit utilization ratio of 6.3 to 1.
- (b) Satellite spacing requirements are determined by interference from the network employing small earth station antennae to the network employing large earth station antennae. Interference in the opposite direction may be less than between two networks employing large earth station antennae.
- (c) Adjustment of the up-link to down-link noise allocation ratios in networks using adjacent satellites may allow closer satellite spacing. The ability to control satellite transponder gain is important in this respect.
- (d) Isolating satellite networks employing small earth station antennae from those employing large earth station antennae by grouping of satellites, coupled with a higher interference noise allocation for the earth stations with small antennae, can improve the overall orbit utilization. However, this technique is effective only if each group contains a minimum of several satellites and it will be necessary to use other techniques for minimising the required satellite spacing within the groups in order that the total orbital arc required by each group shall not be too large.

- (e) Placing adjacent to each other satellites which do not have overlapping satellite antenna coverage areas may improve the overall orbit utilization.

It should be noted that satellite systems have been designed that are not in accordance with the preceding assumptions. In this case, the above postulated conclusions (a), (b), (c) and (d) are not necessarily valid.

8.3.2 *Orbit utilization when a band is shared by satellites of different services*

The Broadcasting-Satellite Service and Fixed Satellite Service share a space-to-Earth frequency allocation at 12 GHz in ITU Region 2 and this presents a special case of inhomogeneous utilization. In the Broadcasting-Satellite Service, well defined service areas and relatively small earth station receiving antennae impose additional constraints on the amount of flexibility in space system configurations after implementation. However, considerable enhancement of orbit utilization can be obtained if certain technical factors are effectively adjusted through co-ordination at a sufficiently early stage in network planning.

The effect of these factors on orbit utilization is discussed in Report 561-1 and in [CCIR, 1974-78]. The latter draft Report uses the following terms in examining sharing between the Fixed Satellite and Broadcasting-Satellite Services.

Spectrum division: A sharing approach in which each service can use the entire orbital segment but only an assigned part of the frequency band.

Orbit division: A sharing approach in which each service can use the entire frequency band but in which satellite locations may be mutually co-ordinated.

Service utilization factor: The ratio, for either service, of the capacity that this service can provide using an assigned fraction of the available bandwidth and orbital arc to the total capacity it would provide if it enjoyed an exclusive allocation.

Utilization factor: The sum of the two service utilization factors.

The following summarizes the conclusions drawn from such studies:

The Fixed Satellite and Broadcasting-Satellite Services can share the orbit-spectrum resource at 12 GHz equitably and effectively. Both orbit-division and spectrum-division approaches permit total utilization factors close to 100 per cent, indicating that sharing does not significantly jeopardize orbit-spectrum utilization.

With spectrum-division there is no interservice interference so that the utilization factor for each service is very nearly proportional to the fraction of spectrum allocated to it and the total utilization factor is always near 100 per cent. The spectrum may be divided between the services in any desired proportion independent of the characteristics of the satellite systems.

With orbit-division, interservice interference is controlled by careful separation of satellites in the orbit and the preferred satellite deployment depends on both the equipment and signal parameters of the sharing systems. However, the problem differs only in degree from that of finding compatible spacings for intraservice sharing and, for any given combination of systems, a deployment can be found for which the utilization factor of the corresponding orbit-division approach approaches 100 per cent. For certain combinations of systems, the total utilization can significantly exceed 100 per cent, although in these cases, there is a limitation on the relative size of the orbit shares that can be assigned.

Compared with an orbit-division approach using the same types of systems, spectrum-division imposes an economic penalty except where multi-purpose satellites are involved. With that exception, each service has to use more satellites to provide the same total capacity. Since an orbit-division approach can provide equally high and in some cases higher utilization factors, it is concluded that orbit division is to be preferred to spectrum division.

The satellite arrangement that characterizes the preferred orbit-division approach for a given set of systems depends on the degree of inhomogeneity among those systems. When satellite e.i.r.p.s, earth-station antenna diameters, or signal modulation indices are quite different, a "clustered" deployment in which two or more satellites of the less powerful system are clustered between adjacent satellites of the more powerful system yields the highest total utilization. When the system parameters are more homogeneous, the arrangement becomes less critical, but even in such cases it is usual that somewhat higher utilization factors are obtained by gathering satellites of the same kind together in clusters and minimizing the number of interfaces between clusters.

8.4 *Methods of implementing spectrum and orbit division*

Studies having shown that it is desirable to use spectrum or orbit division, or some equivalent technique to reduce the inhomogeneity of networks which may interfere with one another, consideration must be given to methods of implementing these principles in practice.

One possible solution that has been proposed is to apply constraints to certain system characteristics in some of the frequency bands allocated to the Fixed Satellite Service. These constraints should be designed so as to allow maximum freedom to designers to optimize their systems, subject to the achievement of some significant reduction of inhomogeneity. For example, it has been suggested [CCIR, 1974-78] that limits might be applied to the following characteristics:

- The maximum permissible e.i.r.p. per unit bandwidth in the direction of the geostationary satellite orbit transmitted at an angle θ from the axis of the main beam of an earth station antenna.
- A limit on the up-path sensitivity such that the interfering spectral pfd at the geostationary satellite orbit which corresponds to 400 pWp of interference noise in a telephony channel due to the up-path alone, should be not less than a value to be specified.
- The maximum spectral pfd produced at the Earth's surface by the satellite emissions. (This value might differ from that given in Recommendation 358-2 for the protection of terrestrial services.)
- A limit on the down-path sensitivity such that the interfering spectral pfd at the Earth's surface, arriving at an angle θ from the direction of the wanted signal, that corresponds to 400 pWp of interference noise in a telephone channel due to the down-path alone, should be not less than a value to be specified.

Limits to be applied to the first of these characteristics are discussed in § 6 of this Report, and Recommendation 524 refers. The limits that have been suggested for the other characteristics for use in the 4 and 6 GHz bands are as follows:

- 151.5 dB(W/(m² · 4 kHz))
- 160 dB(W/(m² · 4 kHz))
- 182 + 25 log θ dB(W/(m² · 4 kHz))

These limits, it is suggested, would not form unacceptable constraints for most applications in the Fixed Satellite Service but they would probably be unacceptable for a few, in particular for earth stations with very small antennae used for television services or single-channel-per-carrier telephony transmissions. These exceptional services might have to use parts of the spectrum where these limits do not apply.

One possible way of separating emissions by frequency in allocated frequency bands to which the proposed constraints applied in general would be, for example, to identify a few preferred carrier frequencies for high density television emissions; the proposed constraints would not be applied in the immediate vicinity of these preferred frequencies. These frequencies would, of course, be available for other services in the absence of a high density television requirement, but it is recognized that the introduction of this concept would impose constraints on carrier frequency assignments in other systems.

This matter needs further study.

9. Frequency re-use by geosynchronous satellites in inclined orbits

In theory, it should be possible to make use, on the same frequencies, of two or three or even more satellites spaced along a narrow figure-of-eight based on any given longitude [Rowe and Penzias, 1968]. If inclined elliptical synchronous orbits are used instead of inclined circular orbits, the satellite moves on a locus of a distorted (pear-shaped) circle when looked at from the Earth. Since this locus has no crossing point within itself, the placement of satellite along the locus may be facilitated.

It is also conceivable that the maximum number of satellites may be increased by adopting a hybrid system in which a combination of stationary satellites and quasi-stationary satellites, either in circular orbits or in elliptical orbits, is used [Shinji and Kurose, 1969].

However, the cost of the space segment would be increased very substantially and the resulting gain in orbit capacity is not expected to be commercially exploited at an early date.

10. Other factors affecting the number and locations of geostationary satellites

10.1 *Economic, operational and technical considerations affecting the capacity of individual satellites*

For very efficient orbit utilization, satellite systems would have to operate in an interference-limited mode, but this would reduce the capacity per satellite and so increase the number of satellites and earth stations needed for a network of given size. Thus, from some economic and operational points of view, a proliferation of satellites within a system is undesirable. Since the technical and economic considerations indicate opposite trends, a compromise may be required to provide both economic viability and reasonable technical efficiency of orbit utilization.

This effect has been studied using different values of modulation index in systems using FDM/FM. Results indicate, for example, that a system of three satellites might provide a total of 50 000 one-way telephone channels using a modulation index of 0.5 and occupying 10° of orbital arc whereas 10 satellites would be needed to provide the same traffic capacity in an orbital arc of 7° using a modulation index of 2.5. Thus, in systems with earth stations at many locations it appears to be more economical to use a small number of higher powered satellites with smaller modulation indices and a consequential slight decrease in orbital efficiency.

This question is, however, a complex technical one and further study will no doubt give clearer guidance in this field.

10.2 *Power flux-density at the surface of the Earth*

Increasing the total power flux-density at the surface of the Earth, either by increasing the power of a few satellites or by increasing the number of less powerful satellites, does generally lead to a better utilization of the geostationary orbit. However, an increase in the number of satellites or in the limit of the maximum permissible flux-density at the surface of the Earth may ultimately lead to excessive interference into sensitive terrestrial radio-relay systems. The impact of power flux-density on terrestrial systems is discussed in Report 387-3.

It is desirable to reduce any unnecessary illumination of the Earth from satellites, such as occurs with conventional global coverage antennae near the centre of the beam. Beam-shaping can be used to avoid this over-illumination. See Report 558-1.

10.3 *Influence of traffic patterns*

The location of the earth stations using a particular geostationary satellite and the circuit network which the satellite network provides determines several primary characteristics of orbit utilization, including orbital location, satellite e.i.r.p., satellite antenna beamwidths and type of modulation.

The degree of inefficiency in the utilization of the orbit will depend upon the extent to which earth stations are, simultaneously, widely dispersed, require large beamwidths and have high channel capacity requirements, and thus necessitate high e.i.r.p.s and small modulation indices. These conditions will tend to make orbital positioning an inflexible matter and will therefore decrease the total orbit capacity.

10.4 *Additional frequency bands*

The allocation of new frequency bands for the Fixed Satellite Service by the World Administrative Radio Conference for Space Telecommunications, 1971, has greatly increased the potential capacity of the geostationary-satellite orbit. Almost all of these new frequency bands are above 10 GHz. Many studies will have to be carried out before it will be possible to assess how the use of these higher frequency bands will affect the application of the orbital economy techniques discussed in this Report, but the following effects can be identified now:

- the use of highly directional satellite antennae will be facilitated and this will considerably increase the opportunity for frequency re-use;
- radio propagation in the troposphere will be much worse than at the lower frequencies now in use. This will make necessary the use of larger down-path power margins and perhaps space diversity at the earth station. These matters are considered in Reports 205-4, and 720;
- the wider bandwidths available in some of these new frequency bands will facilitate the development of satellite networks of very high capacity.

Thus it seems probable that the new higher frequency bands will be attractive for satellite networks of very large capacity, but the lower frequency bands will be preferable for many systems. Priority should be given to propagation studies at these higher frequencies, and more particularly between 10 and 30 GHz.

10.5 *Inter-satellite links*

General aspects of inter-satellite links are discussed in Report 451-2. Aspects of this topic that affect the efficiency of use of the geostationary satellite orbit and the spectrum are considered here.

A direct link offers the following advantages:

- the transmission delay between the terminal earth stations would be less than for a circuit relayed at a third earth station. This might be significant for telephony;
- the problems discussed in § 10.3 would be alleviated;
- arcs of the geostationary-satellite orbit which are not ideal for satellites used to provide networks in global-coverage systems may become usable for this purpose if direct satellite-to-satellite relays are available;
- in an idealized ultimate concept in which all the requirements of an earth station would be served by a single satellite, interconnections to other earth stations being made, if necessary, by inter-satellite links, there would be improved transponder fill, and therefore more efficient bandwidth utilization, as the up-paths and down-paths serve increasingly concentrated groups of earth stations.

In addition, however, the following disadvantage has been identified:

- in cases where it would be necessary to increase the requirement in respect of bandwidth or e.i.r.p. per channel in the Earth-to-space or space-to-Earth path to offset the noise contribution introduced by an inter-satellite link, the efficiency of orbit and/or spectrum utilization could be adversely affected.

10.6 *Flexibility in the positioning of satellites*

There will be a few cases where the coverage requirements of a satellite will be so critical that even a small change in the satellite position would have serious consequences. On the other hand, there will be many cases where the design of the satellite and the associated earth stations is such that the need to change the satellite position slightly would not present any difficulty or penalty provided such changes were required only rarely. Flexibility of this kind could prove very useful in minimizing interference between systems in congested parts of the orbit and should, therefore, be borne in mind by system designers.

It has also been shown [CCIR, 1974-78k] that the length of the orbital arc that is needed for a number of satellites serving different service areas depends upon the relative positions of the various satellites. The service areas were assumed to be distributed north and south of the equator and extended over about 8000 km from east to west, with relatively little overlap of coverage areas. It was found that the minimum length of orbital arc that would be acceptable, for stated interference conditions, varied considerably depending upon the arrangement of the satellites in the orbit. Some arrangements needed only about one-half as much space as other arrangements. It should also be noted that it is not possible to say with certainty which geographical areas would need to be covered at some time in the future from a given part of the orbit; full advantage could therefore be taken of this means of optimizing the use of the orbit only if networks were designed so that their satellites could be relocated, if necessary, within a service arc, after having been put into service.

With a view to achieving an efficient use of the geostationary satellite orbit and to providing the possibility of accommodating future space systems with suitable orbital positions, the World Administrative Radio Conference for Space Telecommunications (Geneva, 1971) provided that the orbital information to be notified should also include the "service arc" and the "visible arc", and further stipulated that the "service arc" should encompass the "visible arc" for a given minimum angle of elevation from its associated earth stations or service areas (Appendices 1A and 1B to the Radio Regulations). Determination of the "service arc" from a geometrical point of view depends on the geographical distribution of the service areas or of the earth stations and their minimum acceptable angle of elevation for a predetermined condition of operation which, in any case, should be no smaller than the minimum angle of elevation of earth station antennae required to prevent interference to terrestrial stations (Article 7 of the Radio Regulations). Hence the size of the service area or the spread of the earth stations and both the "visible arc" and the "service arc" of the geostationary satellite orbit are inversely related. Consequently, any decrease in the service area generally results in greater flexibility regarding the positioning of satellites. On the other hand, however, the "service arc" is directly proportional to the "worst case coverage area" to be considered in studies on the potential interference which is likely to occur. A method for determining the geometrical elements in question is given in [Dolezel, 1977].

It is recognized, however, that to design a system for maximum flexibility of orbital location might impair the performance and increase the cost of the satellites, particularly since it may often require the provision of a facility of redirecting the beams by command to maintain the required coverage. This could reduce the economic viability of the system.

Apart from earth coverage requirements, the more significant problem areas are as follows:

- Technical problems at the earth station. Some degree of antenna steerability would be required. Changes in antenna elevation angle might affect the clear-sky G/T and the severity of propagation degradations. Changes in antenna pointing angle might require the repetition of frequency co-ordination with terrestrial radio services.

Future systems, particularly those employing small earth station antennae, may have only limited steerability or none so that even small changes in satellite positions could present mechanical and operational problems and involve interruptions to service. For a system comprising a large number of unattended earth stations, the cost of sending personnel to each site to redirect the antenna would be significant.

- Satellite antenna. Generally speaking, the antenna coverage which a satellite can provide for a given geographic area is optimum for operation of the satellite from a specific region of the geostationary satellite orbit. If the satellite were designed to operate outside this region of the orbit, the antenna beamwidth would have to be somewhat broader, and consequently a reduction in antenna gain would result. It may also be necessary to change the direction of spot beams relative to the direction of the sub-satellite point.
- Solar eclipse. Satellites without enough battery capacity to sustain services in full during eclipse might be limited to orbital locations where eclipse occurs outside busy traffic periods.

- Propellant requirements for orbit control. The mass propellant required to transfer a satellite from one orbital location to another may be quite significant, particularly if rapid transfer is required. See Report 556-1, § 2.2.
- Operational problems. If it is necessary to move an operational satellite, service may be interrupted if earth stations do not have automatic tracking facilities. This problem would be particularly severe in networks using large numbers of unattended earth stations. If an operational satellite has to be moved through the orbital arc occupied by another operational satellite using the same frequency band, interference may arise if one satellite or the other is not taken out of service.

The flexibility of position of satellites serving areas very extensive in longitude would be small because their arc of mutual visibility would be small and that the problems listed above might severely limit flexibility in other cases. Nevertheless there are ways in which system designers could significantly increase the extent to which satellites could be moved in orbit and it is desirable that the following measures should be taken to the extent that is practicable:

- Earth station antennae to be capable of being redirected to any point in the orbital arc of visibility for the network for which the earth station is intended.
- e.i.r.p. margins, up-path and down-path, to be adequate in spite of changes in angle of elevation at earth stations.
- Satellite battery capacity to be sufficient to maintain services during eclipse.
- The patterns of spot beam coverage to be such as to tolerate changes in orbital location to the extent that interference considerations allow.
- Where more than one spot beam is used on a satellite, it may be desirable for their relative directions to be adjustable in orbit.
- Spare satellites to be available in orbit.
- A margin of thruster fuel to be available for changing satellite position.
- Frequency co-ordination to take possible future satellite movements into account.

It is recognized that the difficulties of changing satellite antenna characteristics in orbit might be insuperable; if so, it would be beneficial if the design of the spacecraft were such that the antenna characteristics could be adjusted as late in its construction as is practicable.

10.7 *Effect of Propagation Conditions*

The provision of site diversity earth station antennae for reception of satellite signals has been noted as a technique capable of improving the efficiency of use of the geostationary satellite orbit under some conditions, notably at frequencies above 10 GHz. At some geographic locations, the local climatic conditions are such that signals at frequencies above 10 GHz will be severely attenuated for small percentages of the time by cloud formations and rain. In such a location, an earth station receiving a satellite signal without site diversity can provide performance in accordance with Recommendation 353-3 only if the satellite signal is transmitted at a value of e.i.r.p. in excess of that needed to meet corresponding performance for a large percentage of the time. This requirement of an additional margin of e.i.r.p. for fading can be eliminated by the provision of site diversity antennae at the earth stations; then by reoptimizing the modulation parameters the additional e.i.r.p., which would otherwise have been needed as margin for fading, can be utilized to increase the channel capacity of the system. For example, where site diversity could reduce the requirement for extra fading margin by 4 dB in respect of an FDM carrier signal, reoptimization of the modulation parameters would allow the channel capacity of carriers to be increased by 36%. In digital systems the corresponding reduction of the required fading margin might make unnecessary the use of forward error correction, so making additional capacity available for traffic. This increase in channel capacity would represent an improvement in the efficiency of utilization of the geostationary satellite orbit.

At frequency bands above 10 GHz, interference noise power in an up-link, arising from other earth stations, generally increases during local rain-fall at the earth station transmitting the wanted carrier. Accordingly, the satellite spacing which is derived from the noise allowance for a small percentage of time in this case might have to be larger than that acceptable under clear-sky conditions. In order to minimize the increase of satellite spacing, the following means may be useful:

- use of site diversity;
- use of adaptive earth station transmit power control;
- design of the satellite antenna in such a way that its gain in the direction of generally heavier precipitation has a higher value.

10.8 *Crossed-beam arrangement of satellite systems*

If satellites serving limited geographical areas and using common frequency bands are located at approximately the same longitude as their service areas, there will be a tendency for satellites adjacent in orbit to serve adjacent areas. Thus, the reduction in interference between the two networks that satellite spot beam antennae could provide may be quite small. If, however, it is possible to arrange satellite locations so that adjacent satellites serve well-separated geographical areas, and consequently adjacent geographical areas are served by satellites well-separated in orbit, then the directional properties of the satellite antennae can provide greater protection, particularly if these antennae are designed having regard to side-lobe reduction techniques.

The possibility of a crossed-beam arrangement for spot beam satellite systems has been proposed for improving bandwidth and orbital arc utilization. It can significantly reduce interference noise power and permit a closer satellite spacing. In favourable circumstances, this arrangement might lead to a reduction of the minimum satellite spacing of up to about 30 per cent as against the case of the non-crossed-beam arrangement, but further study will be needed for each practical case.

10.9 *Miscellaneous technical factors*

The following factors have not been considered in detail but should not be ignored and may assume considerable importance in particular situations:

- accidental variation of earth-station antenna pointing;
- effects of atmospheric refraction, particularly with respect to earth stations operating at low angles of elevation;
- radiation from unused (including redundant) satellites;
- certain constraints on satellite locations due to atmospheric precipitation effects at low angles of elevation.

11. **Criteria of efficiency in the use of the geostationary-satellite orbit and the frequency spectrum**

As certain parts of the geostationary satellite orbit have become increasingly congested there is now a need to consider satellite systems in the light of their use of the limited resources of bandwidth in the frequency spectrum and orbital-arc in the geostationary satellite orbit. Both resources should be used efficiently but what, in fact, constitutes efficient use of the combined resource is a complex question. In this context "efficiency" does not possess the strictly mathematical sense in which there is an ideal or theoretical maximum capacity of the orbit against which the efficiency of any particular system is expressed as a percentage. What is meant is the "effectiveness" of use, recognizing that this orbit is a commodity of limited proportions, even if we cannot measure or express its capacity in a single figure, permanently fixed for all time. We therefore understand that by aiming towards efficiency of use of the orbit, we mean to use it in the most economical manner. This subject is pursued in detail in Report 711.

12. **Review of possible future CCIR Recommendations for improving efficiency of orbit utilization**

It seems likely that the efficiency of utilization of the geostationary-satellite orbit would be significantly increased by the establishment of new Recommendations or the revision of existing Recommendations on the following subjects when an adequate technical basis has been established:

- A design objective for the radiation pattern of new earth-station antennae.
- Preferred types of polarization and standards of cross-polar discrimination.
- Satellite spot-beam pointing accuracy.
- A reference radiation pattern for satellite antennae.
- Satellite spot beams coverage to be limited to a minimum coverage area.
- Inter-system interference noise allowances.
- Preferred pairings of frequency bands.
- Flexibility in satellite positioning.
- Accuracy of station-keeping.
- Definition of criteria of efficiency of orbit and spectrum utilization.

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REPORT 454-2

METHOD OF CALCULATION TO DETERMINE WHETHER TWO GEOSTATIONARY-SATELLITE SYSTEMS REQUIRE CO-ORDINATION

(Study Programme 2J-2/4)

(1970 - 1974 - 1978)

1. Introduction

Increased use of the geostationary-satellite orbit by satellites and associated earth stations may increase the probability of interference between satellite networks when common frequency bands are used. The number of parameters characterizing a system is so large that it is useful to devise a simple method to determine whether there is any risk of interference between two given satellite networks. The method described in this Report is applicable whenever two networks share a frequency band on at least one of their paths. It is based on the concept that the noise temperature of the system receiving interference undergoes an apparent increase due to the effect of the interference, the interfering signals being treated as thermal noise, whose spectral power density would be equal to the maximum spectral power density of the signals. The method can therefore be used irrespective of the modulation characteristics of the satellite networks concerned and the precise frequencies employed.

In this method, the apparent increase in the equivalent satellite link noise temperature (the equivalent satellite link noise temperature is defined in No. 103A of the Radio Regulations) resulting from interference caused by a given system is calculated and this value is compared with a predetermined increase in the noise temperature (see § 3 below).

2. Procedure for simple frequency-changing transponders

2.1 Radiocommunication satellites require frequency assignments in two bands, one for the up-path and the other for the down-path. It is current practice for frequency bands to be associated in pairs, one of each pair being used for up-paths and the other for down-paths. Case I below is concerned with the possibility of interference between two systems which have been assigned frequency bands in this way. However, it should be feasible to use a pair of frequency bands in the reverse sense for some systems, the up-path band for one network being the same as the down-path band for the network using an adjacent satellite; this is Case II.

In order to simplify the calculations, the following approximations should be used:

- Basic transmission losses on the space-to-Earth path are assumed to be identical, regardless of the satellite and earth station considered. Similarly, the basic transmission losses on the Earth-to-space path are assumed to be identical. For each of these two types of path, the losses are calculated in respect of the minimum Earth-to-satellite distance and the centre frequency of the band shared by the two networks. These assumptions are reasonable in the case of the geostationary satellite orbit because the difference in loss between the shortest and longest free space paths is only about 1.5 dB.
- Angular separation between two satellites as viewed from an earth station (topocentric) is assumed to be equal to the geocentric angle. This is a good approximation, since the largest error incurred is about 18% in angle and about 1.8 dB in earth station off-beam antenna gain. Also, since the geocentric is always smaller than the topocentric angular separation, this approximation will give more conservative results.

Let A be a satellite link of network R associated with satellite S and A' be a satellite link of network R' associated with satellite S'. The symbols such as a, b and c refer to satellite link A and symbols such as a', b' and c' refer to satellite link A'.

The parameters are defined as follows (for satellite link A):

- ΔT_s : increase in the receiver noise temperature of the satellite S caused by interference in the receiver of this satellite (K);
- ΔT_e : increase in the receiver noise temperature of the earth station e_R caused by interference in the receiver of this station (K);
- p_s : maximum power density per Hz delivered to the antenna of satellite S (averaged over the worst 4 kHz band for a carrier frequency below 15 GHz or over the worst 1 MHz band above 15 GHz) (W/Hz);
- $g_3(\eta)$: transmitting antenna gain of satellite S in the direction η (numerical power ratio);
 - η_A : direction, from satellite S, of the receiving earth station e_R of satellite link A;
 - $\eta_{e'}$: direction, from satellite S, of the receiving earth station e'_R of satellite link A';
 - Note.* – The product $p_s g_3(\eta_{e'})$ is the maximum e.i.r.p. per Hz of satellite S in the direction of the receiving earth station e'_R of satellite link A';
 - $\eta_{s'}$: direction, from satellite S, of satellite S';
- p_e : maximum power density per Hz delivered to the antenna of the transmitting earth station e_T (averaged over the worst 4 kHz band for a carrier frequency below 15 GHz or over the worst 1 MHz band above 15 GHz) (W/Hz);
- $g_2(\delta)$: receiving antenna gain of satellite S in the direction δ (numerical power ratio);
 - δ_A : direction, from satellite S, of the transmitting earth station e_T of satellite link A;
 - $\delta_{e'}$: direction, from satellite S, of the transmitting earth station e'_T of satellite link A';
 - $\delta_{s'}$: direction, from satellite S, of satellite S';
- g_1 : transmitting antenna gain of the transmitting earth station e_T in the direction of satellite S (numerical power ratio);
- $g_1(\theta)$: transmitting antenna gain of the earth station e_T in the direction of satellite S' (numerical power ratio);
- g_4 : receiving antenna gain of the earth station e_R in the direction of satellite S (numerical power ratio);
- $g_4(\theta)$: receiving antenna gain of the earth station e_R in the direction of satellite S' (numerical power ratio);
- k : Boltzmann's constant (J/K);

- l_d : free-space transmission loss on the down-path (numerical power ratio);
- l_u : free-space transmission loss on the up-path (numerical power ratio);
- γ : transmission gain of the satellite link evaluated from the output of the receiving antenna of the space station S to the output of the receiving antenna of the earth station e_R (numerical power ratio, usually less than 1), given by

$$\gamma = \frac{p_s g_3 (\eta_A) g_4 l_u}{p_e g_1 g_2 (\delta_A) l_d} \quad (1)$$

- θ : minimum geocentric angular separation between the two satellites, taking the station-keeping tolerances into account.

Case I

The parameters ΔT_s and ΔT_e are given by the following equations:

$$\Delta T_s = \frac{p'_e g'_1(\theta) g_2(\delta_{e'})}{k l_u} \quad (2)$$

$$\Delta T_e = \frac{p'_s g'_3(\eta_e) g_4(\theta)}{k l_d} \quad (3)$$

In the foregoing equations, the gains $g'_1(\theta)$ and $g_4(\theta)$ are those of the earth stations concerned. In the event of precise numerical data relating to earth-station antennae not being available, the reference radiation pattern given in Recommendation 465-1 should be used.

The symbol ΔT is used to denote the increase in the equivalent noise temperature for the entire satellite link at the receiver input of the receiving earth station e_R due to interference from network R'.

This increase is the result of interference entering at both the satellite and earth-station receiver of link A. When satellites S and S' are equipped with simple frequency-changing repeaters having the same translation frequency, the interference received by link A is caused on the up-path and down-path by the same link A'.

This can therefore be expressed as follows:

$$\Delta T = \gamma \Delta T_s + \Delta T_e \quad (4)$$

$$\Delta T = \gamma \frac{p'_e g'_1(\theta) g_2(\delta_{e'})}{k l_u} + \frac{p'_s g'_3(\eta_e) g_4(\theta)}{k l_d} \quad (5)$$

Hence

Equation (5) combines both the up-path and the down-path interference.

When the translation frequencies of the two satellites are not the same, different links in network R' may interfere with link A at the satellite and earth station receivers; let these links be called A' and $\bar{A}'$ respectively (the parameters such as a' , b' and c' relate to link $\bar{A}'$). Then:

$$\Delta T = \gamma \frac{p'_e g'_1(\theta) g_2(\delta_{e'})}{k l_u} + \frac{\bar{p}'_s \bar{g}'_3(\eta_e) g_4(\theta)}{k l_d} \quad (6)$$

In the same way, the increase $\Delta T'$ in the equivalent noise temperature for the entire satellite link at the receiver input of the receiving earth station e'_R under the effect of the interference caused by network R is given by the following equations:

$$\Delta T'_{s'} = \frac{p_e g_1(\theta) g'_2(\delta_e)}{k l_u} \quad (7)$$

$$\Delta T'_{e'} = \frac{p_s g_3(\eta_{e'}) g'_4(\theta)}{k l_d} \quad (8)$$

When both satellites share the same translation frequency, then

$$\Delta T' = \gamma' \frac{p_e g_1(\theta) g'_2(\delta_e)}{k l_u} + \frac{p_s g_3(\eta_{e'}) g'_4(\theta)}{k l_d} \quad (9)$$

When the two satellites have different translation frequencies (calling two links of the R network A and $\bar{A}$ and denoting the corresponding parameters $\bar{a}$, $\bar{b}$, and $\bar{c}$):

$$\Delta T' = \gamma' \frac{p_e g_1(\theta) g'_2(\delta_e)}{k l_u} + \frac{\bar{p}_s \bar{g}_3(\eta_{e'}) g'_4(\theta)}{k l_d} \quad (10)$$

For the two multiple-access satellites this calculation must be made for each of the satellite links established via one satellite in relation to all of the satellite links established via the other satellite.

If only the up-path or the down-path of the wanted satellite network shares a frequency band with the interfering satellite network, the value for ΔT should be obtained from equation (4) with either ΔT_s or ΔT_e having a zero value, as appropriate.

Case II

Retaining the notation of the previous § 2.1, the noise temperature increase ΔT_s at the satellite receiver input of link A is given by:

$$\Delta T_s = 3.28 \times 10^3 \frac{p'_s g'_3(\eta_s) g_2(\delta_{s'})}{k \theta^2 l_u} \quad (11)$$

The apparent increase in equivalent link noise temperature is then given by:

$$\Delta T = \gamma \Delta T_s \quad (12)$$

The increase $\Delta T'$ in the equivalent noise temperature of the link A' caused by emissions from the satellite associated with the link A is given by:

$$\Delta T' = \gamma' \Delta T'_{s'} = 3.28 \times 10^3 \times \gamma' \frac{p_s g_3(\eta_{s'}) g'_2(\delta_s)}{k \theta^2 l'_u} \quad (13)$$

where

l'_u : free space transmission loss on the up-path in link A'.

If only one band is shared by the two links A and A', interference between adjacent-satellite links will occur only into the link which uses the shared band for its up-path.

Interference between earth stations associated with reverse-frequency assignment links is to be dealt with by co-ordination procedures analogous to those used for co-ordination between earth and terrestrial stations.

Interference between near-antipodal reverse-frequency assignment satellites cannot be analysed by means of equations (11) to (13), but must be limited by restricting e.i.r.p. or receiving system sensitivity in the pertinent directions.

2.2 *Comparison between calculated and predetermined percentage increase in equivalent satellite link noise temperature*

The calculated values of ΔT and $\Delta T'$ shall be compared with the corresponding predetermined values. The predetermined values are taken as 2% of the appropriate equivalent satellite link noise temperatures (see Radio Regulations, Appendix 29):

- if the calculated value of ΔT is less than, or equal to, the predetermined one, the interference level from satellite link A' to satellite link A is permissible irrespective of the modulation characteristics of the two satellite links and of the precise frequencies used;
- if the calculated value of ΔT is more than the predetermined one, a detailed calculation shall be carried out following the methods and techniques set out in Reports 388-3 and 455-2, during the co-ordination procedure between Administrations.

The comparison of $\Delta T'$ with the predetermined value shall be carried out in a similar manner.

As an example, it can be seen that in the case of a satellite link operating in accordance with current CCIR Recommendations using FM telephony and having a total noise in a telephone channel of 10 000 pW0p including 1000 pW0p interference noise from terrestrial radio-relay systems and 1000 pW0p interference noise from other satellite links, a 2% increase in equivalent noise temperature would correspond to 160 pW0p of interference noise. A substantial increase in the percentage indicated above is under study by the CCIR in order to increase the efficiency of the use of the geostationary satellite orbit.

3. **Procedure for signal-processing transponders**

In cases where a change in modulation, or re-generation of the signal, occurs in the satellite, computation of the effects of up-path interference on the total link performance will require special procedures. In some cases, for example analogue signal processing transponders involving signal demodulation and re-modulation, it should be possible to compute an appropriate value for γ which will take into account the signal processing and relate the up-path interference contribution to the down-path. For these cases the calculation would be possible using equation (4) and the modified γ factor.

In other cases, it may not be possible to compute a γ which reasonably accounts for the signal processing in the satellite, such as with digital regenerating transponders. In these cases it will be necessary to treat the up-path and down-path separately, and separate up-path and down-path equivalent link noise temperatures will need to be determined. T_{seq} and T_{ecq} would be values notified independently for the up-path and down-path respectively, T_{seq} being the total up-path equivalent system temperature referred to the satellite receiver input, and T_{ecq} the total down-path equivalent system temperature referred to the earth station receiver input. Then $\Delta T_s/T_{seq}$ and $\Delta T_c/T_{ecq}$ will be computed and compared with a predetermined value. This value should be taken as 2% for both the up-path and the down-path, pending further study.

4. **Determination of the satellite links to be considered in calculating the increase in equivalent satellite link noise temperature from the data furnished for the advance publication of a satellite network**

The greatest increase in equivalent satellite link noise temperature caused to any link of another satellite network, existing or planned, by interference produced by the proposed satellite network must be determined.

The most unfavourable potential transmitting earth-station site of the interfering network should be determined for each satellite receiving antenna of the network suffering interference by superimposing the "Earth-to-space" service areas of the interfering network on the space station receiving antenna gain contours plotted on a map of the Earth's surface. The most unfavourable potential transmitting earth station site is the one in the direction of which the satellite receiving antenna gain of the network interfered with, is the greatest.

The most unfavourable potential receiving earth-station site of the network suffering interference, should be determined in an analogous manner for each "space-to-Earth" service area of that network. The most unfavourable potential receiving earth station is the one in the direction of which the satellite transmitting antenna gain of the interfering network is the greatest.

The receiving and transmitting antenna gains cited in the preceding two paragraphs are obtained from the respective antenna radiation patterns requested in Article 9A of the Radio Regulations as part of the Advance Publication Procedure. When one or both of the geostationary-satellite systems under consideration are in existence, it is preferable that actual measured satellite antenna patterns be utilized. Such measured patterns would permit more realistic assessment of the interference potential in the ensuing calculations.

When the satellite of the network suffering interference is equipped with simple frequency-translating transponders, the above determinations are made in pairs, one for the receiving antenna of a particular transponder and one for the "space-to-Earth" service area associated with the transmitting antenna of that transponder.

The calculation procedure described above may be used to determine the greatest increase in equivalent noise temperature caused to any satellite link in a proposed satellite network by interference produced by any other satellite network.

REPORT 455-2

FREQUENCY SHARING BETWEEN NETWORKS
OF THE FIXED SATELLITE SERVICE

(Question 2-3/4, Study Programme 2J-2/4)

(1970 – 1974 – 1978)

1. Introduction

The extent to which the same frequencies may be used by different satellite networks of the Fixed Satellite Service, without causing unacceptable interference, is a subject of considerable importance; bearing as it does on the efficient use of the frequency spectrum and the geostationary-satellite orbit.

Frequency sharing may be affected by:

- the number of satellites sharing a given frequency band channel;
- the orbits in which the satellites move;
- the radiation pattern of the earth-station and space-station antennae;
- any difference in polarization between wanted and interfering signals;
- the relative operating power flux-densities of the wanted and interfering signals, both at the satellites and at the earth stations;
- the interference reduction factor between the input to the space-station, and/or earth-station receiver, and the demodulated output at the earth station;
- the portion of the total noise allowance allocated to interference from other satellite networks.

The problems of frequency sharing between satellite networks are reviewed in this Report.

2. Calculation of interference levels

The extent to which satellite networks may share the same frequency band is predicated on the magnitude of the tolerable interfering-to-wanted carrier levels.

2.1 *Ratio of wanted-to-interfering carrier levels*

The ratio of down-path wanted-to-interfering carrier powers at an earth station can be expressed as follows:

$$(C/I)_D = R + G_4 - G_4(\theta) + Y_D \quad (1)$$

where:

- $(C/I)_D$: the wanted-to-interfering carrier power ratio at the input to the receiving system (dB);
 R : the ratio of the power flux-density of the wanted signal to the power flux-density of the interfering signal (dB);
 G_4 : the receiving gain of the earth-station antenna for the wanted satellite (dB);
 $G_4(\theta)$: the receiving gain of the earth-station antenna for the interfering satellite (dB);
 Y_D : the polarization discrimination of the earth-station antenna against the interfering carrier (dB).

A similar expression can be used to determine the up-path wanted-to-interfering carrier ratio. A method for calculating these ratios for interference between geostationary-satellite networks is given in detail in the Annex I.

2.2 *Post-demodulation signal-to-interference noise ratio*

In FDM/FM telephone links, the ratio of a 1 mW test tone to the interference power in the worst telephone channel can be expressed as follows:

$$10 \log \frac{1 \text{ mW test tone}}{\text{Unweighted interference power in a telephone channel of 3.1 kHz bandwidth}} = \left(\frac{C}{I} \right) + B \quad (2)$$

where:

- B : the interference reduction factor (dB) between the input to the space-station and/or earth-station receiver and the demodulated output at the earth station (B is sometimes called the “receiver transfer factor”).

- $\left(\frac{C}{I} \right)$: the wanted-to-interfering carrier power ratio at the input to the receiving system (dB).

The value of the interference-reduction factor, B , depends on the type of modulation used on the various carriers. An expression similar to (2) can be used for analogue signals in general if the factor B can be meaningfully applied. Reference should be made to Report 388-3 for further information.

The case of digital transmission presents a number of difficulties, one of the most important being that the characteristics and performance of digital modulation systems, which may be used for future fixed satellite networks, are not yet firmly established. Another difficulty is that the nature of digital detection makes it impossible to define the interference performance of the thermal noise performance independently, (in contrast to analogue signals above threshold). Reference should be made to Report 388-3 which sets out the techniques for calculating interference noise in systems carrying multichannel telephony, for the different modulation methods likely to be encountered on wanted and interfering transmissions.

For interference into frequency-modulated television systems reference should be made to Report 449-1.

2.3 *Intermittent exposure to interference*

Generally, in the case of two satellites near to one another (whether they form part of a single system or belong to independent systems), the extent of any resulting interference depends upon whether they both receive signals from their corresponding earth stations at the time of proximity. If they do so, then the form of treatment given in previous sections of this Report will apply. If not, i.e., if one satellite is intentionally energized from the ground and the other only unintentionally, then the effect of any interference will be less marked. This may occur, for example, in an unphased satellite system when the separation between adjacent satellites is temporarily small, or in the case where an interfering satellite is in the vicinity of a geostationary satellite. In these cases, off-beam antenna gain reductions will apply both to the illumination of the interfering satellite and to the reception of its interfering emission. If the output spectral power density of the space-station repeater is a function of the flux illuminating the satellite, the power spectral density produced by the interfering satellite at the earth station would be below its normal operating value. Quite small angular separations between satellites might be tolerable in such situations.

3. **Permissible levels of interference between networks using geostationary satellites**

Interference between networks which use geostationary satellites does not vary greatly with time, and it is feasible to co-ordinate system characteristics so that the degradation of channel performance due to this interference does not exceed an acceptable level.

3.1 *The significance of the level of interference*

Considerable attention continues to be given to the question of what constitutes an acceptable level of interference. It is generally held that the operator of a system should be in essential control of his system's performance and that, therefore, interference should not be a major factor affecting that performance.

However, the gain of earth and space station antennae usually decreases monotonically with increasing angle off the direction of maximum gain. These antennae characteristics may be the only source of isolation between the networks, in which case there is an inverse relationship between the interference level and the separation angles. Thus, the greater the permissible interference between two networks serving more or less the same area on the earth surface, the smaller can be the orbital separation between the space stations of the two networks. Similarly, the greater the permissible interference between two networks whose space stations are in the same, or nearly the same, orbit location and serve different areas on the earth surface through narrow-beam antennae; the closer can those service areas be to each other, and the greater can be the number of times that the frequency band is re-used in different parts of the world.

Thus, the greater the permissible level of interference, the higher will be the potential frequency reuse density between networks both on the geostationary satellite orbit (smaller intersatellite spacing) and on the earth surface (denser coverage). There is therefore, a conflict between the desire to bound, at relatively low levels, the interference between networks, to maintain reasonable design and operating integrity in a network, and the no less significant need to maximize frequency re-use and, thereby, orbit-spectrum utilization.

3.2 *Permissible levels of interference in FDM/FM telephony transmissions*

It is generally agreed that the maximum level of interference noise from all other satellite networks which may be regarded as permissible lies between 10% and 25% of the total noise recommended for the Hypothetical Reference Circuit (HRC) (Recommendation 353-3) a further 10% being permitted for interference from terrestrial systems.

If the lower inter-network figure is taken, then the total interference entry from all sources does not exceed 20%; these levels allow the system operator good control over the performance of his system.

If the higher inter-network figure is taken, and if it is assumed that interference from all sources is additive, then it would seem that 35% of the total noise budget is allocated to sources of noise outside the direct control of the system operator. The practical situation may not be quite as severe as this. Thus, at some earth stations there may be far less than the full 10% of interference noise from terrestrial sources, and the maximum entry of interference from other networks may not fall in the same channel as the maximum entry of interference from terrestrial sources. Nevertheless, while such a high interference entry may increase the number of satellites that can be accommodated in the orbit, it has the following disadvantages:

- the loss by the system operator of control of the performance of his system is substantial;
- interference takes various forms and may lead to degradations of types not simply constrainable by a bound on channel noise power; for example impulsive interference might develop;
- the capacity of a satellite is reduced;
- the feasibility of a large measure of frequency re-use within a satellite network, which is in itself a very powerful method of increasing the efficiency of use of the orbit and spectrum, is reduced by the presence of so much external noise.

This is a general area needing further study.

One possible way of increasing the toleration of interference by systems would take advantage of the difference between the susceptibilities to interference of various carriers of different baseband capacity. Thus, for example, a high capacity FDM/FM carrier usually has low susceptibility, whereas a low capacity carrier has high susceptibility. Thus, if it were agreed that a low capacity carrier might have to accept a larger part of its total noise in the form of inter-network interference, whereas a high capacity carrier would not accept more than a small fraction, then the system as a whole would distribute a large interference component in the most constructive way.

3.3 *Permissible levels of interference in FM/TV transmissions*

For video transmissions the performance specifications in the HRC are given in Recommendations 354-2 and 567 for the appropriate TV standards. Recommendation 483-1 recommends that the inter-network interference noise should not exceed 10% of the total noise in the HRC. An increase in this percentage should be studied further.

First, TV/FM transmissions are relatively insensitive high-power transmissions since they have to meet threshold conditions for a relatively large bandwidth. On the whole, a TV/FM transmission is not much more sensitive to interference than a 972-channel FDM/FM telephony carrier and is thus not likely to constitute the limiting case during co-ordination in which more sensitive carriers need to be protected. This would continue to hold true if an interference criterion were applied which is based on carrier sensitivity as discussed in § 3.2. Thus, there may be no need to increase the interference allowance for video in order to facilitate co-ordination.

Second, interference effects in an FM/TV transmission are highly dependent upon the character of the interference and it would be desirable for further study to be given to the relationship between baseband noise due to interference, the nature of the interfering signal, and the subjective picture quality which, as in the FDM/FM telephony case, is the ultimate, although not quantifiable, criterion. An increase of the allowable interference noise to 25% of the total baseband noise may well produce objectionable picture quality for some types of interference. The matter is aggravated by the fact that, unlike the FDM/FM telephony case, no tradeoff between internal noise and that due to external interference, is possible; a "good" picture tends to be subjectively more sensitive to certain types of interference than a poorer picture.

Thus, a move towards increasing the FM/TV interference criterion, may on the one hand, not be necessary, and on the other, not be readily possible.

3.4 *Permissible levels of interference in digital transmissions*

In the case of digital transmissions, Recommendation 522 gives the performance criterion in terms of the parameter most significant to the user; the bit error rate. The long-term performance criterion stipulates that the bit error rate should not exceed the provisional value of one part in 10^6 , 10-minute mean for more than 20% of any month.

To derive an interference criterion which, as before, should reflect a moderate impact of interference on total performance, one could remain in the bit error rate domain. However, unlike the analogue FDM/FM telephony case, there is no simple linear relationship between contributions to the bit error rate due to internal noise and that due to interference. As a consequence, one is obliged to relate the interference criterion to the actual performance criterion as a reference. Thus, one could choose as the interference criterion, that interference which would raise the bit error rate from $10^{-6}/k$ to 10^{-6} where k is some positive number which would constitute the allowable *increase* in bit error rate due to interference. The matter is discussed further in Report 793.

However, since it is necessary to refer to the performance criterion, it has been found to be advantageous to express the interference criterion in terms of a predemodulation parameter which is usually readily available. Having the choice between the wanted-to-unwanted carrier ratio (C/I) and the external-to-internal noise ratio (I/N), the latter is preferred, because it is largely independent of specific equipment characteristics. The resulting interference criterion is reflected in Recommendation 558. An allowance is also to be made for interference from terrestrial systems where a band is shared with such services.

This criterion has the further advantage that the contributions from various entries may be added in the power domain. In the digital case, as in the analogue FDM/FM telephony case, a trade-off between internal and external noise is possible within reason, and a large digital interference allowance may be considered to facilitate co-ordination. The effect of interference into digital systems is a function of the amplitude and phase distribution of the interfering carrier. Carrier offset of an interfering signal thus has little effect, as long as the main part of the interference spectrum falls within the wanted channel.

3.5 *Relationship between total allowable interference and individual entries*

The total interference in a network of the Fixed Satellite Service is due to contributions of varying levels from many other networks. The question arises how to control all the individual entries so that their cumulative total does not materially exceed the allowable total that a network has been designed to be capable of accommodating.

For a number of years the single interference entry was limited by CCIR Recommendations to 4/10 of the total allowable. This ratio corresponds approximately to the contribution to the total of each of the two neighbour-satellite networks among a homogeneous equi-spaced population, the satellites of which serve essentially the same area on the Earth surface.

In practice, this single-valued bound has proven unsatisfactory because:

- it is not associated with any given spacing between co-coverage neighbour-satellites and may be claimed for quite large spacings. This tends to be wasteful of orbit; and
- it is an insufficient safeguard to ensure that actual cumulative interference will not exceed the total allowable for which networks have been designed.

To remedy these shortcomings, two potential strategies have been proposed:

The first of these strategies is aimed at producing a reasonably high degree of homogeneity among all networks in a given fixed satellite service band by imposing emission and sensitivity constraints on the transmit and receive systems respectively, of the earth and space stations in all networks. These constraints would be chosen in such a way that they allow "reasonable" implementation and transmission parameters to be used for acceptable intersatellite spacing between co-coverage networks (e.g. 4 to 10 degrees of arc). This strategy would be highly effective since it establishes an absolute interference between networks. At the same time, it would be relatively restrictive since the design and operating ranges of the technical parameters in all networks are necessarily bounded.

The other strategy is to establish, for the entire geostationary orbit or for various orbit segments, one or more satellite separation goals, as above (e.g. 4 to 10 degrees), and to allow for spacings not exceeding that goal (of co-coverage spacing), a single entry contribution of which is somewhat less than half the total interference allowance; but which decreases the allowable contribution for greater spacings in some monotonic fashion, perhaps corresponding to the side lobe characteristics of earth station antennae. Interference entries from networks with separate coverage areas may also be accommodated within this strategy. This approach is somewhat less restrictive since it does not directly bound the implementation and operating parameters of networks.

It is clear that any attempts to increase the current levels of maximum interference must be accompanied by safeguards which ensure that cumulative actual interference does not exceed the increased total allowance materially. It would appear that the second strategy could accomplish this. Further study of both of these strategies is required.

Finally, there are certain transmissions which are quite incompatible with each other as regards mutual interference on a co-channel basis. An example is the interference which a high density carrier such as TV/FM with insufficient carrier energy dispersal, or a low-index high-capacity FDM/FM carrier, may cause in a low capacity carrier such as an analogue or digital SCPC transmission. Juxtaposition of such incompatible transmissions would produce extreme imbalance in the characteristics of two networks and should be avoided by convention or in co-ordination.

4. *Technical means to facilitate co-ordination between networks using geostationary satellites*

If during the co-ordination process between two systems evidence is provided that the interference criteria cannot be met over the entire band then it may be necessary to consider segmenting the frequency band and thereby enabling the co-ordination of homogeneous bandwidth segments. Particular attention should first be given to interference from high spectral density carriers such as FM television. Whenever possible these carriers should

be limited to a segment of the RF band free of highly sensitive transmissions such as SCPC telephony. If similar transponder arrangements are used for both networks this could be achieved by allocating different transponders for each type of transmission. If co-ordination is performed at an early design stage, another possibility could be to arrange the transponder frequency plans so that the filter cross-over bands of one network fall within the usable bandwidth of the other. This makes it possible to locate the highest spectral density carriers of one network within the guard bands of the other.

If this is not possible it may be necessary to reduce the interfering spectral density by improving the TV energy dispersal technique. Conventional spreading of a TV carrier, such as is presently employed to alleviate interference in low capacity multichannel carriers, is relatively ineffective in protecting an SCPC transmission since it is based on uniform dispersal of the often otherwise undeviated TV carrier at the video frame rate, i.e. 50 or 60 Hz. The TV carrier, dispersed at such a low rate and over one or, at most, a few MHz, is seen by an SCPC carrier much like pulsed interference of the full TV carrier power with a duty cycle equal to the ratio of the SCPC occupied bandwidth to the peak-to-peak dispersal deviation.

To achieve improved interference reduction for this case, a spreading technique for analogue FM/TV has been proposed and tested by analysis and measurement. This technique simply uses a higher dispersal frequency, ideally of the same order of magnitude as the information element rate of the SCPC signal. In practice, this is approximated by a dispersal frequency at the video line rate. It has been shown that the video signal, for line rate dispersal, does not require additional RF bandwidth. The interference effect on SCPC is then much more like that of a white noise signal uniformly distributed over the dispersal bandwidth, because the SCPC receiver filter can no longer respond to the actual sweeping TV carrier but rather, sees it as occupying an appreciable instantaneous bandwidth.

Both triangular and sawtooth spreading appear to be effective, and either spreading waveform is expected to be easily removable at the receiver. Initial measurement results are quite promising; however, substantial additional work, including subjective and objective measurements, is required. For additional information, see Annex II of Report 384-3.

It should be noted that single-frequency dispersal of analogue FM/TV at the video line rate may prove unattractive for the reduction of interference into FDM/FM multichannel telephony or other analogue FM/TV carriers since the dispersal frequency may appear in the baseband of other carriers sharing common elements of the transmission system with the dispersed carrier.

Frequency interleaving could be another means to facilitate the co-ordination procedure. The extent to which closer satellite spacing and improved orbit/spectrum utilization may be achieved by interleaving the carrier frequencies of one satellite with those of a neighbouring satellite, is critically dependent on the type of modulation (e.g. FM or PSK) and the satellite multiple-access technique (e.g. single carrier or FDMA) applied to the wanted and interfering carriers. The achievable reduction in satellite spacing may be expressed in terms of an improved tolerance to RF interference which, depending on the modulation and satellite multiple-access techniques applied, may vary from about 0 to 12 dB.

For the case of frequency-modulated FDM telephony an improvement in required carrier-to-interference ratio is obtained when interleaved carrier frequencies are used. This is of interest in considering the efficiency of use of the orbit. The improvement is found to be up to about 12 dB, depending upon the modulation indices.

In the case of systems employing a variety of modulation and satellite multiple-access techniques, the maximum interleaving advantage may only be achieved by appropriate co-ordination and the allocation of traffic or transmission modes to specific satellite RF channels. However, this may not be possible in practice because of the difficulty in accurately forecasting traffic requirements or new applications and the loss of flexibility in reassigning traffic. As noted above in § 3.4, there will be little improvement in satellite spacing requirements to be obtained by interleaving digital signals in such cases, but this is not likely to be a limiting factor, since the spacing required by analogue signals will usually be greater.

In view of the above considerations, the advantages of frequency interleaving between satellites may, in practice, be restricted to relatively few applications.

5. Separation of satellites in space and time domains

5.1 Introduction

Frequency sharing between satellites of different networks is feasible if sufficient angular separation exists between their satellites, or if the transmitter of one is turned off when sufficient angular separation is not available. The methods for establishing the required spatial and temporal separations for geostationary and non-geostationary satellites are indicated in the following paragraphs.

5.2 Separation angles between geostationary satellites

Calculations made in a U.S.S.R. contribution show that the required separation angles between satellites are not unreasonable (of the order of 1° to 6°) in most cases. Larger separations are, however, required in the case of multi-channel systems with low modulation indices, or single-channel systems.

5.3 *Interference between geostationary and non-geostationary systems*

5.3.1 *Separation in the space domain through orbit gaps*

Angular separation between satellites with inclined orbits and geostationary satellites can be maintained in the space domain only if parts of the geostationary-satellite orbit are reserved for the equatorial crossings of moving satellites.

This approach puts a limit on the number of geostationary satellites that can be employed.

5.3.2 *Separation in the time and space domains*

Separation between satellites in the space and time domains means that, during periods of insufficient spatial separation, temporal separation is achieved by terminating transmissions from one of the satellites causing mutual interference.

The entire system using non-geostationary satellites is planned to include hand-overs, antenna reorientations, and tracking, as part of the normal operating procedures. The need to transfer traffic from one satellite about to be turned off for interference reasons, to another, will not add unduly to the complexity of the overall system.

Fig. 1 represents the zone within which interference between geostationary and non-geostationary satellites is possible. This is the volume limited by the surface of revolution around the axis of the Earth formed by straight lines tangent to the Earth and intersecting the plane of the equator at the geostationary orbit altitude.

Interference between geostationary and non-geostationary satellites can be prevented by terminating transmissions from one of them when insufficient angular separation exists for earth stations communicating via these satellites. If earth stations working with a non-geostationary satellite are designed for tracking hand-overs, and rapid antenna reorientations, then technically it should be feasible to cease transmissions from such a satellite when sufficient spatial separation is not available between it and a geostationary satellite. When the geostationary satellite orbit becomes fully utilized, this could mean that non-geostationary satellites should technically be capable of ceasing transmissions when they are in the zone of interference as shown in Fig. 1. However, this is a question which would need to be decided by the Administrations concerned.

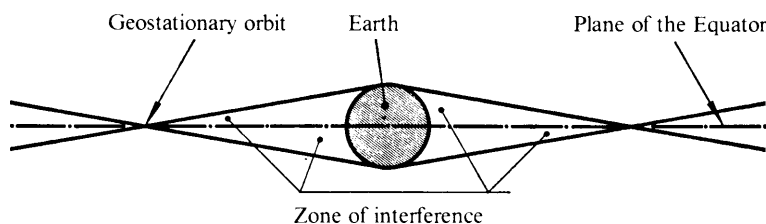


FIGURE 1 — *Zone of interference between geostationary and non-geostationary satellites*

6. Summary

This study shows that the minimum angular separation between satellites depends on the acceptable level of interference noise contributions in the baseband channels from other satellites and earth stations.

Frequency sharing between geostationary-satellite networks is feasible if sufficient angular separation is present. The actual spacing required for satellites in the geostationary-satellite orbit depends on system parameters such as e.i.r.p radiation pattern of earth-station antennae, etc., and cannot be defined in general terms at this time.

Frequency sharing between the networks of geostationary and moving satellites is feasible if one of the satellites is turned off when sufficient angular separation is not provided. The decision on which satellite to turn off will have to be made by the Administrations affected.

The actual spacing required between satellites also depends upon the permissible level of total interference and on the way in which this total is built up from the interference entries from individual satellites. The optimization of these levels and the determination of means for regulating them is an important matter for further study under Study Programme 2J-2/4.

ANNEX I

METHOD OF CALCULATING THE WANTED-TO-INTERFERING CARRIER RATIOS
IN GEOSTATIONARY-SATELLITE NETWORKS

1. Introduction

The amount of interference experienced between two satellite networks depends on the operating parameters of the networks involved. To assess the interference between radiocommunication-satellite networks it is usual to divide the computation process into two stages. The first stage of the calculation is to determine the wanted-to-interfering carrier ratios between any two potentially interfering carriers, at the appropriate receiver input terminals. The second stage is then to relate these ratios to the noise power in the baseband channel. This Annex provides the method for calculating the wanted-to-interfering carrier ratios. For the second stage, reference should be made to Report 388-3.

2. Method

The interference geometry between two satellite networks is shown in Figs. 2a and 2b. The minimum topocentric (as seen from a point on the Earth) satellite spacing angles should take into account the nominal geocentric satellite spacing angle, the satellite position uncertainties (longitude of the orbit nodes and orbit inclinations) and the geographical locations of the earth stations. The use of the geocentric angular spacing, θ , instead of the topocentric satellite spacing angle, is simpler for the computation and its use is justified by the fact that the two angles are nearly equal. Also, the topocentric spacing angle is always greater than the geocentric spacing angle and hence the calculations based on geocentric spacing angles are conservative.

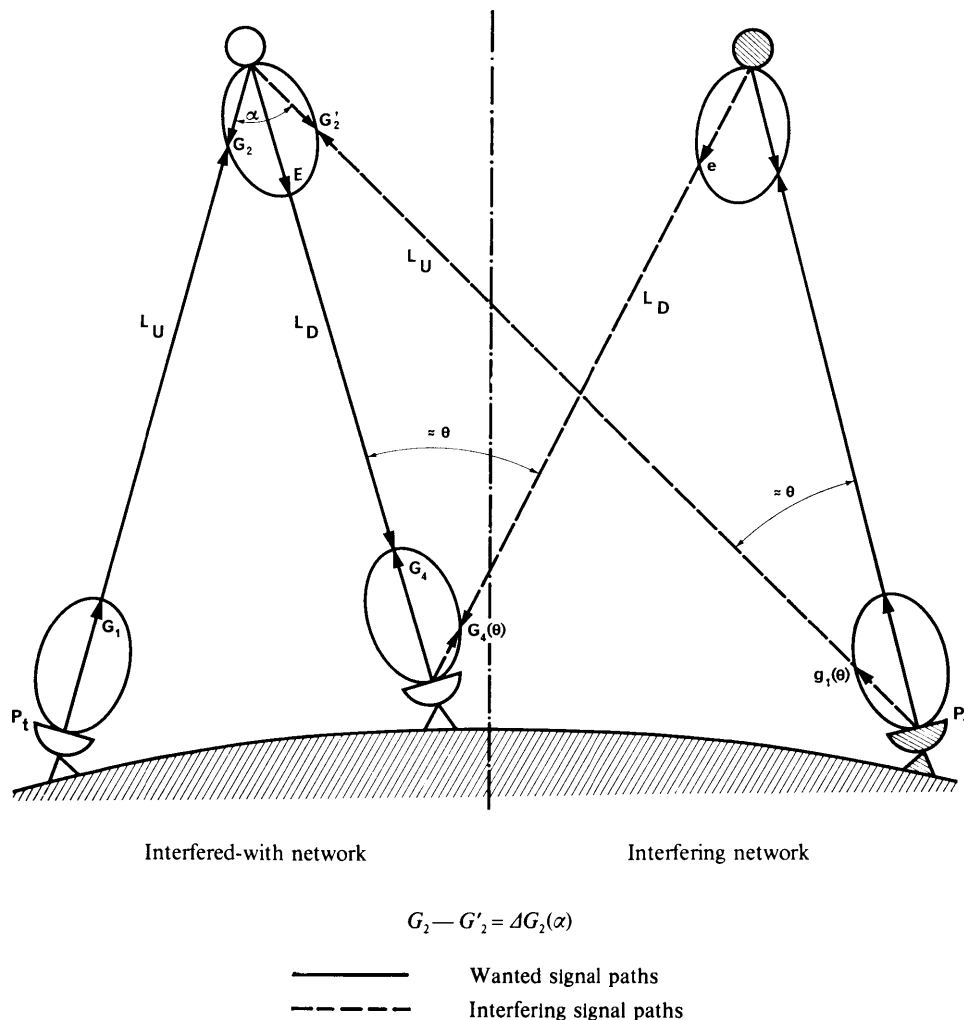


FIGURE 2(a) — Interference geometry between two satellite networks, Case 1

Radiocommunication satellites require frequency assignments in two frequency bands, one for the up-path and the other for the down-path. It is current practice for frequency bands to be associated in pairs, one band being used for up-paths and the other for down-paths. Case I below, is concerned with the possibility of interference between two networks which have been assigned frequency bands in this way; thus interference from an up-path enters the wanted up-path and interference from a down-path enters the wanted down-path. However, it should also be feasible to use a pair of frequency bands in the reverse sense, for some networks, the up-path band for one network being the same as the down-path band for the network using an adjacent satellite; in these circumstances interference from an up-path enters the wanted down-path and interference from a down-path enters the wanted up-path. This is Case II.

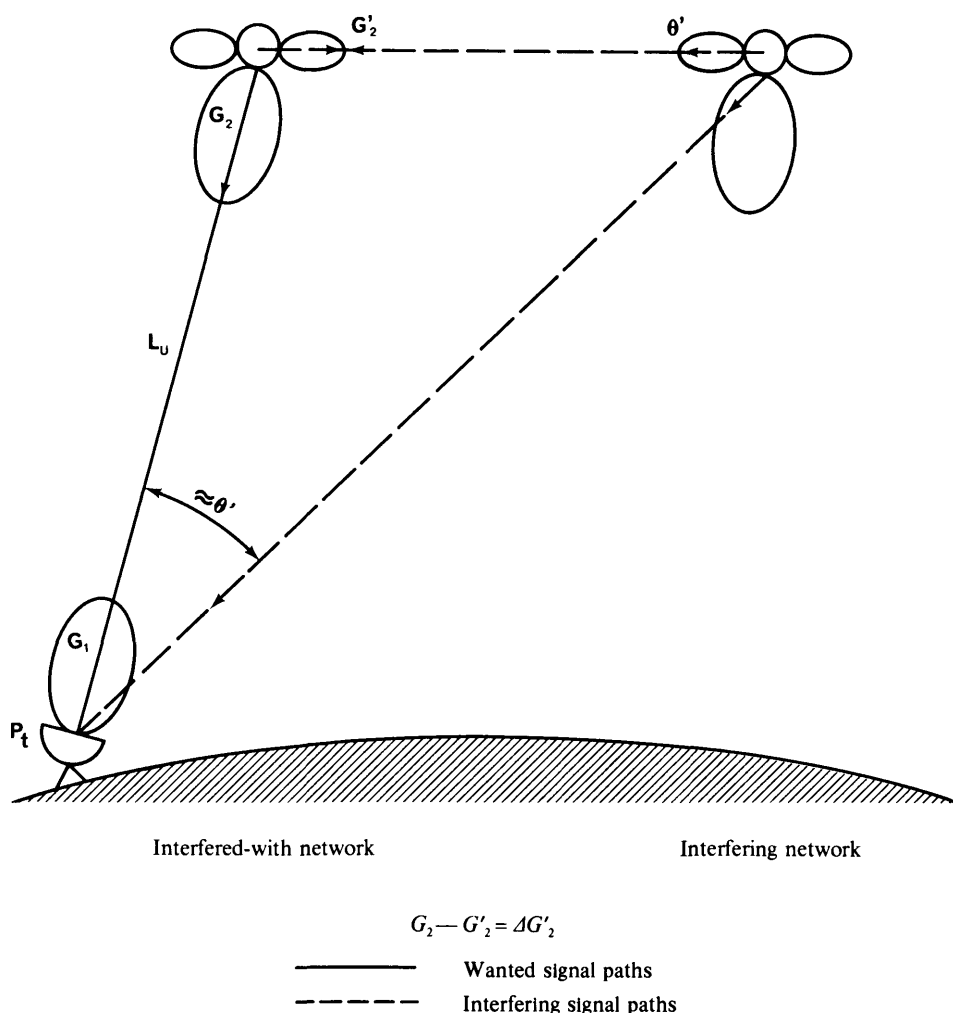


FIGURE 2(b) — *Interference geometry between two satellite networks, Case II*

2.1 Case I

The following propagation conditions are assumed to apply to the up-path and down-path wanted-to-interfering carrier ratios:

- due to propagation effects and local precipitation both the wanted and the interfering signals which are transmitted by earth stations situated at different points on the Earth's surface will fluctuate. Unless the e.i.r.p.s of the earth stations are adjusted so that the levels received by the satellites are always the same, a margin should be introduced in calculating the mean interference value to the up-path equation;
- the ratio of the wanted signal level to the interference level on the down-path does not vary with time. Any interference strong enough to have an appreciable effect would be caused by other satellites close to those of the wanted network so that the discrimination due to the directivity of the earth-station antenna is insufficient to separate the wanted from the interfering signals. Hence the wanted and interfering signals will be attenuated to the same degree when propagation conditions vary, since they will travel through the same disturbed areas. Consequently, fluctuations caused in the received wanted signal will have no significant effect on the level of interference produced in the baseband and, therefore, a down-path margin may usually be neglected.

The first stage of the computation procedure requires solution of the two equations:

$$(C/I)_U = P_t + G_1 - \Delta L_U - M_U - p_i - g_1(\theta) + \Delta G_2 + Y_U \quad \text{dB} \quad (3)$$

and

$$(C/I)_D = E + G_4 - \Delta L_D - e - G_4(\theta) + Y_D \quad \text{dB} \quad (4)$$

where

- $(C/I)_{U,D}$: up- and down-path wanted-to-interfering carrier ratios (dB);
- P_t, p_i : transmit powers of wanted and interfering carriers delivered to the associated earth-station antenna (dBW);
- G_1, G_4 : transmit and receive antenna gains of one or more wanted earth stations (dB);
- ΔL_U : path loss differential in the up-path to the wanted satellite from the two earth stations, $\Delta L = L_{\text{wanted}} - L_{\text{interfering}}$ (dB);
- ΔL_D : path loss differential in the down-path to the wanted earth station from the two satellites, ΔL as above (dB);
- M_U : up-path margin in the wanted network (dB);
- $g_1(\theta)$: antenna gain component at the unwanted earth station towards the wanted satellite (dB);
- (θ) : geocentric minimum angular satellite spacing at the interfering earth station;
- ΔG_2 : differential in receive antenna gains at the wanted satellite toward the two earth stations, $\Delta G_2 = G_{2 \text{ wanted}} - G_{2 \text{ interfering}}$ (dB);
- Y_U : minimum polarization discrimination between interfering up-path carrier and wanted satellite receive antenna (dB);
- Y_D : minimum polarization discrimination between interfering down-path carrier and wanted earth-station receive antenna (dB);
- E, e : e.i.r.p. of the wanted and interfering carriers in the direction of the wanted earth station (dBW);
- $G_4(\theta)$: antenna gain component at the wanted earth station toward the interfering satellite (dB).

Notes on some of the factors in the above equations

- Powers and antenna gains associated with the wanted network are in capitals, those associated with the interfering network use lower case letters. Suffixes associated with the various antenna gains follow the signal path, viz: 1 = earth-station transmit, 2 = satellite receive, 3 = satellite transmit, 4 = earth-station receive.
- The antenna gains $g_1(\theta)$ and $G_4(\theta)$ should, if possible, be computed using measured earth-station antenna patterns. However, for preliminary calculations, the generalized earth-station antenna radiation pattern given in Recommendation 465-1 may be applied.
- For very precise calculations the topocentric angles may be used in the expressions for g_1 and G_4 .
- The terms ΔG_2 , E and e should, if possible, be computed using measured satellite antenna patterns. Variations of path geometry with time may affect these terms; however, these variations are likely to be small and may usually be neglected.
- In the absence of information on satellite antenna polarization, the factors Y_U and Y_D must be set at 0 dB. The subject of polarization discrimination is discussed in Report 555-1.

2.2 Case II

When a given up-path frequency assignment in a wanted network is the same as the down-path frequency assignment in an interfering network, the up-path carrier-to-interference ratio in the wanted network may be approximated by:

$$(C/I)'_U = P_t + G_1 - M_U + \Delta G'_2 - e' + Y' + 20 \log \theta' - 35.2 \quad \text{dB} \quad (5)$$

where (in addition to the preceding definitions):

$\Delta G'_2$: differential in receive antenna gains at the wanted satellite, in the directions of the wanted transmitting earth station and the interfering satellite,

$$\Delta G'_2 = G_{2 \text{ wanted}} - G_{2 \text{ interfering}} \quad \text{dB};$$

e' : satellite e.i.r.p. of the interfering carrier in the direction of the wanted satellite (dBW);

Y' : minimum polarization discriminations between the interfering-satellite carrier and the wanted-satellite receive antenna (dB);

θ' : geocentric minimum angular satellite spacing for the wanted earth station (degrees).

The calculation of interference from an unwanted up-path to the wanted down-path, that is, from an earth station transmitter into the wanted earth station receiver should be based on the techniques discussed in Report 448-2 and Report 388-3. However, it should be possible to reduce such interference to a negligible level by a careful choice of earth station sites.

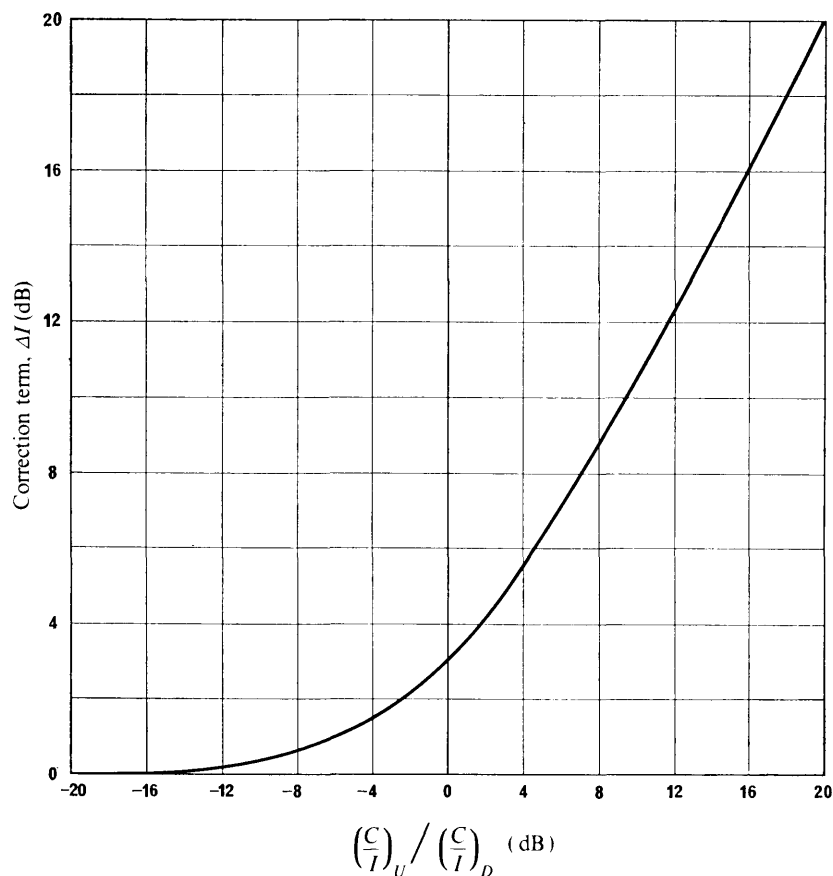


FIGURE 3 — Correction term ΔI for up-path to down-path wanted carrier to interfering carrier ratios.

$$(C/I)_U / (C/I)_D$$

2.3 Link wanted-to-interfering carrier ratio

For Case I, the overall wanted-to-interfering carrier ratio of the link depends on the up- and down-path ratios. Fig. 3 may be used to derive a correction term ΔI (in dB) from up- to down-path interference ratio which is obtained by subtracting the result of equation (3) from that of equation (4). This correction term is used as follows:

$$(C/I)_{link} = (C/I)_D - \Delta I \quad \text{dB} \quad (6)$$

For Case II, use simply:

$$(C/I)'_{link} = (C/I)'_U \quad \text{dB} \quad (7) *$$

3. Interference

§ 2 provides the formula for calculating the wanted-to-interfering carrier ratio. The specific effects on system service will depend on many additional factors such as: (1) type of service, e.g., telephony, television, data, etc., (2) type of modulation used, e.g., digital, FM, AM, (3) modulation parameters, and (4) desired carrier-to-system thermal noise ratio. Many different types of interfering signal interactions are possible. This is a subject of continuing investigation.

The most common types of transmission used for systems in the fixed satellite service are: (a) FM telephony, (b) frequency-modulation television, and (c) digitally modulated carriers. The effect at baseband of interference between similar and dissimilar signal types is required in order to predict overall link performance and establish allowable interference guidelines. This Annex presents only a method for calculating the wanted-to-interfering carrier ratios which serve as an input parameter to such calculations.

4. Summary

A step-by-step method for the calculation of interference levels between two satellite networks for one set of parameters encompasses the following:

- 4.1 designate one satellite as the "wanted", the other as the "interfering" satellite;
- 4.2 choose the parameters required to solve equations (3), (4) or (5) for one of the potential interference entries and designate the parameters in accordance with § 4.1 above;
- 4.3 solve, for the set of parameters chosen, equations (3), (4) or (5);
- 4.4 determine the network wanted-to-interfering carrier ratio in accordance with equation (6) or (7), as applicable;
- 4.5 using the result of § 4.4, and the modulation and frequency spacing data pertaining to the carriers under investigation, determine, by means of Report 388-3 the interference noise power in the interfered-with carrier;
- 4.6 repeat the above steps with the designations of "wanted" and "interfering" satellites reversed, wherever applicable;
- 4.7 repeat the above steps for all combinations of carrier and earth station which might be expected to cause interference in the two networks.

Note. — In some cases a given carrier will be subject to interference from more than one interfering carrier. In such cases, it seems permissible to add interference noise contributions on a power basis.

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* Interference between earth stations needs to be considered separately since different propagation conditions and different criteria apply.

REPORT 555-1

DISCRIMINATION BY MEANS OF ORTHOGONAL CIRCULAR AND LINEAR POLARIZATIONS

(Study Programmes 1B/4 and 1C-1/4)

(1974 - 1978)

1. Introduction

The use of orthogonal polarization can provide an effective way of increasing the capacity of the geostationary-satellite orbit.

The possible applications for orthogonal polarization are:

- frequency re-use within the main beams of satellite and earth-station antennae;
- on adjacent satellites to permit closer satellite spacing;
- on neighbouring or overlapping, satellite spot beams to reduce interference;
- reduction of interference to low-power links from more powerful links via the same satellite.

Various factors must be taken into consideration, such as cross-polarization discrimination obtainable in different parts of antenna beams and in different frequencies within the operating bands, the characteristics of polarizers, the depolarizing effects experienced in the atmosphere and ionosphere, the stability of satellite orientation, and the implementation of polarization tracking and correction.

2. Factors affecting polarization discrimination

2.1 *Earth-station antenna systems*2.1.1 *Earth-station antennae*

In the case where frequencies are re-used within one satellite, the main beam centre is the most important region.

In the boresight direction the polarization discrimination depends mainly on the feed components (orthomode transducers, polarizers etc.). Within the main beam, but away from boresight, the discrimination depends mainly on the primary radiator (e.g. feed horn), but may also be affected by the use of offset reflectors or beam waveguides. The performance of different antenna designs is considered in Annex I to this Report, together with the results of measurements on a number of antennae.

2.1.2 *Earth station polarizers*

In circularly polarized systems polarizers are used to convert between linear and circular polarization. For linearly polarized systems, rotatable polarizers may be used to align earth-station polarization to that of the received wave. In both cases adjustable polarizers may be used to compensate for depolarization effects.

If a common polarizer is used for transmission and reception, it must cover both up-link and down-link frequencies, so that wide bandwidth characteristics are required. In addition, this polarizer will be required to carry high microwave power levels while meeting the requirements of low noise temperature. Fig. 1 shows, as a function of frequency, the polarization discrimination of an earth-station polarizer specially designed for the purpose of frequency re-use and operating in the 6/4 GHz band. The noise temperature contribution is about 2K at 4 GHz.

Another approach is to design feed systems in such a way that the transmit and receive frequency bands are separated so that narrowband polarizers and orthomode junctions with improved polarization discrimination can be used.

2.1.3 *Earth-station performance*

In this section the overall performance of an antenna system consisting of antenna and polarizer is considered.

In the main beam, up to the -1 dB region, typical earth-station antennae could provide in excess of 30 dB of discrimination for circular polarization and 35 dB for linear polarization.

Well away from the main beam little cross-polar discrimination can generally be depended upon [Haidle and Fitzgerrell, 1977].

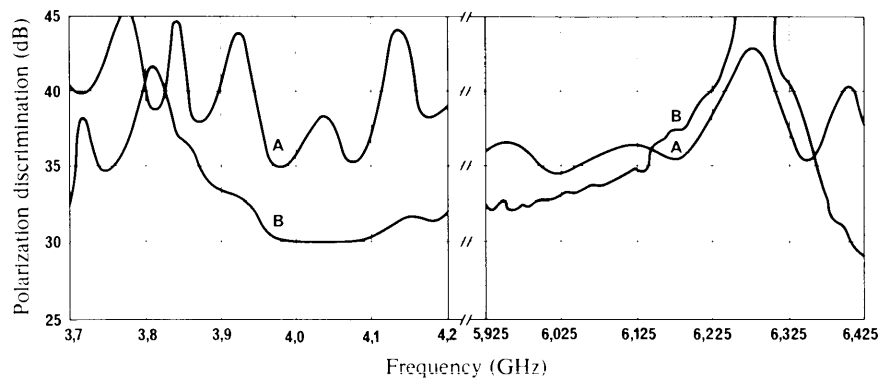


FIGURE 1 — *Characteristics of polarizers for an Earth-station*

A: Circular polarization
B: Linear polarization

2.1.4 *Measurement of earth-station antenna polarization discrimination*

The practical difficulties of measuring discrimination ratios of individual components of a system are considerable, and additional analytical studies and experimental efforts are needed before a standard method can be recommended for measuring an earth-station antenna's polarization discrimination characteristics. Possible methods include providing high purity polarized signals radiated from a satellite in orbit and the use of a co-located calibrated polarization reference antenna to be used for signal comparison with the earth-station antenna.

2.2 *Satellite antenna systems*

2.2.1 *Satellite antennae*

For satellite antennae the region of interest coincides with the beam coverage and extends to at least the -3 dB contour. Typical measurements presented in Annex I show that, in this region, satellite horn antennae with beam patterns having near perfect rotational symmetry about the focal axis can provide 40 dB of discrimination for both circular and linear polarization. Satellite antennae with aperture blockage may provide discriminations of 35 dB with linear and 30 dB with circular polarization within the same region. The problem of aperture blockage may be overcome by the employment of offset reflector designs. A practical dual linear polarized paraboloid reflector antenna with an elliptic beam of 2 : 1 aspect ratio can be expected to yield between 30 and 35 dB discrimination within the -3 dB region. Special designs utilizing gratings may have to be used to maintain high values of linear polarization discrimination.

2.2.2 *Satellite polarizers*

For satellites, the polarizers required for the generation of circular polarization, handle the transmit and receive bands separately and can be designed so as to achieve excellent polarization discrimination. For example, polarizers with 40 dB of polarization discrimination have been realized throughout 500 MHz bandwidths in the 4 GHz and 6 GHz bands.

2.3 *Propagation path*

2.3.1 *Faraday rotation*

Faraday rotation is important in the case of linear polarization but has negligible effect on circular polarization.

The change in angle of the electric field vector due to Faraday rotation depends upon the direction of propagation in relation to the Earth's magnetic field, the conditions in the ionosphere through which the wave passes, and the strength of the Earth's magnetic field. The magnitude of this rotation is also

inversely proportional to the square of frequency. Ionospheric conditions depend on many factors including the season, time of day and solar activity. Faraday rotation may occasionally reach a peak value as high as 9° at 4 GHz, 4° at 6 GHz and 1° at 12 GHz. This peak value, however, depends on the geographical locations of the earth station and satellite and may be negligible in many cases for frequencies above 10 GHz. If Faraday rotation is significant at the frequency of operation, differential rotation of the planes of polarization must be provided at the earth station as the direction of rotation as seen in the direction of propagation, is opposite for transmit relative to receive.

2.3.2 *Precipitation*

Rain and snow are important factors which may degrade polarization isolation. Precipitation can cause differences in attenuation and phase shift between orthogonal linear components of the signal so that the discrimination between either linearly or circularly polarized signals is degraded. The effect of rain on linear polarization depends on raindrop orientation angles, relative to the plane of polarization, being equal to circular polarization for an angle of 45° and less at other angles. The primary depolarization effect is caused by the difference in phase shift, but above 10 GHz the difference in attenuation becomes important as well. It is possible to correct for rain induced depolarization effects in an earth-station antenna; however, the correction for attenuation effects may reduce G/T by increasing waveguide and feed losses.

Experimental and theoretical work has shown that there is a good statistical correlation between co-polar attenuation and the discrimination between orthogonally polarized signals during rainfall. An empirical relationship has been found to provide a reasonable fit to the measured data and can be used to predict cross-polar discrimination at a site from co-polar attenuation statistics at frequencies between 8 and 40 GHz. However, although in some cases depolarization is associated with rain attenuation, in others it is not associated with significant attenuation and has been attributed to the presence of ice clouds along the path.

A more complete summary of measurements and theory is given in Report 722 of Study Group 5.

3. **Cross-polarization in satellite systems**

3.1 *Position and attitude of satellites*

The direction of the polarization plane of satellite antennae, as observed by earth-station antennae, varies as a function of satellite position relative to earth station location, and satellite attitude. These variations in the direction of the polarization plane can be kept small using current satellite attitude control and stationkeeping techniques.

3.2 *Polarization tracking*

For earth stations operating with linear polarization, tracking or periodic adjustment of the angle of polarization may be necessary to compensate for the effects of Faraday rotation and of the geometric factors discussed in § 3.1. Realignment of the angle of polarization may also be required when switching to another satellite or to another beam of the same satellite. For example, misalignments of the polarization plane of 1° and 6° result in polarization discriminations of 35 and 20 dB respectively. Polarization tracking may be achieved by rotating the entire feed assembly or by rotating only certain components such as an orthomode transducer or a suitable polarizer.

3.3 *Polarization correction*

It is possible to correct for the differential phase shift component both of residual equipment cross-polarization and of rain-induced cross-polarization, by providing in the earth-station antenna means for adjusting the orientation of the polarization ellipse and the magnitude of its axial ratio. This can be done directly by means of a rotatable polarizer and a variable differential phase shifter, or by two rotatable polarizers, in the paths of the transmitted and received signals, or by means of cross-coupling between the two orthogonal feed ports themselves. In the latter case, a small amount of one orthogonal signal would be coupled to the other to deliberately depolarize the latter until it matched the incoming depolarized signal. This does not theoretically degrade earth station G/T . A system designed to achieve polarization correction will also provide polarization tracking.

For differential attenuation effects a variable differential attenuator in the common waveguide would also be required. To restore the orthogonality, additional loss must be added to the signal path by the differential attenuator, to balance that due to rain. Cross-polarization of 30 dB due to rain-induced differential attenuation would require approximately 0.3 dB of loss. The insertion of additional loss ahead of the low noise amplifier will, of course, degrade the noise temperature of the receiving system. However, other methods may be developed for inserting the additional loss after the low noise amplifier, which could avoid this degradation of G/T .

It may be possible to correct for propagation effects on an up-link by predicting the necessary differential phase and amplitude adjustments from those required for the down-link. This possibility may be limited, however, by the difficulty of identifying separately the rain-induced and ionosphere-induced polarization rotations.

3.4 Comparison of linear and circular polarization

It is useful to summarize the considerations which should be taken into account in choosing between circular and linear polarizations in satellite systems:

- Linear polarization requires adequate alignment to be maintained between the polarization directions of the satellite and earth-station antennae.
- For linear polarization at frequencies below 10 GHz, Faraday rotation may require polarization tracking at the earth station.
- The angle of polarization of a linearly polarized antenna may vary over its design bandwidth.
- The performance of polarizers, which are required in circularly polarized systems and may also be used in linearly polarized systems, may vary with frequency.
- Suitably aligned linearly polarized systems perform better than circularly polarized ones, in the presence of rain.

4. Conclusions

As regards polarization discrimination and the efficient use of the frequency spectrum and the geostationary-satellite orbit, various factors should be taken into consideration. These are, for example, the question of choice of frequency re-use for a single satellite or for adjacent satellites; questions of the cross-polarized radiation patterns for wide angles as well as at the beam centre; and questions concerning system operation such as polarization tracking and correction. Techniques to reduce the cross-polarization component either in the case of circular or linear polarization such as, for example, adaptive techniques involving the use of pilot signals, are also the subject of study to be pursued.

Administrations are invited to submit further data on measured cross-polarization discrimination in the main beam of satellite and earth-station antenna systems and in the wide angle sidelobes of earth-station antenna systems. The cross-polarized peak sidelobe data should preferably be given as a statistical distribution in the format used in Report 391-3. Descriptions of adaptive systems for polarization correction and measured results on polarization discrimination achieved over satellite paths, with and without such systems, are also solicited.

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ANNEX I

CROSS-POLARIZED RADIATION PATTERNS OF ANTENNAE

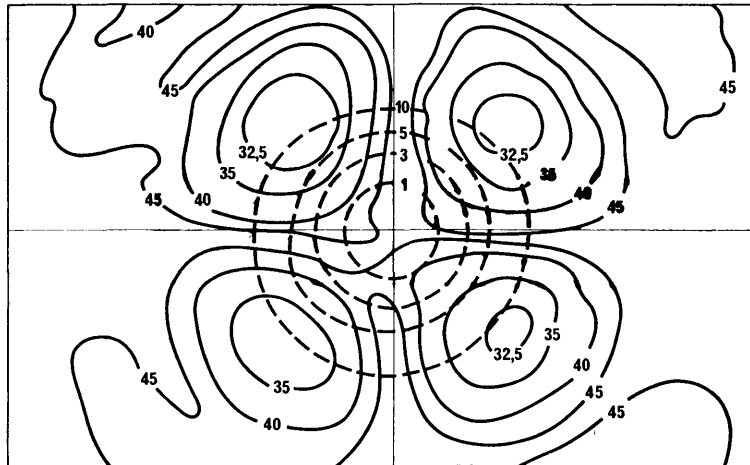
1. Theoretical considerations

The cross-polarized radiation pattern of a reflector antenna depends on both the feed horn and on the reflector configuration.

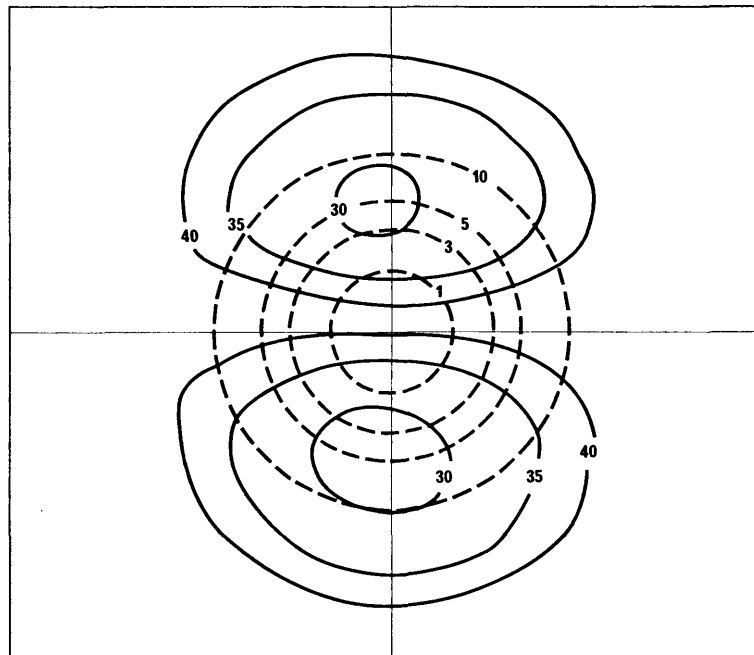
The cross-polarized radiation pattern of a conical horn in Fig. 2a shows a four-lobe structure characteristic of straight horns and symmetrical reflector configurations, with a null (high polarization discrimination) on-axis. The peaks of the cross-polarized pattern appear around the -10 dB contour of the co-polarized main lobe, well outside either the normal tracking range of an earth-station antenna or the coverage area of a satellite antenna. The cross-polarization discrimination within the main beam of a smooth-walled single-mode horn is too low for such a horn to be used in a dual polarization system. Improved performance may be achieved either by deliberately generating higher-order modes at discontinuities within the smooth-walled horn or by horn with corrugated walls so that they support hybrid modes containing less cross-polarized energy.

The performance of the feed horn is the dominant factor determining the polarization performance of a symmetrical reflector antenna. The curvature of the reflector or reflectors themselves should make a very small contribution to the cross-polarized lobes (of the order of 50 dB below the co-polarized peak). The effects of feed or sub-reflector supports may increase the cross-polarized radiation in some parts of the beam, but these effects are difficult to predict.

Fig. 2b shows that the cross-polarized radiation pattern of a horn-reflector is fundamentally different from that of the symmetrical horn. Curved offset reflectors, as incorporated in horn-reflectors, characteristically give rise to two cross-polarized peaks on either side of the plane of symmetry of the reflector with maxima rather nearer to the co-polarized peak [Gans and Semplak, 1975]. This inherent weakness of offset reflectors may be substantially eliminated in practice, either by generating an appropriate asymmetrical higher mode in the feed horn [Rudge and Adata, 1975] or by providing an appropriate curved offset sub-reflector. Figs. 3a and b show measured cross-polarization of recently developed offset-fed dual reflector antennae with almost axially symmetrical beams [Mizugutch *et al.*, 1976]. Almost perfect cancellation of cross-polarization due to the asymmetrical reflectors takes place, so that only the residual cross-polarization of the feed horn is observed.



(a) Conical horn with an almost axially symmetrical beam
(Beam symmetry factor ≈ 1.05)

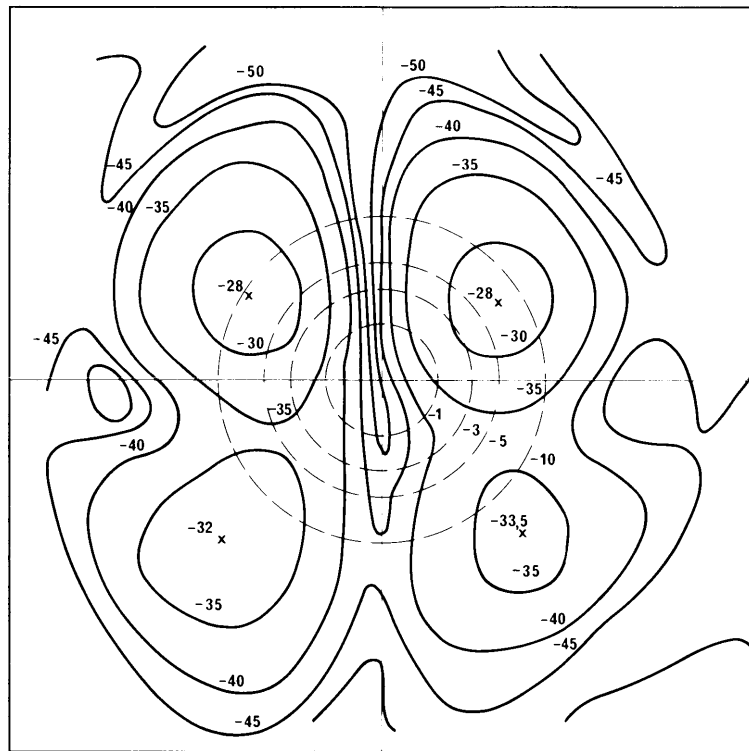


(b) Conical horn-reflector with an almost axially symmetrical beam *
(Beam symmetry factor ≈ 1.05)

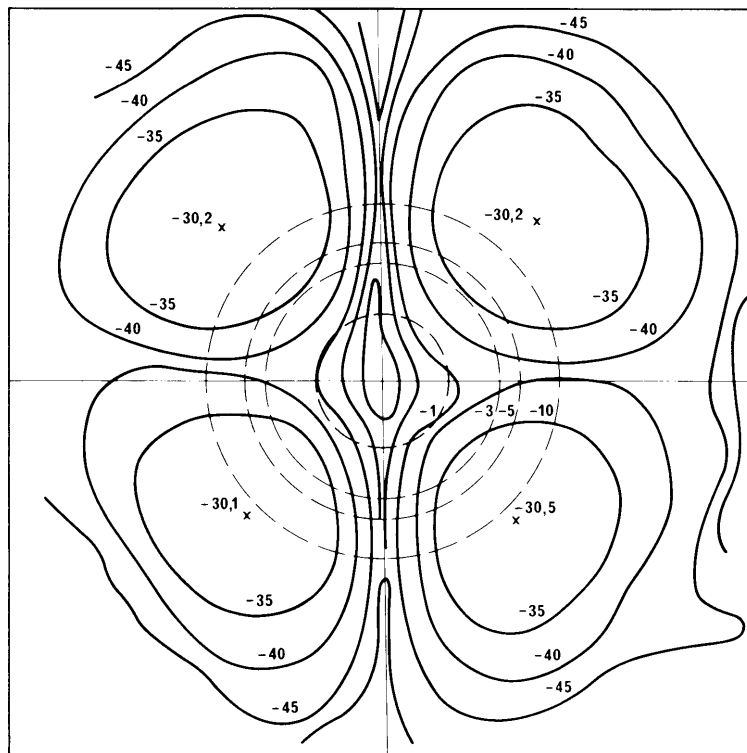
FIGURE 2 — Measured cross-polarization levels (linear polarization)

- Notes. — Solid line shows the contour of the cross-polarization level referred to the peak of the main beam in principal polarization.
- Dashed line shows the contour of the level of principal or normal polarization of the main beam.
- Figures in the diagrams show relative levels in dB referred to the peak of the main beam in principal polarization.
- The centre cross-point in the diagrams shows the peak of the main beam in principal polarization.
- The plane of electric vector in principal polarization is in the up-to-down direction on the diagrams in linear polarization.
- The axis of the horns of the horn-reflector antennae lies in the left-to-right direction in the diagram, with their vertex on the left side.

* Polarization plane perpendicular to horn axis.



(a) Offset Gregorian Antenna with dielectric-loaded conical horn feed



(b) Offset Cassegrain Antenna with corrugated conical horn feed

FIGURE 3 — Measured cross-polarization levels of offset dual reflector antennae
(Main Polarization : Horizontal)

The curved offset reflectors incorporated in a beam waveguide feed give rise to similar cross-polarized lobes, but two such reflectors can be arranged so that their effects largely cancel one another out and the resultant cross-polarized lobes incident on the Cassegrain sub-reflector are more than 30 to 35 dB below the co-polarized peak [Gans, 1976].

The discussion above has assumed linear polarization throughout. In the case of circular polarization the behaviour of both symmetrical and offset horns and reflectors is fundamentally different. In the case of symmetrical horns and reflectors the four cross-polarized lobes of the linearly polarized case become a single circularly symmetric lobe of the same magnitude and at the same distance from the co-polarized peak. In the case of horn-reflectors and curved offset reflectors there is only a very low level of cross-polarization (less than 50 dB below the co-polarized peak), but the co-polarized peak is displaced sideways by a fraction of a beamwidth, the sense of the displacement depending on the hand of circular polarization.

Earth-station antennae are generally exposed to the weather and parts of their surfaces will frequently be covered by films of water. Theoretical calculations have shown that the effects of these thin water films on the reflectors of practical earth-station antennae, will not degrade the isolation with linear polarization in directions near the antenna axis below about 35 dB at frequencies below 30 GHz [Popović, 1975 and 1976].

2. Earth-station antennae

Measurements made on 1.2 m and 3.0 m diameter Cassegrain earth-station antennae with corrugated horn feeds and designed to operate in the 11 and 14 GHz band in linear polarization provided the following results, when measured at 11.6 GHz:

Polarization discrimination of two antennae (dB)		
Antenna diameter	Region of the main-beam	
	- 1 dB	- 3 dB
1.2 m	50	42.5
3.0 m	42.5	40.0

The polarization discrimination performance of these antennae is somewhat better at 11.6 GHz than at 14.25 GHz.

Measurements at 11.6 GHz on a Cassegrain type antenna with a 10 metre parabolic main reflector and a 1.1 metre hyperbolic sub-reflector, supported by struts positioned in the 45° planes, revealed no significant differences in the co-polarization diagrams when the axis of the polarization vector was tilted by 45° from vertical, i.e. parallel to one pair of struts. However, the differences in the cross-polarization diagrams, as shown in Fig. 4, are evident with the cross-polarization discrimination improving when the polarization vector was parallel to the struts. For vertical polarization, lower values of polarization discrimination are measured in the planes parallel to the struts. This effect is caused by the different influence of the struts on the incident wave polarized parallel and perpendicular to them.

Some examples of wide-angle pattern measurements using linear polarization with relatively small size earth-station antennae without polarizers, are shown in Figs. 5 and 6. However, other measurements on larger antennae have shown that such high discrimination may not always be achieved [Haidle and Fitzgerald, 1977].

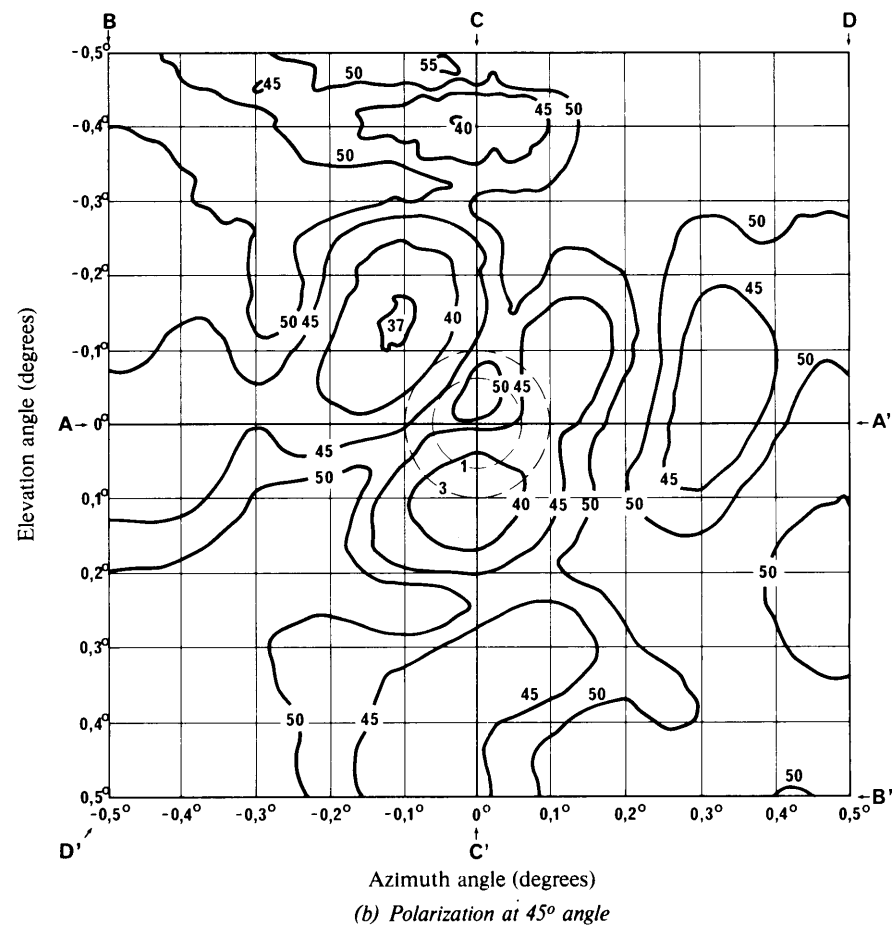
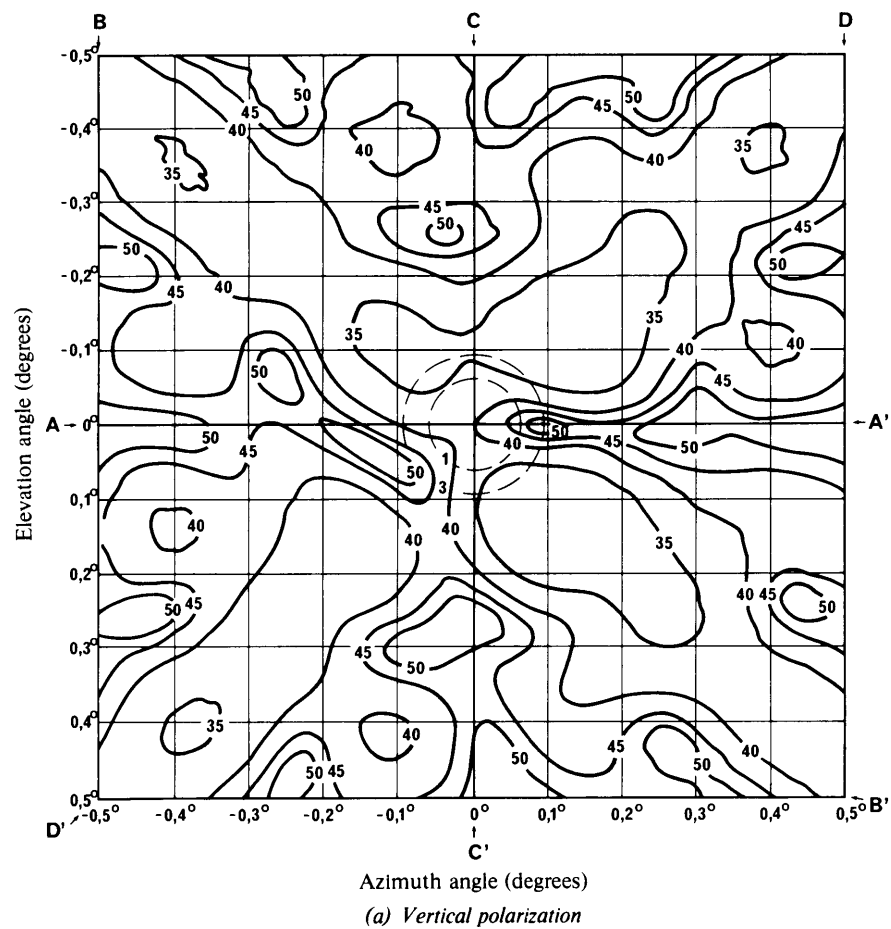


FIGURE 4 — Measured cross-polarization levels of a 10 m antenna (11.6 GHz, Linear Polarization)

— Cross-polarization
 --- Co-polarization

3. Satellite antennae

Measured cross-polarization contour diagrams for conical horns and conical horn reflectors, both used extensively on satellites, are shown in Fig. 2a and b for almost axially symmetrical beams indicating the high level of performance when rotational symmetry of the pattern can be approached.

It has been experimentally demonstrated that polarization isolation of 30 dB is achievable from reflector antenna configurations specially designed for satellite applications for linear and circular polarization, in a front-fed configuration (see Fig. 7 and Fig. 8). The elliptical beam shown in Fig. 8 is obtained by shaping the reflector. When the same antenna was used for circular polarization the contours for cross-polarization exhibited a complex structure indicating strut effects and interaction of the primary feed horn phase pattern.

It is to be noted that the front-fed configurations tested had relatively small apertures and hence the polarization discrimination and efficiency had been significantly and adversely affected by the presence of feed supporting struts. However, offset-fed configurations offer a greater potential in both respects (see Fig. 3a and b and Fig. 9). In the case of circular polarization, the overall cross-polar discrimination of these antennae is likely to be constrained by the achievable ellipticity of the polarizer.

Offset reflector configurations are of special value for satellites requiring shaped or multiple beams since the associated feed assemblies would otherwise provide excessive blockage. More complicated problems, including the interaction of adjacent feed elements, have to be taken into account in designing these antennae with high polarization discrimination.

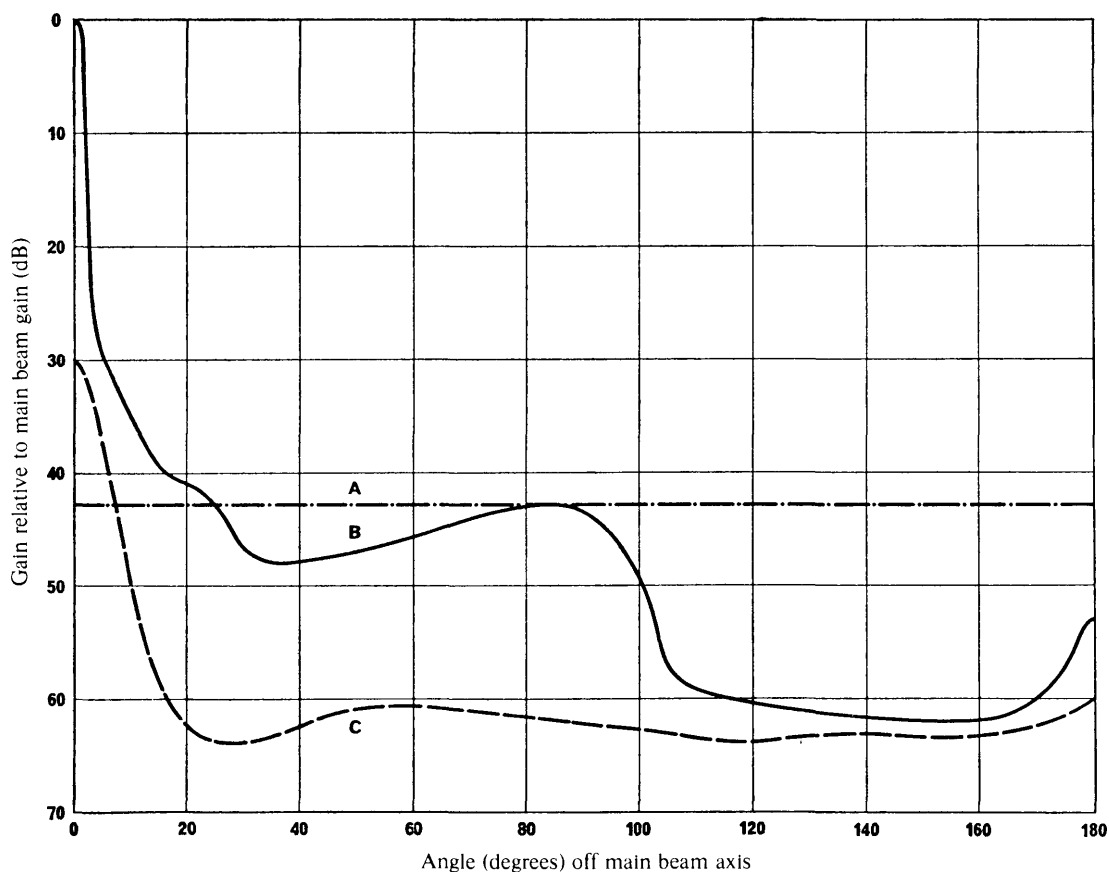


FIGURE 5 — Co- and cross-polarized pattern envelope of 10-foot (3 m) antenna

Smoothed envelope of side-lobe peaks in the horizontal plane at 6 GHz

- A: Isotropic
- B: Response to vertically polarized signal
- C: Response to horizontally polarized signal

Gain 42.8 dB at 6 GHz

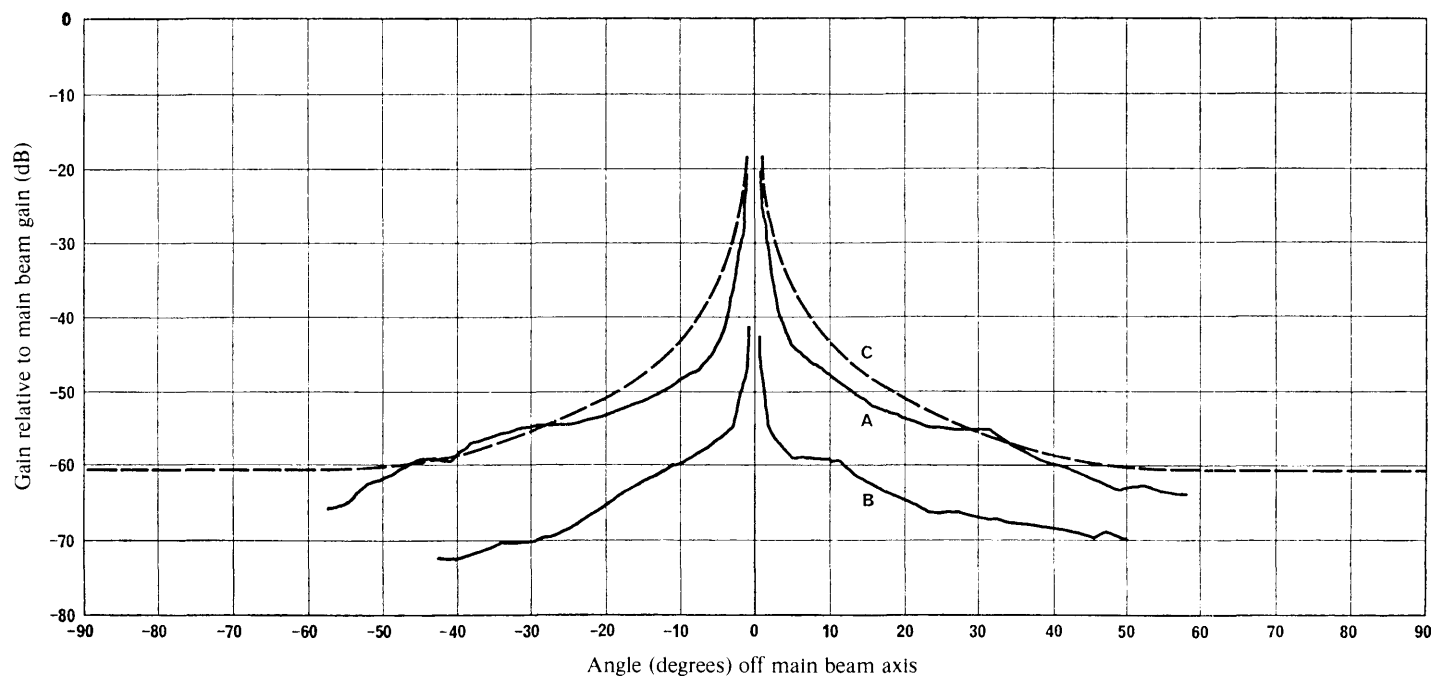
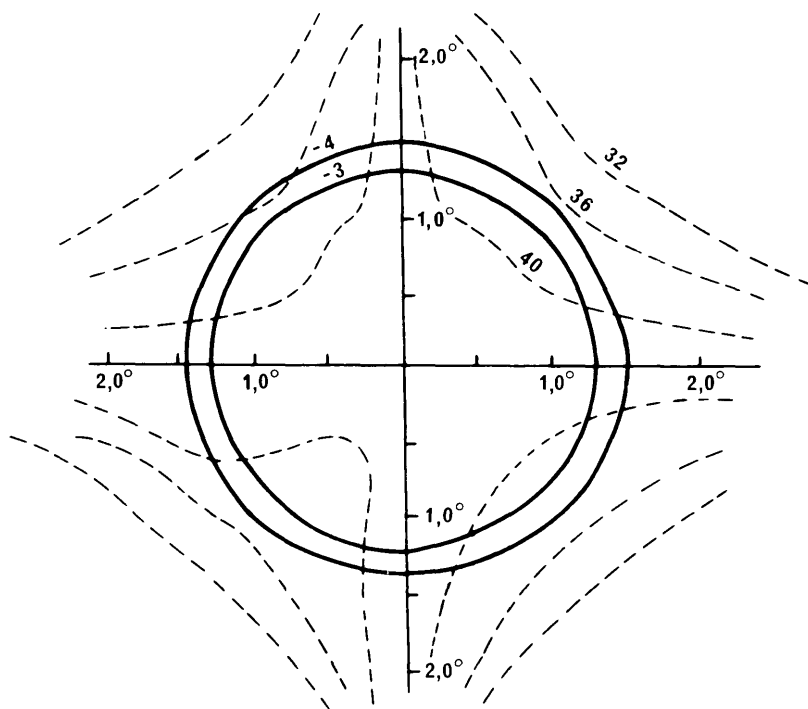
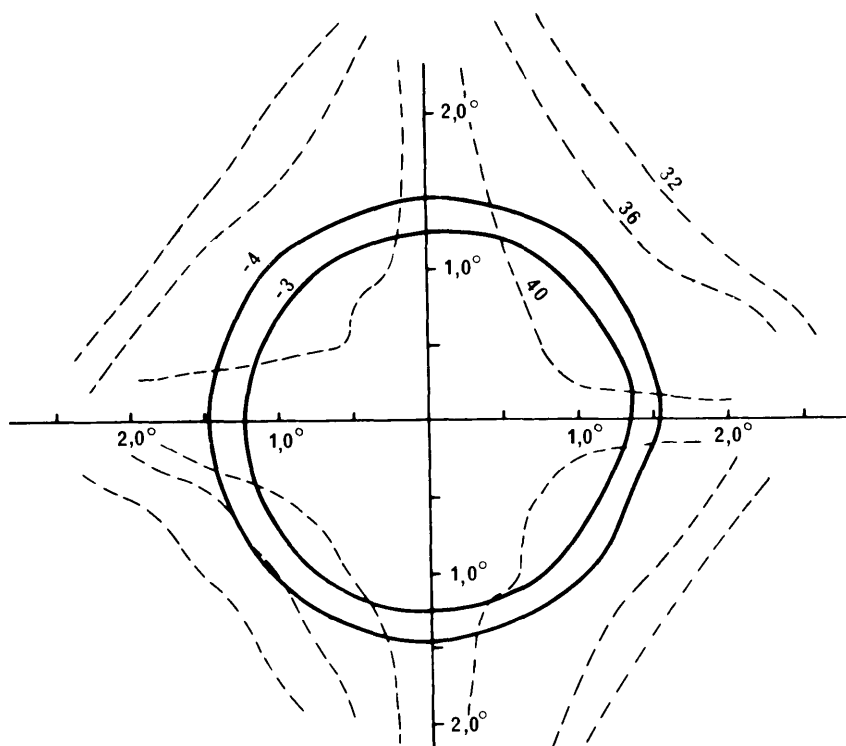


FIGURE 6 — *E-plane co- and cross-polarized antenna patterns of a linearly polarized 12-foot (3.6 m) diameter Gregorian-fed circular reflector at 10.5 GHz*

A: Co-polarized
 B: Cross-polarized
 C: Reference pattern of Recommendation 465-1



(a) Port 1



(b) Port 2

FIGURE 7 — Contour plots for linearly polarized circular beam
(values in dB)

— Co-polar isolines
 --- Polarization isolation isolines

Frequency: 11.58 GHz

Design BW (3 dB): $2.5^\circ \times 2.5^\circ$

Measured peak gain: 36.4 dB

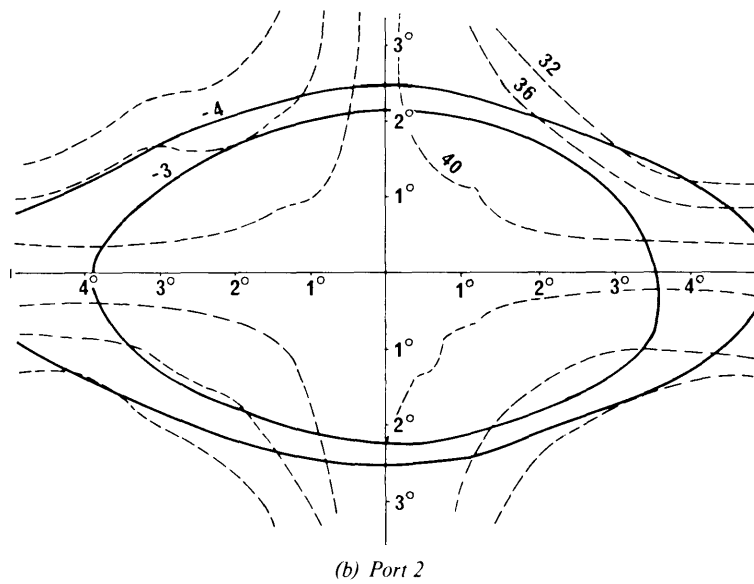
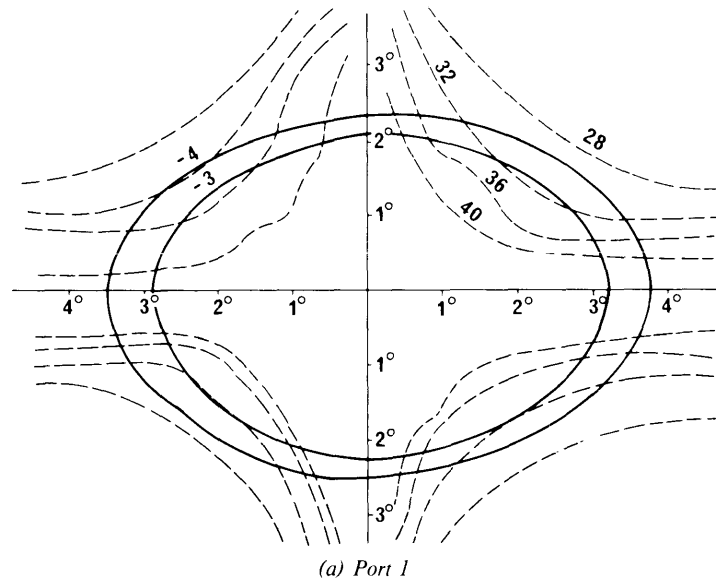


FIGURE 8 — Contour plots for linearly polarized elliptical beam
(values in dB)

— Co-polar isolines
 - - - Polarization isolation isolines
 Frequency: 14.173 GHz
 Design BW (3 dB): $7.5^\circ \times 4.25^\circ$
 Measured peak gain: 28.8 dB

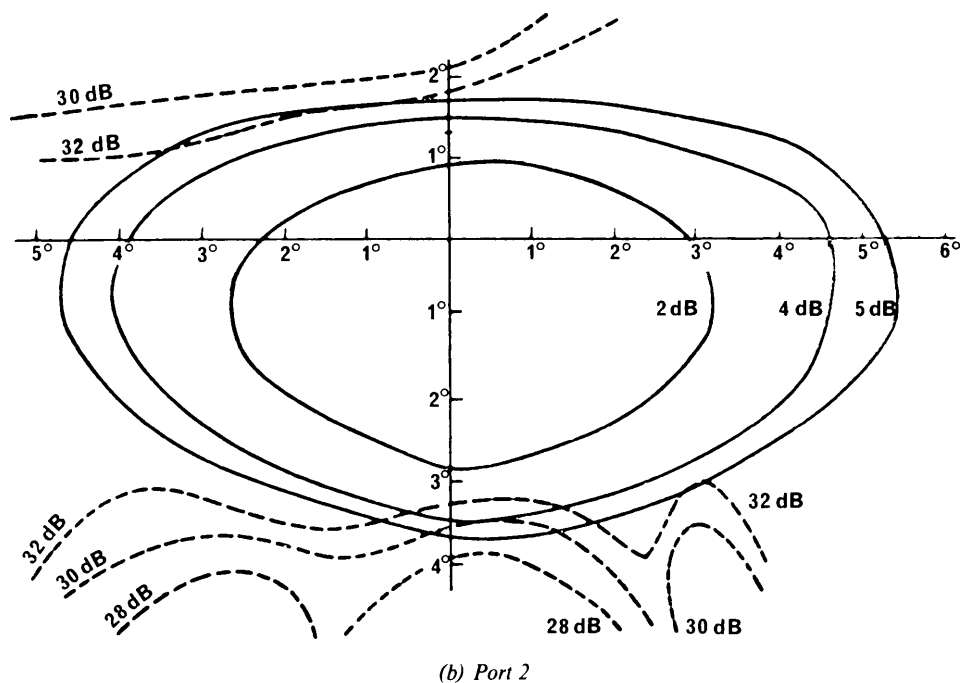
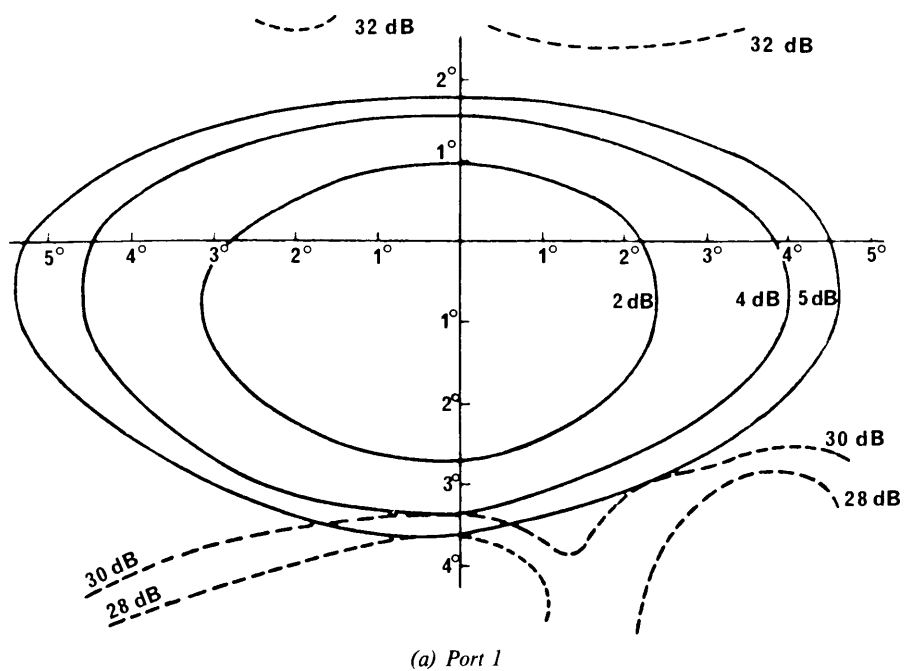


FIGURE 9 — Contour plots for circularly polarized offset-fed antenna
(values in dB)

———— Co-polar isolines
 - - - - - Polarisation isolation isolines

Frequency: 11.8 GHz

Design BW (3 dB): $7.5^\circ \times 4.25^\circ$

Measured peak gain: 28.8 dB

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REPORT 557

**THE USE OF FREQUENCY BANDS ALLOCATED TO THE
FIXED SATELLITE SERVICE FOR BOTH THE UP-PATH AND
DOWN-PATH OF GEOSTATIONARY-SATELLITE SYSTEMS**

(Study Programme 2J-2/4)

(1974)

1. Introduction

Frequencies in two different bands are assigned to a radiocommunication satellite, one for up-paths and the other for down-paths and it is usual for a given band to be used for up-paths or down-paths but not for both. Thus, two inter-system interference paths may arise, as follows:

- interfering earth station transmitter to wanted space station receiver, and
- interfering space station transmitter to wanted earth station receiver.

When the frequency bands occupied by two systems overlap, satellite spacing must be sufficient to reduce this interference to an acceptable level.

However, if two such satellites are separated by the minimum required orbital arc, it may be feasible to use another satellite, located between them and occupying the same frequency bands, the bands being assigned in the reverse sense. Thus, for example, the up-path frequency band of the third satellite would be the same as the down-path band of the other two. This may increase the total capacity of the spectrum and orbital arc occupied. The inter-system interference paths that may arise between pairs of satellite systems with reversed frequency assignments are:

- interfering space station transmitter to wanted space station receiver,
- interfering earth station transmitter to wanted earth station receiver.

This Report examines this possible frequency utilization mode as regards space radiocommunication services considered alone, and also its effect on terrestrial services in shared frequency bands. Study so far has been confined entirely to the geostationary-satellite case, but consideration should also be given to the problems that would be raised by the bidirectional allocation of frequencies to geostationary satellites in bands also used by non-geostationary satellites.

2. The increased orbit capacity obtainable by reverse frequency assignments

The carrier-to-interference ratio at the receiver input of an earth station which receives an emission from another earth station through a repeating geostationary space station, in the presence of a second similarly operating system, the space station of which is separated by a geocentric angle φ from the first space station may be approximated by:

$$(C/I)^{-1} \approx \frac{p'_e g'_1(\varphi) g_2(\delta)}{p_e g_1 g_2} + \frac{p'_s g_4(\varphi) g'_3(\eta)}{p_s g_4 g_3} \quad (1)$$

where

- p_e, p'_e : the available transmitting powers at the earth station antenna inputs of the wanted and the interfering system, respectively;
- p_s, p'_s : the available transmitting powers at the space station antenna inputs of the wanted and the interfering systems, respectively;
- g_1, g_2, g_3, g_4 : the nominal main beam antenna gains in the wanted system; the suffixes follow the transmission path: 1 = earth station transmit, 2 = space station receive, 3 = space station transmit, 4 = earth station receive;
- $g'_1(\varphi), g_4(\varphi)$: the antenna gain at the interfering transmitting earth station in the direction of the wanted space station, and the antenna gain at the wanted receiving earth station in the direction of the interfering space station, respectively;
- $g_2(\delta), g'_3(\eta)$: the receiving antenna gain at the wanted space station in the direction of the interfering transmitting earth station, and the transmitting antenna gain at the interfering space station in the direction of the wanted receiving earth station, respectively (δ and η are the discrimination angles between the wanted and interfering directions).

When, in the interfering system, the directions of up- and down-path frequencies are reversed from those in the wanted system, the carrier-to-interference ratio may be approximated by equation (2), it being assumed that all significant interference will be received from satellites in orbital positions within 60° of the wanted satellite.

$$(C/I)^{-1} \approx \frac{p'_s g'_3(v) g_2(\varepsilon) l_u}{p_e g_1 g_2 l_0} \quad (2)$$

where

- $g_2(\varepsilon), g'_3(v)$: the receiving antenna gain at the wanted space station in the direction of the interfering space station, and the transmitting antenna gain at the interfering space station in the direction of the wanted space station, respectively;
- l_u, l_0 : the free-space attenuations in the wanted system's up-path, and between the interfering and the wanted space stations, respectively, in the same frequency bands.

To assess the orbit utilization obtainable with the use of reverse-direction frequency assignments relative to that obtainable with co-direction assignments only, several normalizing and simplifying assumptions can be made:

(a) Homogeneity of systems

- equal earth station and satellite powers:

$$p'_e / p_e = p'_s / p_s = 1$$

- equal space station antenna beamwidths:

$$g_2 = g_3 (= g'_2 = g'_3)$$

- equal earth station antenna diameters and side-lobe patterns of the form:

$$g_1(f) = a_1 / \rho^b$$

$$g_4(f) = a_4 / \rho^b$$

where ρ is the angle off the beam axis and where a_1, a_4 and b are parameters;

(b) topocentric and geocentric angular spacing between space stations to be small and about equal. With this assumption,

$$l_0 \approx \varphi^2 l_u$$

* The values for v and ε will not be less than 60° .

(c) underestimation of interference between co-direction frequency systems by postulating:

$$g_2(\varepsilon) = g'_3(v) = 1$$

- (d) overestimation of interference between reverse-direction frequency systems by postulating $g_2(80^\circ) = g'_3(80^\circ) = 1$ (space stations see each other at an angle of about $\pi/2$ off their beam axes);
- (e) in a given frequency band, assume the space station receiver noise temperatures to be about 10 times the earth-station receiver noise temperatures; and assume the up-path carrier-to-thermal noise ratio to be not less than twice the down-path carrier-to-thermal noise ratio.

With these assumptions, summing the interference contributions from many co-direction frequency systems at uniform satellite spacing φ_c , one obtains the approximate expression:

$$(C/I)_c^{-1} \approx \frac{2\zeta(b)^*}{\varphi_c^b} \left[\frac{a_1}{g_1 g_2} + \frac{a_4}{g_3 g_4} \right] \quad (3)$$

where a_1 and a_4 correspond to the transmitting and receiving earth station antennae, respectively, in the wanted system.

When co-direction and reverse-direction frequency space stations are alternated, with spacing φ_{rc} , along the orbit, summation of all the interference contributions yields:

$$(C/I)_{rc}^{-1} \approx \frac{2\zeta(b)}{(2\varphi_{rc})^b} \left[\frac{a_1}{g_1 g_2} + \frac{a_4}{g_3 g_4} \right] + \frac{3\zeta(2)^{**}}{20 g_1 g_2 \varphi_{rc}^2} \quad (4)$$

Since, for both cases, the interference in the wanted system should be the same (for equal capacity at equal performance), setting $(C/I)_c$ equal to $(C/I)_{rc}$ establishes a relationship between φ_c and φ_{rc} :

$$(\varphi_{rc}/\varphi_c)^b \approx 2^{-b} + \varphi_{rc}^{b-2} \frac{0.1233}{(a_1 + a_4 g_1/g_4) \zeta(b)} \quad (5)$$

Equation (5) may be solved for the "relative orbit utilization ratio" φ_c/φ_{rc} as a function of φ_c , for specific frequencies and antenna patterns.

Postulating two types of patterns for earth-station antennae, namely, the CCIR reference pattern for which $a_1 = a_4 = 0.063$ and $b = 2.5$, and an advanced-design pattern for which, optimistically, $a_1 = a_4 = 0.016$ and $b = 3.0$, and assuming a ratio $g_1/g_4 \approx f_{up}^2/f_{down}^2 = 2.25$ (which corresponds to the band pairings 6/4 GHz, 15/10 GHz and 30/20 GHz), one can derive the two curves shown in Fig. 1.

It is apparent that the use of reverse-direction frequency assignments on alternate satellites holds the promise of substantially better orbit utilization than the use of only co-direction frequency assignments, particularly with implementation and operating parameters which allow close spacing between co-direction frequency space stations.

The foregoing argument applies to homogeneous orbit utilization as described above, but a similar advantage may not be obtained in an heterogeneous situation.

* $\zeta(b)$, Riemann's Zeta function.

** The contribution from reverse-direction frequency systems was taken twice over in order to account for an equal amount of interference between the earth stations.

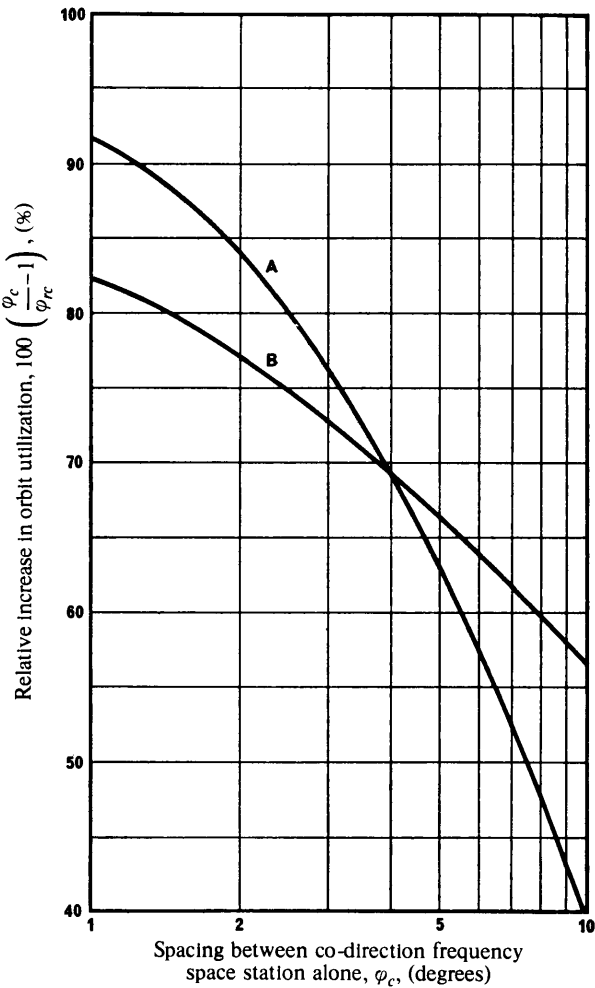


FIGURE 1 — Increase of orbit utilization with reverse-direction frequency systems relative to that with co-direction frequency systems only

A	B
$a_1, a_4 = 0.016$	$a_1, a_4 = 0.063$
$b = 3.0$	$b = 2.5$
$g_1/g_4 = 2.25$	$g_1/g_4 = 2.25$

3. Interference between quasi-antipodal space stations with reverse frequency assignments

Space stations which use narrow-beam antennae and high values of e.i.r.p. may cause interference into each other when they are at nearly antipodal locations (Fig. 2).

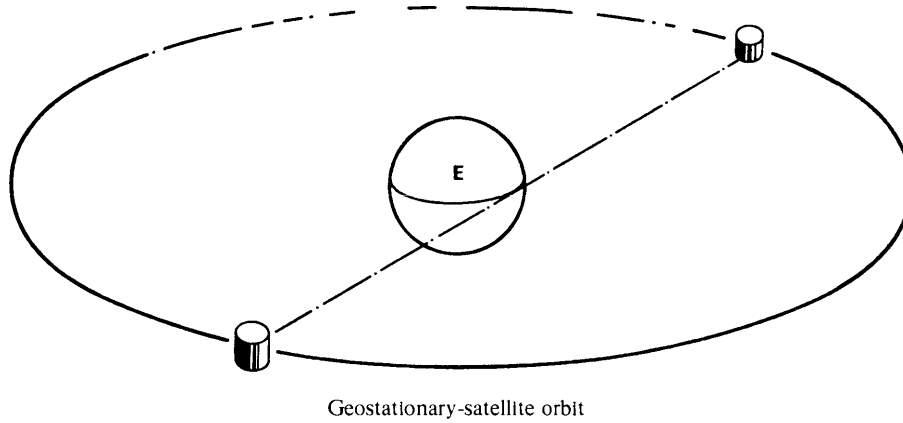


FIGURE 2 — Geometry of near antipodal satellites

E: Earth

To avoid such interference, appropriate sharing criteria must be adopted.

The level of near-antipodal interference power may be assessed as follows:

Let the receiving antenna gain at a space station in the direction of the equatorial limb (i.e., toward a near antipodal space station) be designated by g_a and let the near antipodal space station radiate an e.i.r.p. designated by e'_s in the direction of its earth limb (i.e., toward the first space station), then the received interference power is given by:

$$i = \frac{e'_s g_a}{I_a} \quad (6)$$

where I_a is the antipodal free-space attenuation between the two space stations:

$$I_a \approx 1.27f^2 \times 10^{19} \quad (7)$$

with f = frequency in GHz.

When considering the thermal noise power at the receiver input, given by $n = kT_R B$, where T_R is the receiving system noise temperature and B is the effective receiver bandwidth, one may assume that the receiving system noise temperature is frequency-dependent. Stipulating a receiving system noise temperature at a spacecraft of 1500 K at 6 GHz, it is suggested that for other frequencies the noise temperature be considered to follow a half-power law:

$$T_R(f) = 1500(f/6)^{0.5} = 612f^{0.5} \quad \text{K} \quad (8)$$

Furthermore, signal characteristics in the Fixed Satellite Service indicate that a reference bandwidth of 1 MHz might be appropriate for interference assessments. Hence, it is suggested that e'_s in equation (6) be the (interfering) equivalent isotropic radiated power in a 1 MHz bandwidth, and that the thermal noise power also be normalized to 1 MHz.

Then, the interference-to-thermal noise ratio in a 1 MHz bandwidth may be expressed by:

$$I/N = \frac{e'_s g_a}{I_a k T_R B} = \frac{e'_s g_a}{1.07 f^{2.5} \times 10^5} \quad (9)$$

Assuming further that the up-path thermal noise in a space communications system accounts for no more than 1/3 of the total intrasystem noise, and that the interference be allowed to be about 1/20 of the intrasystem noise, the ratio I/N should not exceed a value of 3/20. Hence, equation (9) may be reformulated to establish a relationship between the permissible e.i.r.p., e'_s , in a 1 MHz bandwidth, from the interfering space station and the antenna gain in the interfered-with space station, both in the direction of the equatorial earth limb (points A or B in Fig. 3):

$$e'_s g_a < 1.6 f^{2.5} \times 10^4 \quad (10)$$

Fig. 4 shows the relationship between e'_s and g_a for various frequency bands of interest.

Where these bands are used in the down-path and are shared with terrestrial services, limitations on power flux-density establish maximum values for e'_s , as shown for the frequency bands 4, 6, 12 and 20 GHz. Values of g_a corresponding to values of e'_s greater than the limits shown can safely be used.

Where the bands are used in the up-path and are shared with terrestrial services, permissible values for e'_s need not be less than those from terrestrial transmitting stations; these are shown for the frequency bands 6, 12, 20 and 30 GHz. Values of g_a corresponding to values of e'_s greater than those indicated for terrestrial emissions can safely be used.

In exclusive bands, restrictions on both e'_s and g_a may have to be adopted in order to avoid interference between near antipodal space stations.

It must be emphasized that these restrictions apply only in the directions towards the equatorial earth limb; i.e. towards points A and B of Fig. 3.

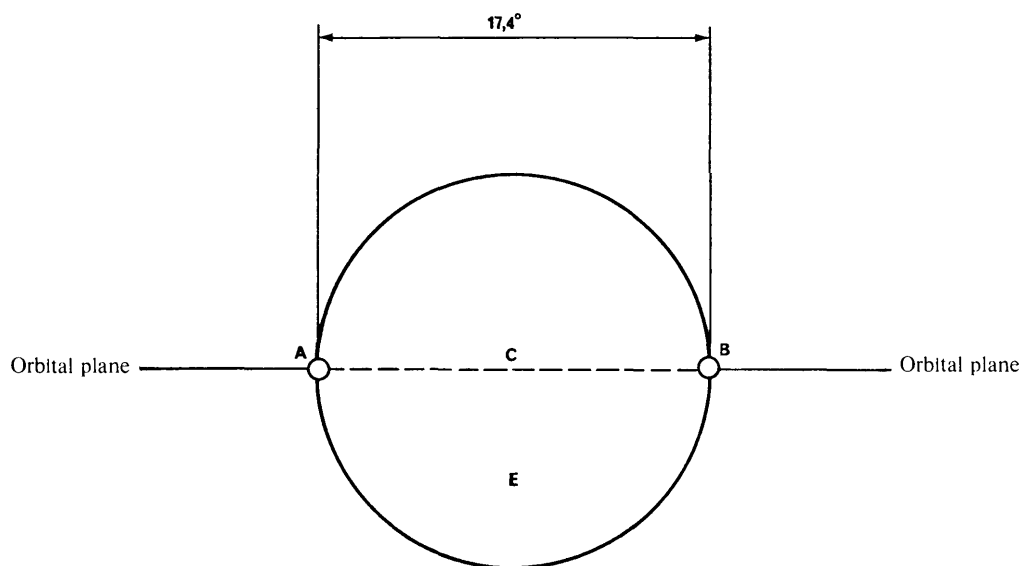


FIGURE 3 — The Earth and the geostationary-satellite orbit as seen from a geostationary-satellite

C: Equator
E: Earth

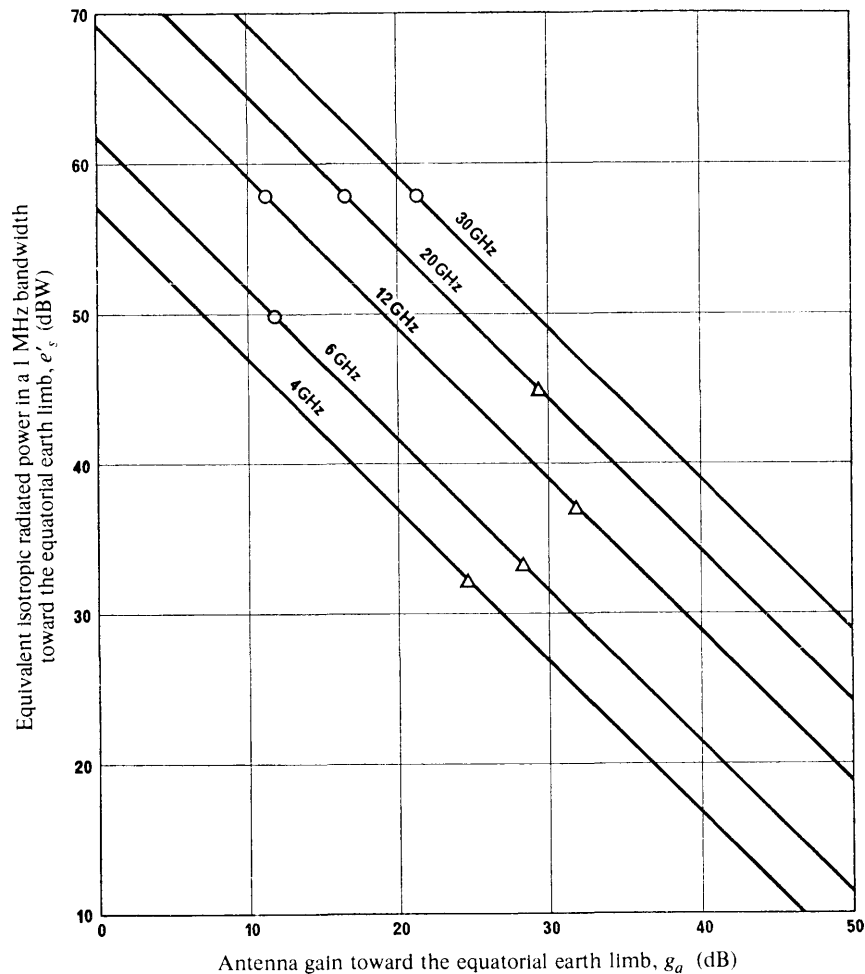


FIGURE 4 — Relationship between the maximum permissible values of e'_s towards the equatorial earth limb

- Terrestrial station emissions
- △ Power flux-density limits

4. The effect of the bidirectional use of frequency bands on other techniques for improving orbit utilization efficiency

Polarization discrimination or spot-beam satellite antennae could be used to provide isolation between communication satellites which are closely spaced in orbit using the same frequency band assignments. The minimum spacing between satellites could be halved if polarization discrimination were used, and reduced to one-third or even less, if satellite spot-beam antennae, or a combination of both techniques, were used. However, frequency re-use techniques such as polarization discrimination introduce inhomogeneity into the satellite system which might reduce or even eliminate the further improvement in orbit capacity which reversed frequency band operation could otherwise provide. This tendency for one orbital economy technique to exclude the advantage of another would not arise if polarization discrimination on spot-beam antennae were employed for frequency re-use within a single satellite.

5. Interference between earth stations with reversed frequency band assignments

The physical spacing which is necessary to limit interference between earth stations using reversed frequency bands is one of the major earth segment problems. When there is no site shielding, it is estimated that a separation of between about 100 km and 140 km would be needed between earth stations using the same bands in the opposite sense in a temperate climate if interference noise per telephone channel from this source is to be limited for most of the time to 1000 pW. The separation should perhaps be less where the earth stations operate at high angles of elevation or have good site shielding. Care should be taken to avoid coupling between earth stations via common volumes in the main beams in the troposphere.

If reversed frequency band assignment is to be taken into use, it will be desirable for Administrations to determine a preferred direction of transmission (i.e., space-to-Earth or Earth-to-space) for each frequency band used in this way. It will then be particularly desirable for earth stations which have been assigned frequency bands in the mode which is not preferred to be located where site shielding is good, in order to minimize interference to and from earth stations which have been assigned frequency bands in the preferred mode.

6. Bidirectional use of frequency bands shared with terrestrial services

Reversed frequency band operation of space services in bands shared with terrestrial services would lead to a number of serious consequences which require consideration. It is the purpose of this section to expose some of the new problems which will arise.

6.1 *New problems for terrestrial services*

In shared frequency bands, space-station transmitters interfere with terrestrial service receivers over wide areas in the down-path bands. In particular this places constraints upon terrestrial systems which would desirably be oriented towards the azimuth at which the geostationary-satellite orbit intersects the horizon. Also, in up-link bands the Radio Regulations place limits on terrestrial transmitter power and e.i.r.p. If reversed frequency band operation were used in the space service, both of these disadvantages would be suffered by terrestrial services in all shared bands.

Interference is also suffered in up-path bands by terrestrial receivers in the vicinity of earth stations, and it is necessary for these terrestrial systems to be designed to reduce such interference to acceptable values, by choice of station location or frequency. To limit such interference the operation of both services is coordinated, and terrestrial services are constrained in the vicinity of earth stations. This constraint will often be minimized in geographical extent by concentrating several earth stations in one locality. If reversed frequency bands were used in the space service, it would be necessary to site the earth terminals in well-separated locations to limit interference between earth terminals. This would usually extend the area within which terrestrial services are constrained. Furthermore, within these areas the feasibility of expanding existing terrestrial systems, say by taking into use additional frequency bands not used by the space service for up-paths, may be severely curtailed.

Finally, the terrestrial system noise allocation for interference from space services would have to be divided between interference received from satellite and earth station transmitters both in terms of interference levels and the proportion of time during which these levels may be tolerated. This could lead, either to greater limitation of terrestrial services in the vicinity of earth stations, or to more restrictive sharing criteria.

6.2 *New problems for space services*

§ 5 refers to the problem of interference between earth stations using frequency bands in opposite modes. In shared bands, this problem would make more difficult the problem of finding suitable sites for earth stations where interference from existing terrestrial services between entries from earth-station and space-station transmitters, referred to in § 6.1, would probably require the maximum permissible power flux-density from space stations to be reduced, which could have an economic impact on future systems.

6.3 *Total impact on spectrum utilization*

It is possible that the improvement in spectrum utilization foreseen by this technique for the space service would be negated by a reduction in the value of the spectrum for the terrestrial service. This point should be studied carefully.

7. Conclusions

Bidirectional use of up- and down-path frequencies in the Fixed Satellite Service may lead to an enhancement of the utilization of the geostationary-satellite orbit and the radio-frequency spectrum. However, in order to keep interference from near antipodal space stations within tolerable bounds, restrictions may have to be placed on the equivalent isotropic radiated power densities or on the antenna gains, or on both, in directions toward the geostationary-satellite orbit which are not shielded by the Earth.

In frequency bands in which power flux-density limits have been imposed upon space station emissions, reverse-frequency space stations may use substantial receive antenna gains in the antipodal directions without experiencing unacceptable interference. In frequency bands where space station receivers are exposed to interference from sharing terrestrial station emissions, they cannot realize high receive antenna gains in the antipodal directions, but reverse-frequency space station emissions in the antipodal directions may assume substantial values of e.i.r.p.

However, there are other valuable techniques of spectrum and orbit economy, such as the reduction of earth-station antenna side-lobe response, polarization discrimination and the use of satellite antenna directional discrimination and their application may diminish the additional advantage to be obtained from using frequency bands in both up- and down-path directions.

Furthermore, in frequency bands shared with terrestrial services, the use of frequency bands in both up- and down-path directions would have disadvantages for both services; in particular:

- terrestrial services would have their e.i.r.p. and transmitter power limited in bands which would not otherwise be used for communication satellite up-links;
- terrestrial services might suffer interference from satellite emissions in bands which would not otherwise be used for communication satellite down-links;
- the development and growth of terrestrial services in the vicinity of earth stations is likely to be more severely restricted;
- it might be necessary to make more restrictive the sharing criteria, in view of the additional interference modes.

It is concluded that the use of frequency bands in both up- and down-path directions may lead to improved efficiency of orbit utilization and that it might be of particular value in bands which are allocated exclusively for space radiocommunications services. However, further study of the problems involved is necessary.

REPORT 558-1

SATELLITE ANTENNA PATTERNS IN THE FIXED SATELLITE SERVICE

(Study Programme 2J-2/4)

(1974 – 1978)

1. Introduction

Satellite antenna patterns have a significant effect on the utilization of the geostationary-satellite orbit, particularly when narrow beamwidths are employed. Improved control of satellite antenna patterns, particularly side-lobe levels, can lead to better utilization of the orbit. Additionally, a reference radiation pattern for satellite antennae is needed, in the absence of specific information on the performance of the antennae involved, for use in applying the procedure for calculating inter-system interference levels which are set out in Appendix 29 of the Radio Regulations and in Reports 454-2 and 455-2. This Report is a preliminary examination of the problems in defining such a reference radiation pattern and offers a tentative pattern for further study.

2. Design considerations of satellite antennae

The satellite antenna is an integral part of a dynamic platform in a space environment. Mass and size are of paramount importance and are constrained by the launch vehicle payload envelope. The platform attitude stability, orbit inclination and longitudinal variations introduce tolerances which must be considered in the satellite antenna patterns.

Some satellite antennae are required to radiate beams of high polarization purity. This aspect of antenna design is discussed in Report 555-1.

2.1 *Satellite antenna types*

The particular type of antenna utilized will depend on frequency, beamwidth and launch vehicle payload envelope (physical size and mass). Minimum beamwidths will depend upon the precision with which the satellite attitude can be stabilized as well as service requirements, such as area of coverage and frequency re-use.

Current pointing stabilities for spacecraft antenna platforms are in the order of $\pm 0.2^\circ$. Unless tracking capability is included in the satellite, the antenna gain is limited to about 50 dB on-axis gain by the pointing stability. Higher gains require a considerable increase in satellite complexity.

To date, at frequencies above 1 GHz, horns have been used extensively for the larger beamwidths and focus-fed parabolic reflector for smaller beamwidths. Physical constraints usually dictate the cross-over from one type of antenna to the other, since the focus-fed parabola is much more compact for the same aperture size. These two types have been used extensively in the past, but several spacecraft are using an offset-fed reflector (e.g. INTELSAT IV-A and V), and multi-beam lens antennae are used on some prototype spacecraft. In the long term where TDMA systems are concerned, beam switching, possibly using phased array antennae, may be appropriate. This would imply a multiplicity of very narrow beams on the satellite and would lead to a need for beam steering flexibility to adapt to new earth station location requirements.

2.2 *Main lobe patterns*

Ideally, the radiation pattern of the antenna should be such that energy is concentrated toward the earth stations in the network.

From a practical standpoint, the radiation pattern of a satellite beam should provide uniform illumination of the coverage area and none outside it (Fig. 1). This objective can be approached, but to do so requires the use of an antenna which is larger and heavier than a simple antenna which would provide almost as much gain within the coverage area. A simple antenna, having appreciable radiation outside the coverage area also provides a tolerance for attitude and orbital control errors. Fig. 2 shows how the minimum gain in the coverage area varies with aperture area, assuming that the main lobe radiation pattern is of the form $(\sin^2 x)/x^2$. It is noted that there is an optimum aperture size for a given coverage area at a given frequency, but the aperture can be varied over a range of 2.4 to 1 about this optimum with only 0.5 dB variation in minimum gain. Another factor which also tends towards broader beamwidths, is the gain slope at the edge of coverage which increases with narrow beamwidths. This factor is significant because the platform instabilities, in conjunction with gain slope, affect the stability of the power levels throughout the network. Thus, there will be a tendency to minimize antenna size and mass and to provide tolerance for attitude and orbital control errors by using an aperture which is even smaller than this optimum, corresponding to a relative aperture area of less than 1 as shown in Fig. 2.

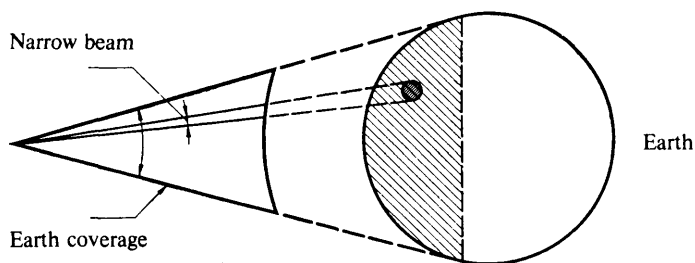
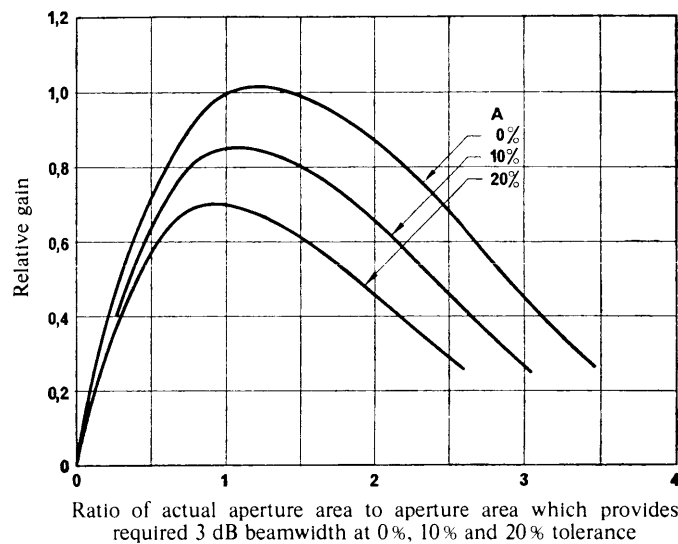


FIGURE 1 — *Ideal satellite antenna patterns*

FIGURE 2 — *Gain in the coverage area versus aperture area*

A: Tolerance for antenna pointing errors as a percentage of 3 dB beamwidth

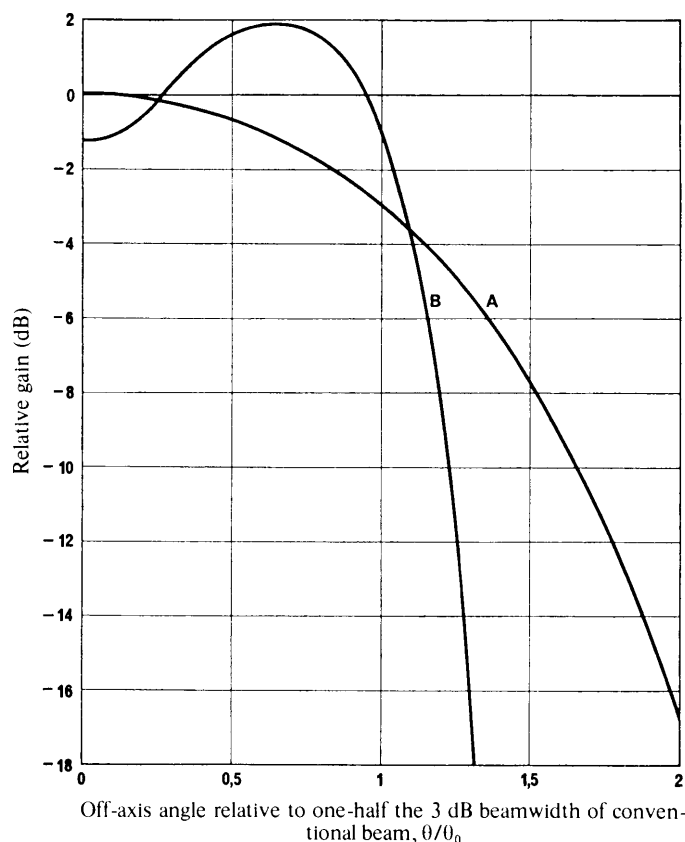
On the other hand, the optimum aperture size of an antenna operating in one pair of frequency bands is the one which gives approximately the same minimum gain at both frequency bands, in the sense of obtaining minimum gains as high as possible within the coverage area. This minimum gain is about 0.5 dB lower than the optimum value given in Fig. 2 for a single frequency, when the frequency ratio is equal to 1.5, as in the case of 6/4 GHz or 30/20 GHz.

Since beamwidth is frequency sensitive, the gain frequency function is analogous to the gain aperture function as shown in Fig. 2. Large fractional bandwidths with little gain change are achievable near the peak of the function. But this factor does not necessarily provide an incentive to operate in this region, since power control can compensate for any gain/frequency slope.

Thus, there are incentives for the spacecraft designer to use an antenna with a small aperture, providing a broad beam with a low gain slope outside the coverage area. Such antennae reduce orbit utilization, therefore, it is desirable that antennae with shaped main beams be used instead.

Two methods of shaping satellite antenna patterns can be considered in relation to the improving of coverage area gain and reducing inter-systems interference, namely (1) shaping to conform to a coverage area (shaping in the plane normal to the axis of propagation); and (2) shaping within the coverage area (shaping in the propagation axis plane). There will be a natural tendency to shape a beam to fit the coverage area to the extent that it is the most feasible and economical means of maximizing the e.i.r.p. towards the earth stations in the coverage area.

Shaping a beam to equalize the energy over the surface of the coverage area (see Fig. 1) can be considered. Fig. 3 shows the idealized patterns of a $(\sin^2 x)/x^2$ function and the sum of two displaced $(\sin^2 x)/x^2$ functions producing a 3 dB gain ripple. The minimum gain between the 3 dB points will be approximately the same for both patterns, but the aperture area required to produce the shaped beam, is an order of magnitude larger and the gain slope at the 3 dB points is much greater.

FIGURE 3 — *Shaped and conventional beams*A: Conventional beam: $\frac{\sin^2 x}{x^2}$

B: Example (shaped beam)

Note. — In the formula for the relative gain of the conventional beam, $\frac{\sin^2 x}{x^2}$, the argument, x , can be expressed as $1.39 \frac{\theta}{\theta_0}$ radians. Thus, when $\theta = \theta_0$ the relative gain of the conventional beam becomes: $\frac{\sin^2 1.39}{1.39^2} = 0.707^2 = 0.5$; ratio - 3 dB

Recently, there has been a considerable amount of research and development effort in the area of shaped-beam antennae for spacecraft. Two configurations now being developed are the multi-feed parabolic reflector and the multi-beam lens antenna.

Beam shaping and the generation of spatially separate beams by multiple feeds on a common parabolic reflector have been employed on several existing spacecraft. Fig. 4 shows a sample pattern utilizing this technique for satellites providing coverage in the United States of America. This technique is very attractive from a main lobe standpoint since there is little loss in main lobe gain. A main lobe gain loss as a function of normalized off-axis angle is shown in Fig. 5. It is noted that a 1° beam can be offset from earth centre to earth edge with only a 3 dB loss in gain. This technique can also be used to shape beams within a coverage area, such as shown in Fig. 3. The relative power to each feed can be adjusted to form asymmetrical main lobe patterns. The utilization of e.i.r.p. may be increased by asymmetrical arrangements which provide the most gain toward earth stations with the highest traffic density. Thus utilization of this technique leads to a large variety of main lobe pattern shapes which can be utilized by a system designer to maximize the utilization of e.i.r.p. (Also see Annex II).

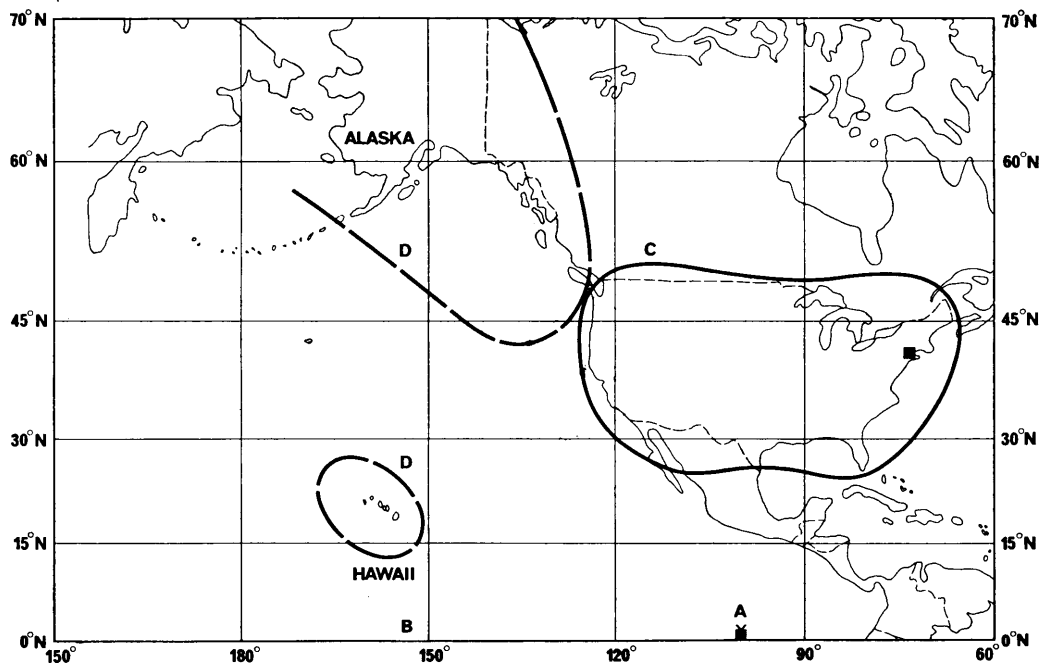


FIGURE 4 — Example of antenna coverage contours

($6.8^\circ \times 3.5^\circ$ beam and 2.8° circular spot beams produced by a 5 ft. (1.5 m) antenna with multiple feeds)
(system uses 4 GHz down and 6 GHz up)

A: Satellite

B: Equator

C: $6.8^\circ \times 3.5^\circ$ beam

D: 2.8° circular spot beams

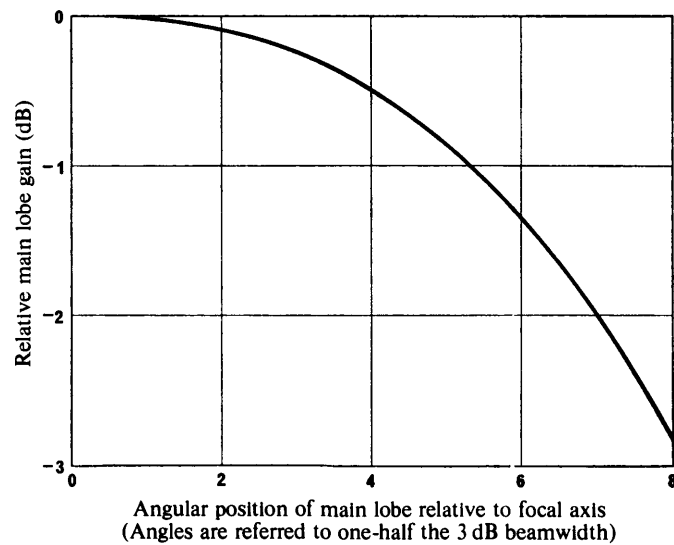


FIGURE 5 — Main lobe gain versus angular position of main lobe relative to focal axis

20 dB taper, $f/D = 1$

Additionally, reflector type multi-beam antennae are potentially attractive because of their design simplicity, inherent wide bandwidth, ease of construction, light weight, and low cost. However, studies have shown that the usual large multibeam structures cause excessive blockage and consequently high sidelobe levels for all configurations except the offset-fed types.

Multiple beam antennae may also be created by focusing energy from a primary array of feed horns through a microwave lens. The axial symmetry of such a configuration allows low aberration for scanned beams, resulting in lower sidelobes and better beam isolation than is possible with the reflector type multi-beam antennae, an important consideration for frequency re-use applications.

In addition, a beam-forming network can be used either with a reflector, or a lens antenna, to generate a great variety of different spot-illumination footprints on the earth, or to provide, as an aggregate of several combined spots, a footprint of specially shaped contour to fit almost any desired geographic service area. Computer techniques have been developed in parallel with prototype lens fabrication to calculate the proper phase and amplitude response for the beam-forming network. These techniques provide for variable beam shapes commandable from the ground.

Thus, for simple main lobe patterns, main lobe gain considerations lead towards the design of satellite antennae which may result in inefficient orbit utilization. However, when the size and mass of the antenna is quite small compared to the total size and mass of the satellites, shaped beams may be attractive from a system design standpoint. Reference is made to Annex I which shows the feasibility of shaped beams for earth coverage antennae. An example of the beamshaping of a narrow beam mechanically de-spun horn reflector antenna [Shinji *et al.*, 1974] is shown in Figs. 6 and 7; the minimum gain contours at 4, 6, 18 and 28 GHz, including the losses of a feeder, polarizer, duplexer and band selecting filter assembly are shown.

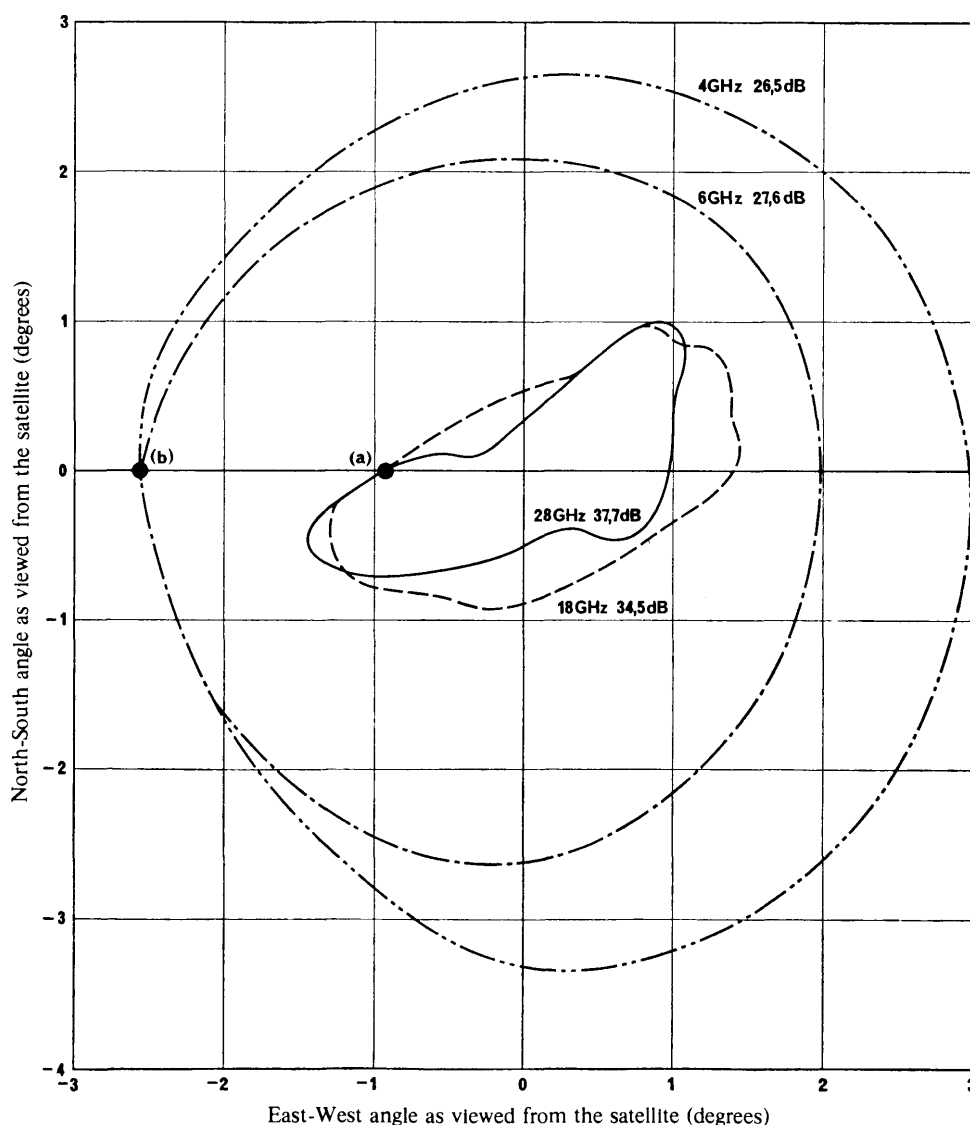


FIGURE 6 — Constant gain contours of the shaped-beam horn-reflector antenna

(Which meet coverage requirements of Japan with circular polarizations)
[For (a) and (b) see Fig. 7]

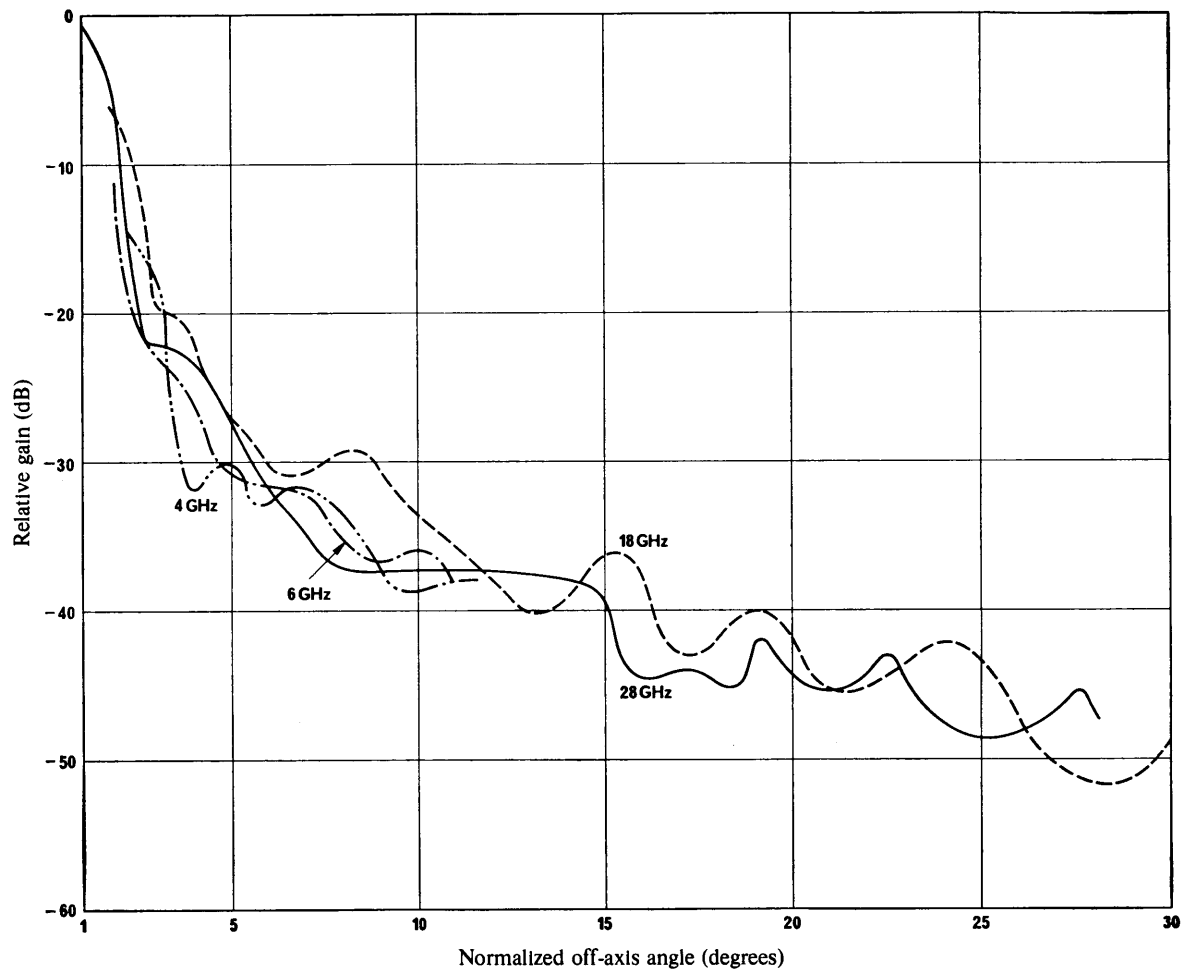


FIGURE 7 — *Measured patterns of side-lobe peak envelopes of the shaped narrow-beam horn-reflector antenna*

Frequency and polarization normalizing angles

————	28.3 GHz circular (L) 1.0°	} see point (a) in Fig. 6
-----	18.3 GHz circular (R) 1.0°	
- . - . - .	6 GHz circular (L) 2.7°	} see point (b) in Fig. 6
- . . - . .	4 GHz circular (R) 2.7°	

Note. — The off-axis angles are referred to the origin of Fig. 6 and are in the plane through point (a) and (b) of Fig. 6.

2.3 Side-lobe gain pattern

In terms of orbit utilization and interference reduction, side-lobe radiation patterns are most significant. Side-lobes are the result of several design features of the antenna systems, including diffraction and spill-over around the edges of a reflector or subreflector, aperture blockage, amplitude and phase distribution over the aperture, and off-focus feeds. Aperture blockage can be a limiting factor in reflector systems if the D/λ is low. The amplitude and phase distribution over the aperture is significant for all antenna types. As the aperture illumination is varied from uniform to more tapered distributions, the peak gain decreases slightly and the side-lobes are significantly reduced where blockage is not a factor. This effect is shown in Fig. 8.

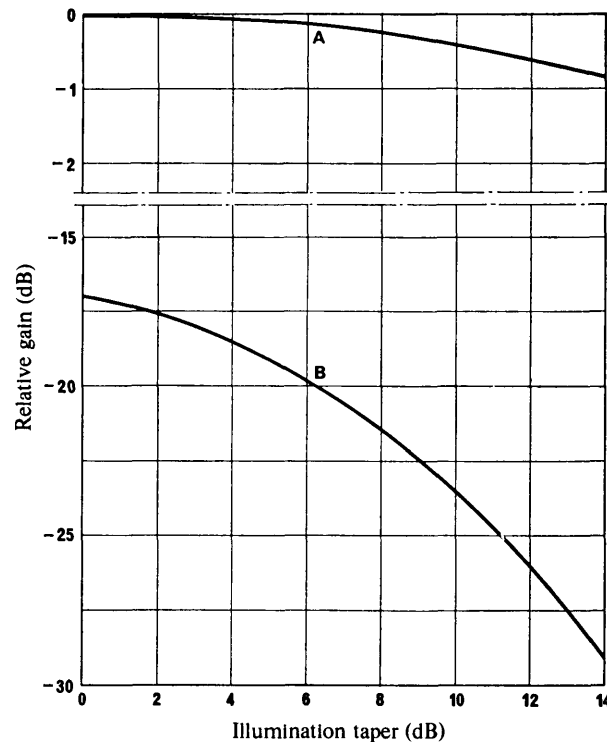


FIGURE 8 — Effects of aperture illumination

A: Main lobe
B: First side lobe

For single focus-fed prime focus parabolic reflectors with 10 dB illumination tapers and a D/λ of about 10, the first side-lobe level is usually about -20 dB relative to on-axis gain. As the D/λ is increased, the first side-lobe level will decrease to about -25 dB relative to the on axis-gain. Aperture blockage accounts for higher side-lobe levels at low D/λ . For focus-fed parabolic reflectors for earth coverage ($D/\lambda \approx 4$) the first side-lobe would be about -15 dB relative to the on-axis gain. Changing the illumination taper does not materially improve the near side-lobe levels when aperture blockage is the limiting factor. It is likely that antennae without significant aperture blockage will have to be used to achieve low side-lobe levels. This leads to asymmetrical arrangements which have potential disadvantages in other respects.

The slope of the envelope of the side-lobes must also be considered. For antenna types, other than horns, and where no special attention is given to side-lobe reduction, the slope is generally in the order of -7.5 dB/octave of off-axis angle. For horns without reflectors the slope is more typically in the order of -9 dB/octave.

When emphasis is placed on low side-lobe levels, first side-lobe levels of -30 dB relative to the on-axis gain and side-lobe envelopes of -12 dB/octave appear attainable. These values are generally achievable with antenna types with effectively no aperture blockage and characteristics of such antennae must be studied in other respects before conclusions can be drawn.

For multiple feed parabolic reflector systems, the side-lobe levels increase with displacement of the main lobe. As the displacement of the main lobe increases, the side-lobe levels on the axial side (coma side-lobes) increase, while those opposite tend to merge with the main lobe. The coma side-lobes tend to increase less rapidly when large illumination tapers or large f/D ratios are employed. Fig. 9 shows the first coma side-lobe level as a function of normalized off-axis angle for an $f/D = 1$ and a 20 dB illumination taper antenna. The relative angular position of the first coma lobe is approximately coincident with the position of the normal first side-lobe. Thus, if multiple feeds are utilized to form complex main lobe shapes (offset angles in the order of one beamwidth) some of the coma lobes may fall within the coverage area. When spatially separate beams are generated with multiple feeds, the coma side-lobes may fall within the coverage areas of other satellite systems.

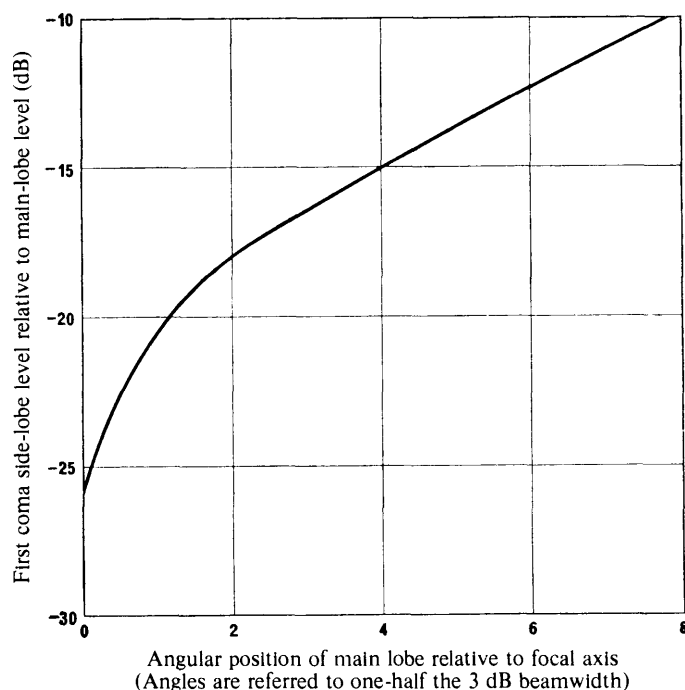


FIGURE 9 — First coma side-lobe level versus angular position of main lobe relative to focal axis

20 dB taper, $f/D = 1$

Coma side-lobes are a fundamental property of off-focus fed parabolic reflector antennae and can result in high side-lobe levels. Multiple feeds mounted within the aperture on a common reflector also increase the aperture blockage which increases the level of the near side-lobes.

Beam shaping can also be achieved with arrays. Because of the relatively small angular coverage required, a few high gain elements can be used. However, grating lobes may be an important consideration in the side-lobe regions.

As noted previously, the degree to which polarization is maintained in the side-lobe regions is uncertain at this time and requires study.

An example of side-lobe gain characteristics of a shaped narrow beam antenna operating in two pairs of frequency bands [Shinji *et al.*, 1974] is given in Fig. 7. The side-lobe peak envelope patterns in the azimuth plane normalized by the angular distance from the beam centre to the minimum gain contour are shown in Fig. 7 for each frequency. Reference is made to Report 390-3 for additional considerations on side-lobe levels. Examples of side-lobe gain characteristics are shown in Annex II and III.

3. Orbit utilization

3.1 Effects of side-lobe envelopes

Ultimately, main lobe gain must be reduced or aperture size increased, or both, in order to improve orbit utilization. The first effect is shown in Fig. 8. By increasing the illumination taper, the first side-lobe level is reduced, and the side-lobe envelope slope is increased. However, the relative position of the near side-lobes is not significantly altered. Fig. 10 shows the relative improvement in orbit utilization (assuming a homogeneous system with circular narrow beam satellite antennae and a -7.5 dB/octave side-lobe envelope slope) as the overall side-lobe envelope level is reduced. It is assumed that a number of narrow beams are formed at a point in the geostationary orbit (no earth station discrimination), and then the relative number of beams which can be formed for a given interference is computed as a function of the side-lobe envelope level. Side-lobe envelope improvements of relatively small amounts have significant effects on orbit utilization.

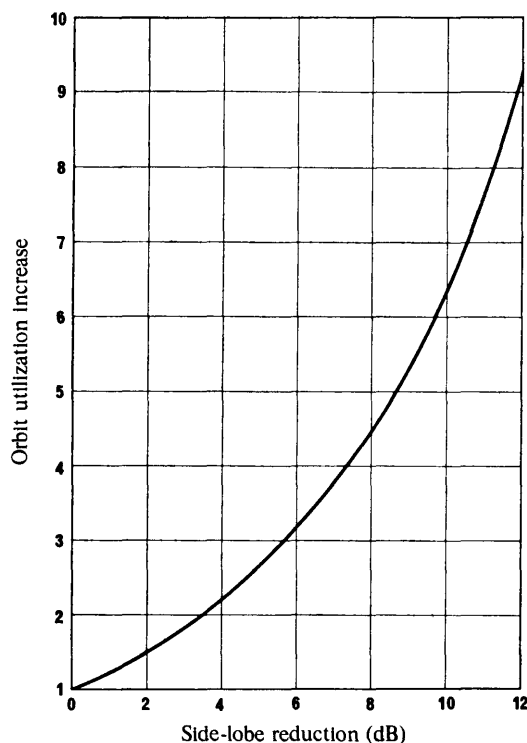


FIGURE 10 — Effect of side-lobe level on orbit utilization

The effect of increasing the aperture size is to reduce the off-axis angle at which the side-lobe peaks occur, even though the side-lobe levels may not be improved. It was shown in Fig. 2 that there is a relatively large range of aperture size over which minimum antenna gain over a given area is not significantly changed for un-shaped beams. When beam shaping is employed, the aperture size is increased. The relative improvement in orbit utilization as aperture size is increased, making use of the same assumptions as above, is directly related, to a first order approximation, to aperture area.

These improvements are based on a side-lobe envelope slope of -7.5 dB per octave. However, a function which fits the far side-lobe envelope is generally pessimistic for the first side-lobe region, which is usually more important from the frequency sharing viewpoint. A typical function for the far side envelope is shown in Fig. 11 as function E.

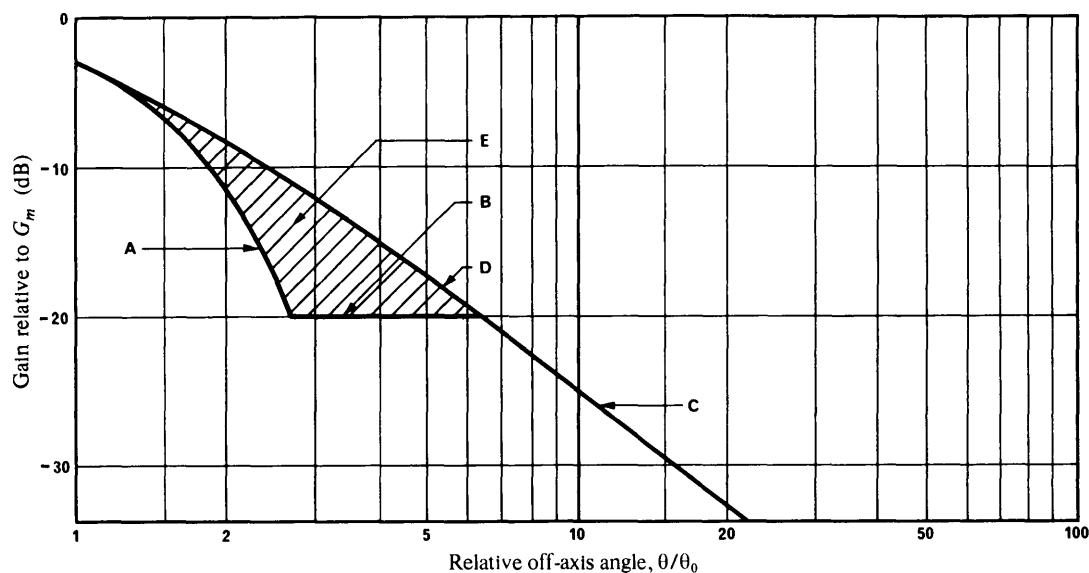


FIGURE 11 — Radiation pattern envelope functions

θ_1 : value of θ when $G(\theta)$ in (C) is equal to -10 dB
 [When θ exceeds θ_1 , $G(\theta)$ should not be greater than -10 dB]

Curves A: $[G(\theta) - G_m] = -3 \left(\frac{\theta}{\theta_0} \right)^2$ dB for $(\theta_0 \leq \theta \leq 2.6 \theta_0)$

B: $[G(\theta) - G_m] = -20$ dB for $(2.6 \theta_0 < \theta \leq 6.3 \theta_0)$

C: $[G(\theta) - G_m] = -25 \log \left(\frac{\theta}{\theta_0} \right)$ dB for $(6.3 \theta_0 < \theta \leq \theta_1)$

D: $\left[1 + \left(\frac{\theta}{\theta_0} \right)^{2.5} \right]^{-1}$

E: First side-lobe area

G_m : maximum gain in the main lobe

θ_0 : 3 dB half beam width in the considered plane (3 dB below G_m)

This curve is above the -20 dB level in the first side-lobe region, this value being typical for simple antennae without beam shaping. There is up to a 3 to 1 angle range in which the side-lobe level will generally be below the referenced function.

Considering the range of satellite and earth station terminal beamwidths, this region may be quite significant.

The satellite beamwidths fall generally into three categories:

- beamwidths of about 17° (earth coverage);
- beamwidths of from earth coverage to about 5 to 10° ;
- narrow beamwidths, considerably less than earth coverage.

For the full earth coverage case, the main lobe encompasses the Earth and somewhat beyond with no side-lobes directed towards it. Beyond the Earth's edge as viewed from a satellite, the only concern is the possible interference to a satellite operating with reserve frequencies; for example, transmitting in the 6 GHz band and receiving on 4 GHz. Fig. 12 shows typical measured patterns for INTELSAT-IV and IV-A global coverage antennae out to angles far beyond the Earth's edge.

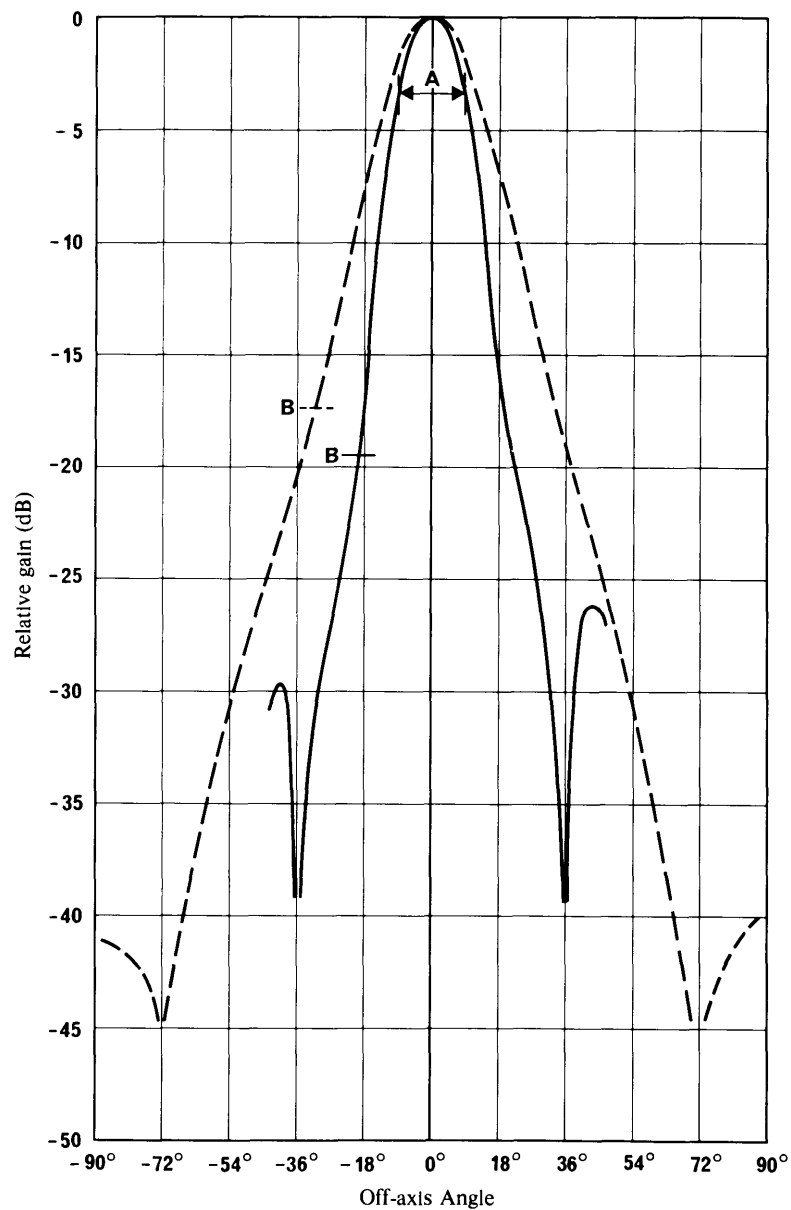


FIGURE 12 – Circularly polarized global coverage satellite antennae – typical measured patterns at $f = 3\,950\text{ MHz}$

- INTELSAT-IV, conical horn
with flat 45° reflector
- - - Multimode conical horn,
for use on INTELSAT-IV A

A: Angle at Earth edge as viewed from a geostationary satellite
B: Isotropic levels

For the second case, the main lobe and the first side-lobe area are the principal sources of interference to earth terminals, and for the third case, the higher order side-lobes also represent a source of interference to earth stations.

With satellite antennae having less than earth coverage, the earth station antenna radiation patterns must also be considered in assessing orbit utilization. Considering a limiting condition where adjacent satellites provide coverage to adjacent earth areas, two conditions can be postulated: (1) the earth station D/λ is considerably larger than the satellite D/λ ; and (2) the earth station D/λ is comparable or less than the satellite D/λ . In the first case, most of the discrimination is achieved with the earth station antennae. Operation with overlapping of the satellite first side-lobe is quite feasible. For the second case above, where little discrimination is achieved from the earth-station antennae, the first side-lobe region of the satellite antenna may be very significant. Near side-lobe levels ≤ -30 dB could materially enhance orbit utilization when the satellite antenna D/λ is comparable to or greater than, the earth station antenna D/λ . This level may be achievable with certain antenna designs.

3.2 Narrow-beam antenna steerability

Another aspect which should be considered in the design of satellites using narrow-beam antennae, is the steerability of these antennae. It is anticipated that, as the satellite orbit density increases, repositioning of existing satellites may be necessary to accommodate new satellites. The repositioning capability of a satellite may be very restricted if the satellite antenna beam angle with respect to the satellite platform is fixed. While the usable arc of the geostationary-satellite orbit for a given system is limited by line-of-sight considerations, it should not be unduly restricted by steerability limits of narrow-beam satellite antennae.

4. Satellite antenna reference radiation pattern

It appears desirable to postulate guidelines for a pattern as a basis for further consideration for satellite antennae which have relatively simple pattern envelopes, such as those having simple circular main lobes. It is also desirable to have an interim reference for these conditions for the co-ordination computations of Appendix 29, of the Final Acts of the World Administrative Radio Conference, if actual patterns are not available.

As noted previously, the radiation pattern of the satellite antenna is important in the region of the main lobe as well as the farther side-lobes. Thus, the following postulated pattern commences at the -3 dB contour of the main lobe and is divided into four regions.

$$G(\theta) = G_m - 3 \left(\frac{\theta}{\theta_0} \right)^2 \quad \text{dB for } \theta_0 \leq \theta \leq 2.6 \theta_0 \quad (1)$$

$$G(\theta) = G_m - 20 \quad \text{dB for } 2.6 \theta_0 < \theta \leq 6.3 \theta_0 \quad (2)$$

$$G(\theta) = G_m - 25 \log \left(\frac{\theta}{\theta_0} \right) \quad \text{dB for } 6.3 \theta_0 < \theta \leq \theta_1 \quad (3)$$

$$G(\theta) = -10 \quad \text{dB for } \theta_1 < \theta \quad (4)$$

where

$G(\theta)$: gain at the angle (θ) from the axis,

G_m : maximum gain in the main lobe,

θ_0 : one half the 3 dB beamwidth in the plane of interest (3 dB below G_m),

θ_1 : value of (θ) when $G(\theta)$ in equation (3) is equal to -10 dB.

These functions are shown in Fig. 11.

Equation (1) is one of a number of functions which may be utilized to approximate the main lobe pattern of a simple (un-shaped) beam. In the region from -3 dB to -20 dB as postulated herein, this function provides gain values which are generally higher than those encountered with actual simple beam antennae. Equation (2) covers the region of the first, or the first few side-lobes, and is based on typical values achieved when no attempt is made to reduce the first side-lobe levels. Equation (3) covers the region of the farther side-lobes. A slope of -7.5 dB/octave is utilized as in the earth station reference patterns. The fourth region (equation (4)) is also derived from the earth station reference pattern.

Difficulties arise, however, in attempting to apply the postulated pattern to an elliptical beam, as shown in [CCIR, 1974-78]. Administrations are therefore requested to submit measured radiation patterns for antennae with other than simple circular beams, including elliptical beams.

5. Conclusions

From the standpoint of satellite antenna design, it cannot be assumed that efficient orbit utilization will be obtained unless it is specifically sought. In general, apertures which are larger than those required to achieve the necessary e.i.r.p., will enhance orbit utilization over a coverage area. Therefore, satellite antenna radiation pattern objectives appear to be desirable. To enhance orbit utilization, the spacecraft antenna should have the following general characteristics:

- the main lobe patterns of the satellite antennae should conform to the coverage area as closely as possible (beam shaping in the plane normal to the axis of propagation is desirable);
- the side-lobes should be controlled outside the coverage area. The utilization of techniques to reduce the first side-lobe level and to increase the far side-lobe envelope slope are to be encouraged;
- the position of a geostationary satellite should not be unduly restricted by steerability limits of narrow beam antennae.

There are many parameters involved with complex satellite antenna patterns which affect orbit utilization, and additional study is required before any general conclusions can be drawn.

It is not known at present whether a spacecraft antenna reference pattern can be developed which will be applicable to the large variety of complex patterns which may be utilized.

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ANNEX I

SATELLITE ANTENNAE WITH SHAPED GLOBAL BEAMS

1. Introduction

Due to the difference in the range and the atmospheric attenuation from a satellite to various points on the Earth, a conventional global beam with maximum gain toward the centre of the Earth is non-optimum because it has the highest gain where the path losses are minimum. Since the paths tangential to the Earth are the longest and since their path through the atmosphere is the longest, the antenna gain ought to be highest in this region and somewhat less in the direction normal to the Earth's surface. Shaped global beams of this kind are desirable, from the point of view of the efficient use of satellite power. Antennae with such beams have been studied and developed using techniques of dielectric-loading of a horn [Satoh, 1972] or of an array of multiple horns [Ajioka and Harry, 1970].

2. Example of a radiation pattern that has been obtained

An example of an antenna radiation pattern that has actually been obtained is shown in Fig. 13. This is the pattern of a dielectric-loaded antenna at 23.3 GHz.

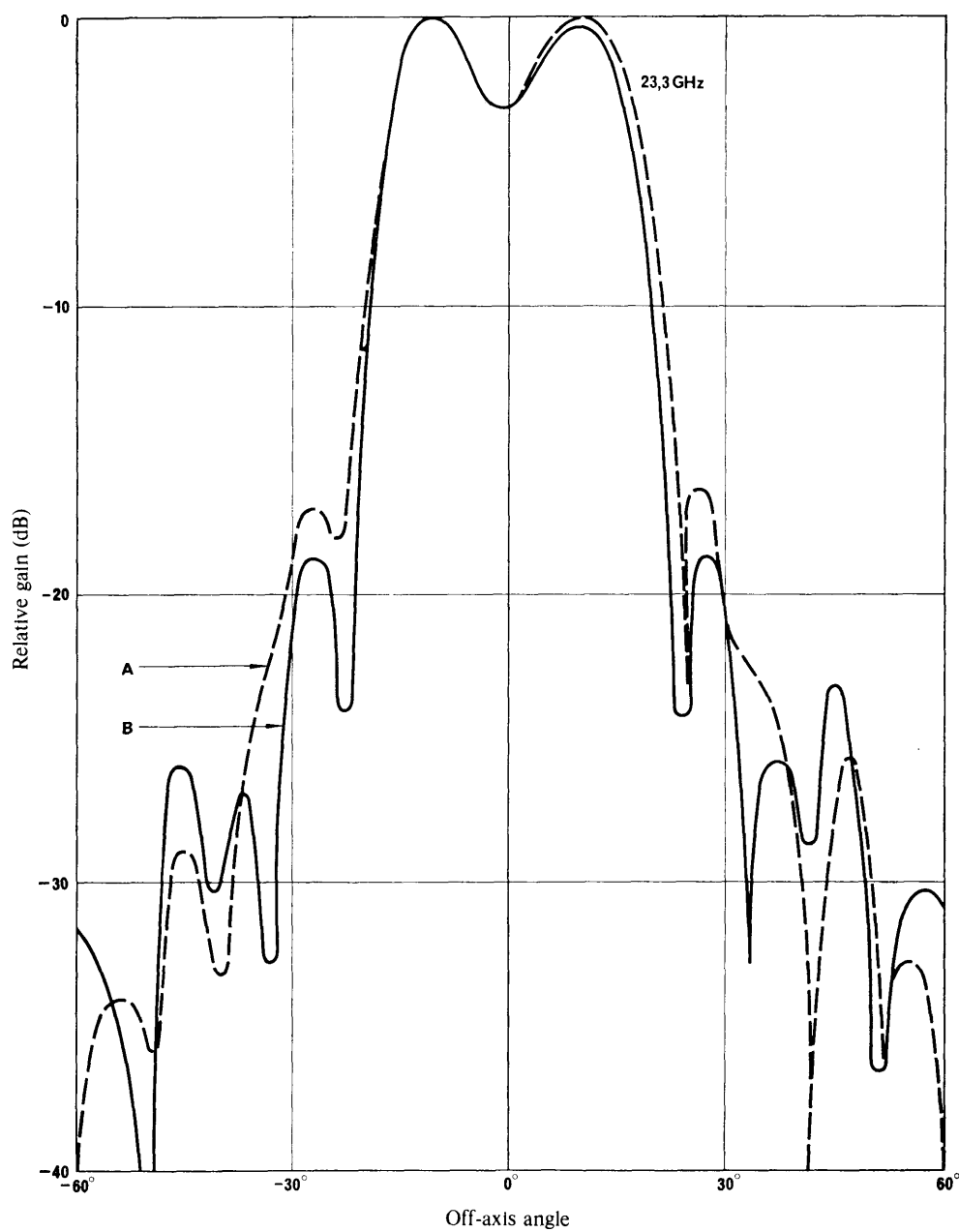


FIGURE 13 — Pattern of shaped global beam given by a dielectric-loaded horn antenna

A: H-plane
B: E-plane

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- SATOH, T. [March, 1972] Dielectric-loaded horn antennae. *IEEE Trans. Ant. Prop.*, Vol. AP-20, 2.

ANNEX II

BEAM SHAPING BY COMBINING MULTIPLE FEEDS
IN A COMMON PARABOLIC REFLECTOR

The Atlantic Ocean area INTELSAT-IVA satellite antenna design provides an example of beam shaping to meet coverage area requirements while also achieving sufficient isolation between coverage areas to allow frequency re-use.

Fig. 14 shows typical minimum service area contours required with east-west frequency re-use. The specification requires a given e.i.r.p. and up-path and down-path carrier-to-interference ratios of 27 dB to be exceeded within these contours. The earth station locations within the specified coverage contours are shown by a dot, and the pointing margins required to accommodate the variations of satellite attitude permitted by the specification are shown by rectangles surrounding the data.

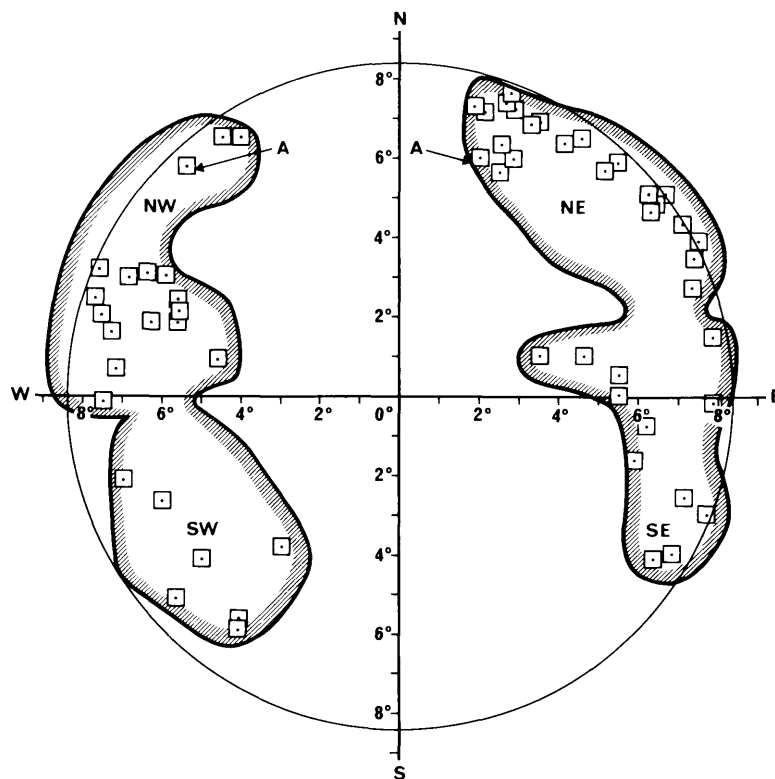


FIGURE 14 — Specified coverage areas for INTELSAT-IV A satellite antenna as viewed from the satellite

A: Earth station locations

Fig. 15 shows the contours for each beam of the common parabolic reflector. Each of these beams is generated by a group of feeds in order that the beam shape may be related to operational requirements; in this way a sharp gain roll-off is obtained outside the service area in directions where it is particularly necessary to control inter-beam interference levels. The coverage required by the specification is achieved by combining the pair of east beams in proper phase, and likewise the two west beams.

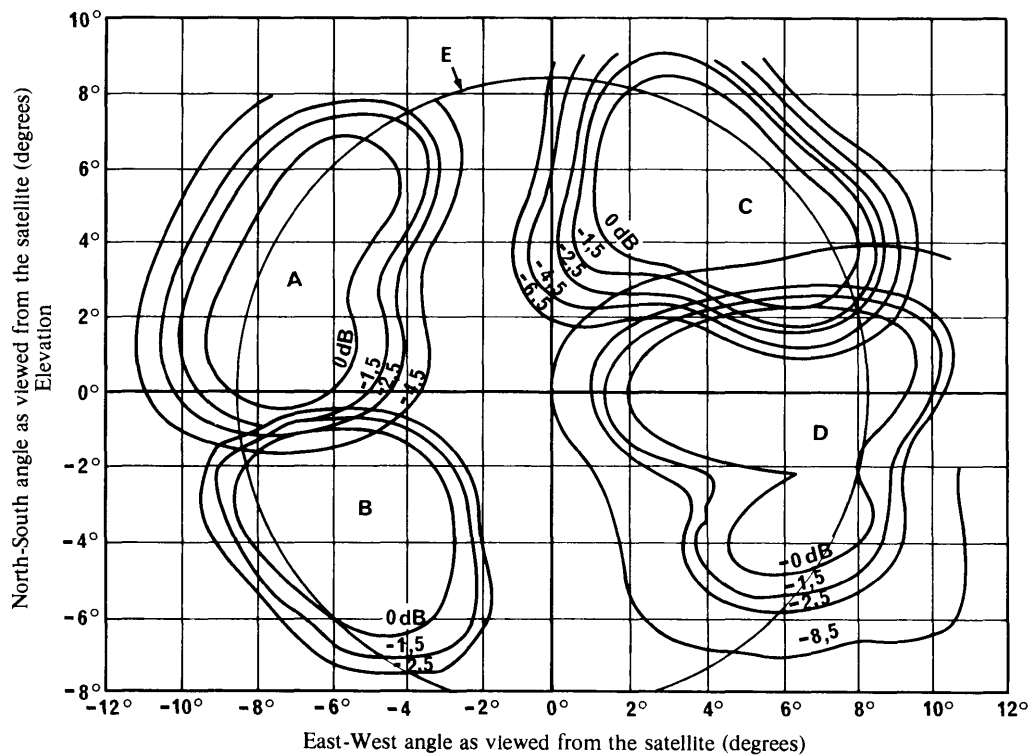


FIGURE 15 – Typical INTELSAT-IV A measured satellite antenna beam contours, the e.i.r.p. being expressed in dB relative to the specified edge-of-coverage value. Frequency = 3 975 MHz

- A: North West Beam
- B: South West Beam
- C: North East Beam
- D: South East Beam
- E: Edge of the Earth

Fig. 16 shows the measured coverage contour for the south-east beam in relation to the specified coverage and isolation contours. Also shown are the predicted contours for the multifeed antenna. It can be seen that while the predictions are reasonably accurate for the high gain contours of the composite beam, the predictions for the lower side-lobe levels are inaccurate. The principal reason for the prediction inaccuracies in this region is the difficulty in estimating lower level coupling effects.

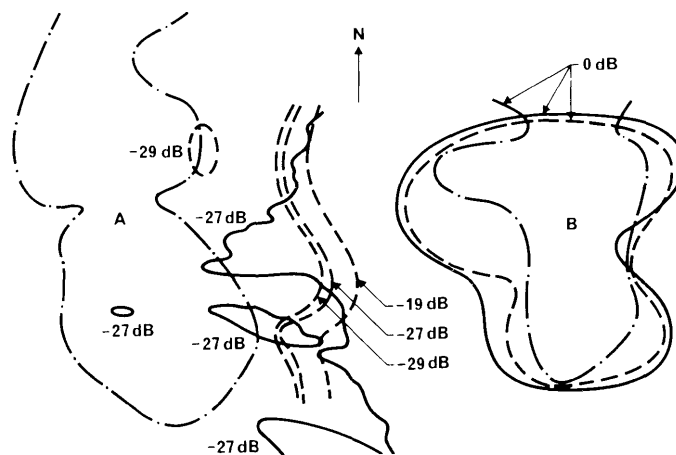


FIGURE 16 — *INTELSAT-IV A antenna southeast beam contour as viewed from the satellite, e.i.r.p. at the contours being expressed in dB relative to the specified edge-of-coverage-over value. Frequency = 3950 MHz*

- Measured
- Computed from feed distribution
- · - · - Specified
- A: Isolation Region
- B: Coverage Region

Mutual coupling between feeds may be considered in two respects. First, in the case of an individual beam, it results in weak parasitic excitation of all other feeds in proximity to the driven feed. Secondly, when several component beams are excited simultaneously to form a group, the effect of mutual coupling is to change the input impedance of each feed so that the intended relative amplitude and phase division between feeds is not exactly realized. Thus, the major advantage of predictive computations is to obtain estimates of the number of feeds required and their approximate positions in the focal plane of the antenna, but these predictive computations cannot be expected to provide accurate predictions of isolation contours.

ANNEX III

SIDE-LOBE CHARACTERISTICS OF HIGH-GAIN SATELLITE ANTENNAE

Frequency re-use by means of high-gain satellite antennae require antennae with side-lobe attenuation which is as high as possible, to achieve effective discrimination with respect to adjacent coverage areas in which use is made of the same frequency band. Moreover, it is desirable to know the exact side-lobe patterns of satellite antennae for the purpose of co-ordinating satellite systems using adjacent angular positions of the geostationary-satellite orbit.

Figs. 17 and 18 show results of measurements made on a partly optimized test antenna for geostationary satellites intended to cover a circular area with an angle of aperture of 1.35° , as seen from the antenna. The antenna is a centre-fed circularly-symmetric paraboloid having a 1.20 m diameter and an f/D ratio of 0.38. It operated in the frequency band from 11.7 to 12.5 GHz and allows both linear and circular polarization modes. The primary feed consists of a circular waveguide radiator with its flange being almost in the aperture plane of the reflector. This flange has several concentric corrugations which ensure a circularly symmetric broadband pattern of the primary feed. The dimensions are such as to obtain in the aperture plane of the paraboloidal antenna, an in-phase illumination, which is tapered as much as possible from the centre to the edge of the aperture. At the same time the attempt was made to approximate the function $J_0(2\eta \frac{x}{\lambda} \sin \phi_0)$ (where J_0 = Bessel function, x = radius, $2\phi_0$ = illumination angle of the coverage area), which is optimal for an in-phase illumination.

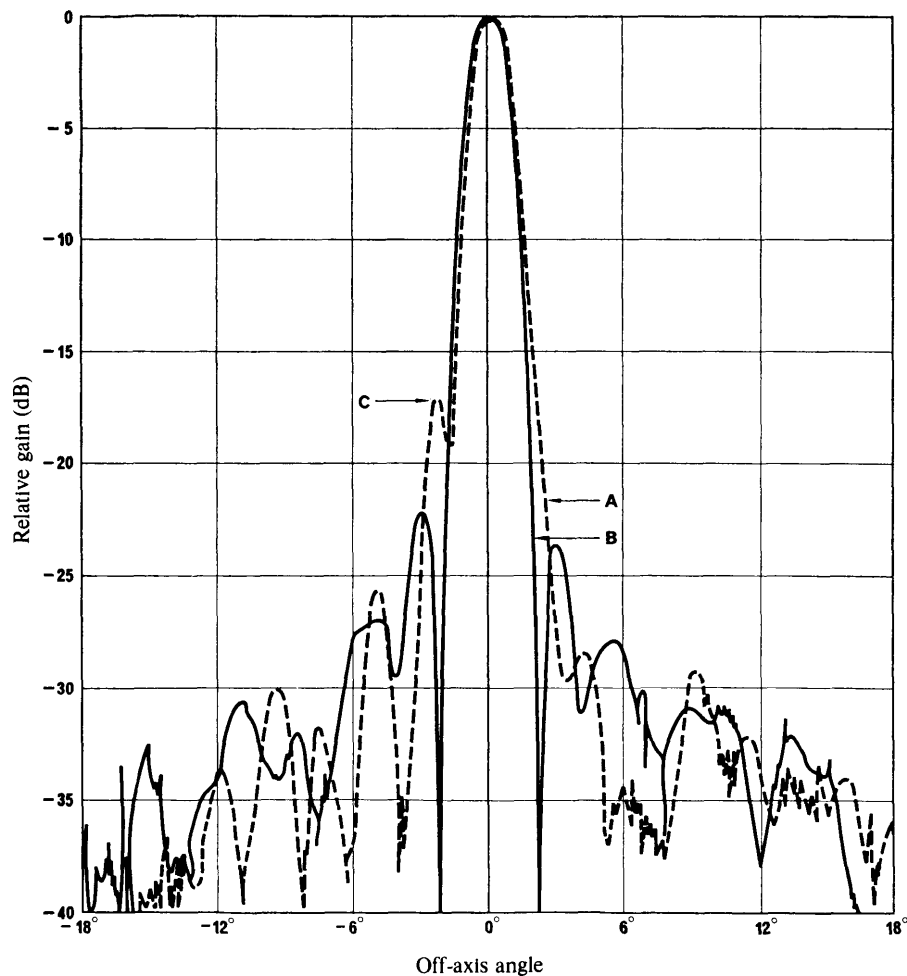


FIGURE 17 — Pattern of a focus-fed paraboloid

11.7 GHz, horizontal polarization

A: H-plane

B: E-Plane

C: ground reflection

Similar patterns with considerably improved circular symmetry are to be expected in the case of circular polarization. It is not yet possible to make a definite statement on the most favourable type of polarization for high-gain satellite antennae. There are, however, some indications that when transmitting with linear polarization only a slight de-polarization occurs in the coverage area and in the disturbed adjacent areas. The cross-polarization suppression in Fig. 18 is not yet optimized and cannot be regarded as representative for other antennae, since it depends, among other things, on the special support structure of the feed.

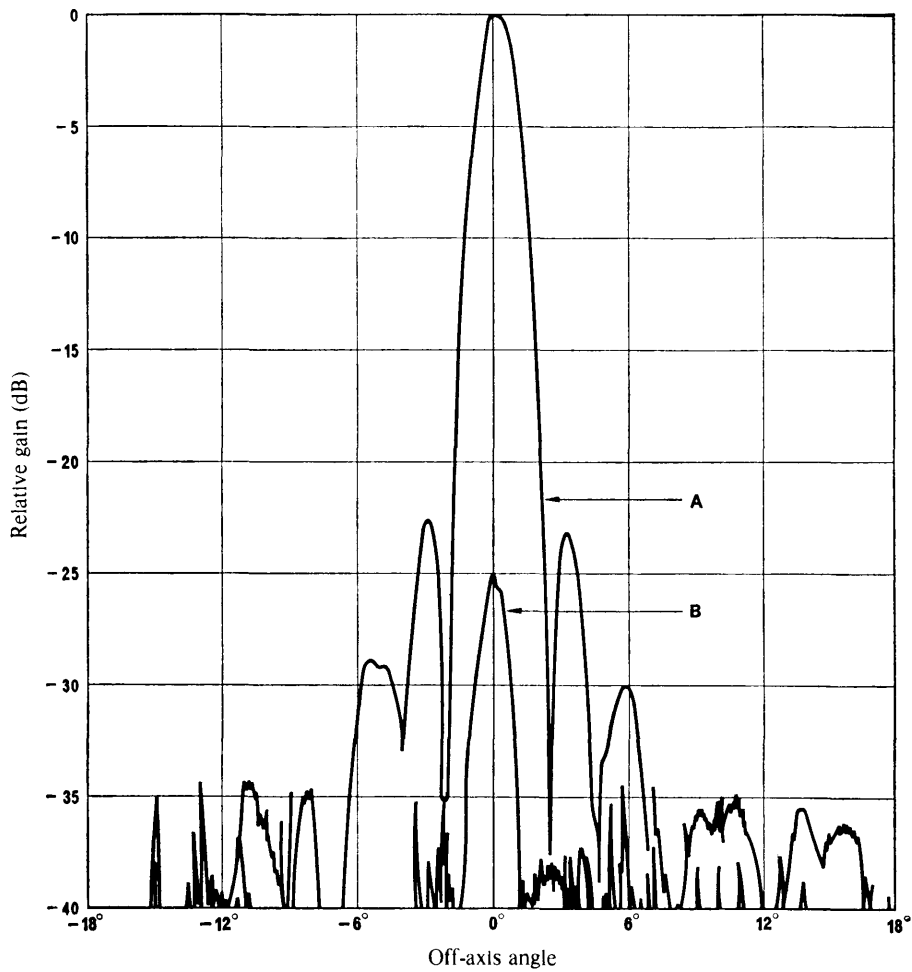


FIGURE 18 — *Pattern showing orthogonal polarization response*
11.7 GHz, E-plane
A: Co-polarization B: Orthogonal polarization

REPORT 559

**THE EFFECT OF MODULATION CHARACTERISTICS ON THE EFFICIENCY
OF USE OF THE GEOSTATIONARY-SATELLITE ORBIT
IN THE FIXED SATELLITE SERVICE**

(Study Programme 2J-2/4)

(1974)

1. Introduction

Modulation of the carrier in frequency or phase has been employed in most satellite communication to date, with frequency-shift keying (FSK) or phase-shift keying (PSK) being used for digital transmissions. An important parameter which affects the efficiency of use of the geostationary-satellite orbit is the ratio of the necessary radio frequency bandwidth, B , to the information bandwidth, the latter being expressed as the highest baseband frequency, f_m , for analogue transmissions or as the transmitted bit rate, r , in bit/s, for digital transmissions. Given good system design, these ratios, B/f_m and B/r , are related to the interference immunity of the modulated signal [Tillotson *et al.*, 1973]. Thus, for a given standard of circuit performance, as these ratios are increased, the minimum acceptable carrier-to-interference ratio may be reduced.

Two specific cases are analyzed in this Report, both involving homogeneous sets of satellites in orbit. One consists of networks using FDM/FM and the other consists of networks using digital PSK transmissions. Each case has been examined by two techniques, a general analytical appraisal discussed in § 2 and a more specific examination in which only a limited number of characteristics are varied, discussed in § 3.

2. A general analytical study

The relationship derived in Annex I (equations (1) and (2)) indicates that for these modulation techniques there is a trade-off between the carrier-to-noise ratio and B/f_m or B/r . To maximize the capacity of a single transmission channel, it may be desirable to use low values of B/f_m or B/r . However, this may increase θ , the minimum required angular spacing between satellites so much that it leads to lower total orbit capacity.

Equations (5) and (6) of Annex I may be used to show this trade-off and are plotted in Figs. 1 and 2 for the following assumptions:

- an interference-to-total-noise fraction of 0.1;
- an earth station antenna gain of 59 dB;
- an earth station side-lobe envelope pattern of $(32 - 25 \log \phi)$ dB.

The other assumptions used in this study are to be found in [CCIR, 1970-74a].

Fig. 1 shows that total orbit utilization efficiency increases as B/f_m increases for analogue FM. It has however been shown that the efficiency becomes almost independent of B/f_m if a much better side-lobe envelope pattern is assumed.

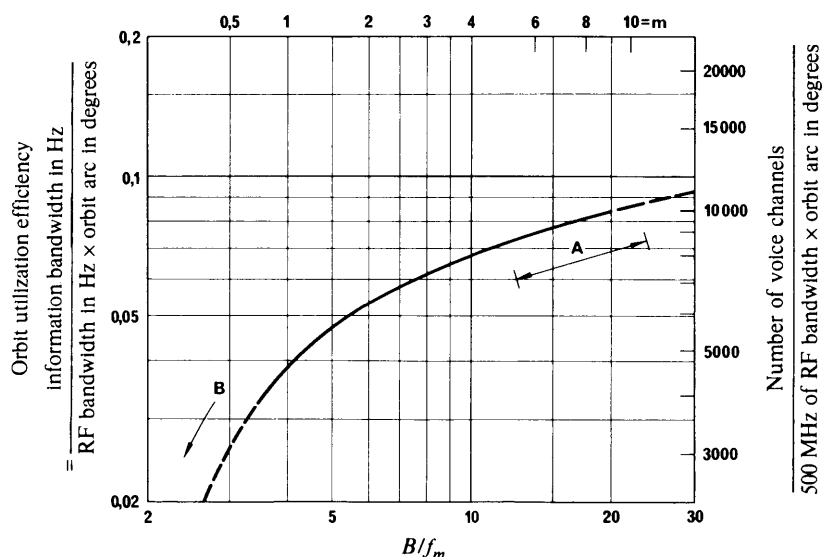


FIGURE 1 — Orbit utilization efficiency versus B/f_m for frequency modulation Earth antenna receive gain = 59 dB

A: Threshold region

B: Region in which networks become limited by down-path pfd

m : Peak modulation index

Fig. 2 shows distinct optima for PSK digital transmissions. For coherent phase detection, the optimum B/r is between 0.4 and 1.0. These optimum values of B/r are essentially independent of the earth station antenna side-lobe radiation pattern. For rate 1/2 convolutional-encoding/sequential-decoding the optimum B/r is about twice as great. In both cases, optimum conditions typically occur with 4-phase or 8-phase PSK and with the bandwidth-to-symbol-rate ratio BT (where T is the symbol period) in the range 1.2 to 2.0. Thus, forward error-correction coding can provide some improvement in orbit utilization efficiency but in this case also the advantage would be less if side-lobe suppression were better.

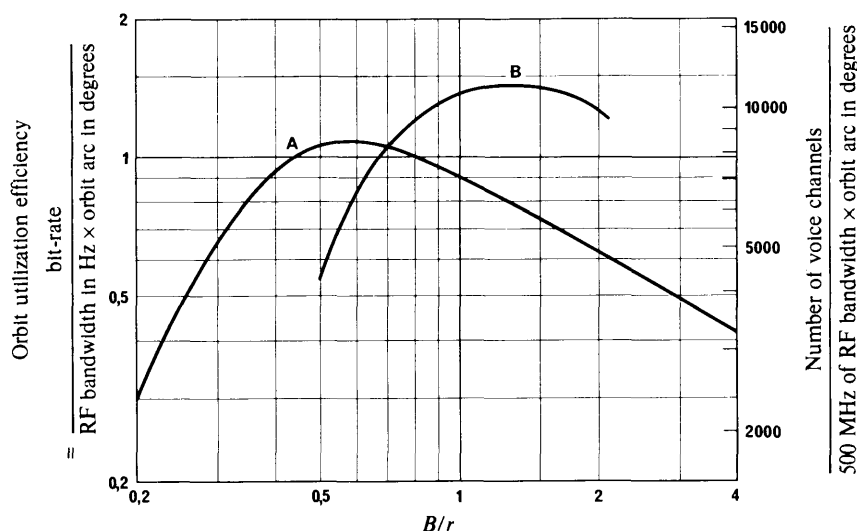


FIGURE 2 — Orbit utilization efficiency versus B/r for digital modulation — Earth antenna receive gain = 59 dB

A: Coherent phase detection
B: Sequential decoding rate 1/2

The analyses in Annex I assume that the satellite networks are optimized in the sense that all available power and bandwidth are utilized. However, a network may be either power-limited (excess bandwidth) or bandwidth-limited (excess-power). In such case B/f_m or B/r might be varied either to maximize network capacity or to minimize satellite spacing. In a power-limited network, it seems that orbit utilization efficiency will usually be increased more by the former course than by the latter. In a bandwidth-limited network, the orbit utilization efficiency will usually be increased more by reducing space.

It should be noted that optimum carrier energy-dispersal has been assumed in this analysis. If less than optimum energy-dispersal were used, the orbit utilization efficiency might be decreased.

3. Bandwidth-limited systems

The effects of modulation on orbit utilization efficiency under bandwidth-limited conditions have been analyzed employing currently feasible system parameters [CCIR, 1970-74b]. The following characteristics were assumed for the analyses:

- frequency bands, 4 and 6 GHz,
- earth station G/T , 40.7 dB, (where T is expressed in K),
- satellite bandwidth, 36 MHz/transponder, 12 transponders per satellite,
- antenna side-lobe envelope as Recommendation 465-1,
- FM interference allowance, Recommendation 466-2,
- CPSK interference noise allowance, no limit within assumed performance objectives,
- maximum e.i.r.p., 35 dBW/transponder.

Some results are shown in Fig. 3 which indicate that the orbit utilization efficiency increases as satellite spacing is reduced under bandwidth-limited conditions.

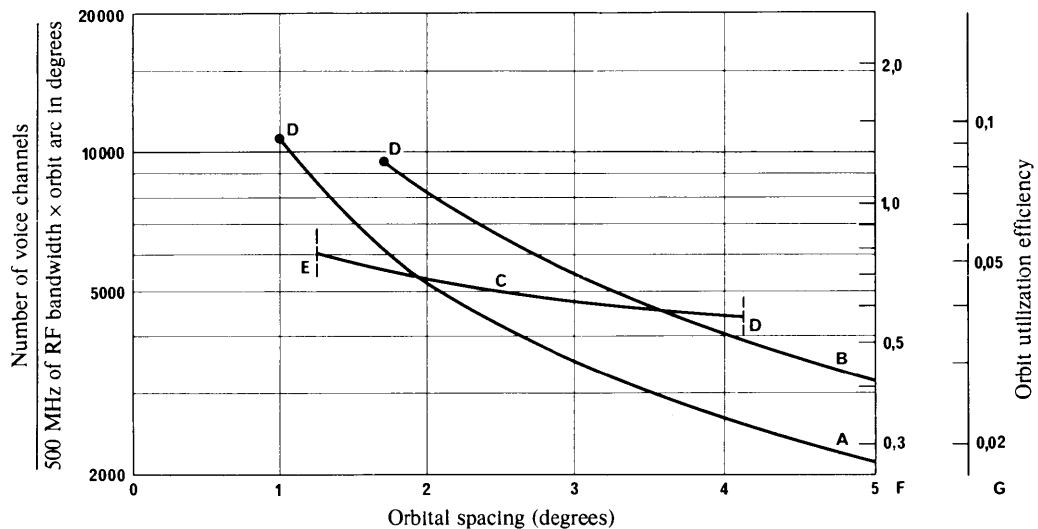


FIGURE 3 — Orbit utilization efficiency versus orbital spacing

($G/T = 40.7$ dBK: perfect station-keeping)

A: 4-phase CPSK D: Power-limited
B: 8-phase CPSK E: Threshold-limited
C: FDM/FM

F: Scale for digital modulation
G: Scale for frequency modulation

For the FDM/FM case the modulation index is varied to maintain a constant level of total noise in a voice channel. It is noted that the orbit utilization efficiency is relatively independent of satellite spacing between the limits imposed by threshold and satellite power limitations.

For the digital phase modulation functions in Fig. 3, the B/r ratio is fixed and thus orbit utilization efficiency and spectrum utilization are inversely proportional to satellite spacing. As the spacing is reduced, more satellite power is required until concurrent power and bandwidth limits are reached at the points indicated. As indicated by Fig. 2, 4-phase modulation provides a somewhat higher efficiency under these conditions.

It should be noted that maximum orbit utilization efficiency and spectrum utilization are achieved at close satellite spacings (1° - 2°) with earth-station antenna gains of about 59 dB. In some cases satellite spacings may be limited by other considerations such as station-keeping tolerances and down-link power flux-density limitations, but power flux-density is not a limiting factor with the conditions assumed.

At these small angular separations, station-keeping tolerances become significant. The present tolerance of $\pm 1^\circ$ may limit nominal spacings to the order of 3° even though as indicated in Fig. 3, 1° spacings may be achieved with perfect station-keeping.

If a digital system is constrained to bandwidth-limited conditions, then 8-phase modulation provides better orbit utilization efficiency than 4-phase modulation. This implies that further reduction of B/r would further enhance orbit capacity. However, satellite power requirements and the resultant down-link power-flux densities increase rapidly (as shown in Fig. 5, Annex I) for B/r values less than 0.4.

The effects of other practical considerations in satellite system design, as they affect orbit capacity, are reviewed in Annex II. It is shown that the use of high B/f_m ratios or modulation indices can significantly increase the number of satellites and earth-stations antennae for a large system with numerous earth-station sites.

4. Conclusions

The satellite and earth-station power requirements and the interference immunity of a signal are affected by the ratios B/f_m , the bandwidth required per unit of information bandwidth and B/r , the bandwidth required per bit-rate. Thus, these ratios are parameters affecting the efficiency with which the orbit is used.

Some general conclusions may be summarized as follows:

- for analogue FM systems, orbit utilization efficiency increases as B/f_m is increased;
- for digital systems employing m -ary phase modulation, optimum values of B/r correspond to 4- or 8-phase modulation for coherent phase detection;
- sophisticated modulation techniques such as convolutional encoding with sequential decoding may provide some improvement in total orbit utilization efficiency but currently, implementation of high bit-rate sequential decoders is not considered practicable;
- for the same external interference allocation, and assuming that 64 kbit/s is required for an encoded voice channel, the orbit utilization efficiency is essentially the same for FDM/FM and PCM/PSK;
- for power-limited systems, orbit utilization efficiency is generally enhanced more by increasing B/f_m or B/r than by reducing satellite spacing;
- for bandwidth limited systems the converse is generally true. If satellite spacing is limited by other factors, then orbit utilization efficiency may be improved by reducing B/f_m or B/r ;
- increasing the slope of the off-axis gain of earth-station antennae tends to make orbit capacity less sensitive to variations in B/f_m but has little effect on the optimum value of B/r ;
- the range of values of B/f_m and B/r also tends to be constrained by practical considerations relative to numbers of antennae and satellites (Annex II);
- optimum energy-dispersal should be employed to ensure that satellite spacing is not limited by down-link power flux-density limitations and to maximize orbit capacity;
- with large earth-station antennae maximum orbit utilization efficiency is achieved at small angular separations and thus station-keeping tolerances may be a significant factor affecting orbit capacity.

For power-limited satellite systems, the tendency in system design toward maximum utilization of satellite power tends to lead to the selection of modulation parameters which enhance orbit utilization efficiency, but this is not necessarily true under bandwidth-limited conditions.

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ANNEX I

GENERALIZED ORBIT UTILIZATION EFFICIENCY FUNCTIONS

1. Analogue frequency modulation

The multi-channel frequency-modulation transfer function can be expressed in terms of B/f_m (as defined in § 1 of the main text) for typical conditions. With a modulating signal in the form of white Gaussian noise with a peak-to-r.m.s. ratio of 4, a Carson's Rule bandwidth of B , ideal pre-emphasis (equivalent to phase modulation) and a typical channel test-tone-to-weighted-noise ratio of 48 dB, the normalized carrier-to-noise ratio required is:

$$E_0/N_0 = \frac{64\,000}{3} \times \frac{1}{B/f_m(B/f_m - 2)^2} \quad (1)$$

where

f_m : highest modulating frequency (Hz)

B : RF required bandwidth (Hz)

$E_0 = C/B$, (watts per Hz) where C : the carrier power

N_0 : the noise power per Hz (watts per Hz)

2. Digital phase modulation

For carriers modulated with digital signals, the normalized receiver input signal-to-noise ratio is expressed as E_b/N_0 (energy per bit/noise power per Hz) and the circuit performance is expressed as a bit rate. For multiple-phase PSK, the E_b/N_0 required for a given output error-rate depends on a number of factors, including the number of significant phase conditions (m), the method of encoding and detection, and BT , the ratio of the bandwidth (B) to the symbol rate ($1/T$), T being the symbol duration. When m is greater than 2, the binary information signal is normally grouped into symbols conveying n bits, where $2^n = m$. The lowest value of E_b/N_0 for a given performance is obtained in the absence of intersymbol interference, and this requires large values of BT . In practical systems, with limited bandwidth, a larger value of E_b/N_0 is required for the same performance. For example, when $BT = 2$ and $m = 4$, E_b/N_0 must be about 2 dB above the minimum value.

The actual performance of two- and four-phase PSK systems is well-established, but performance when $m \geq 8$ is not well-established and an additional penalty, called a composite loss function, $L(BT, m)$ should be allowed for. An approximate relationship between this function, E_b/N_0 , n and m is given by:

$$E_b/N_0 \approx (E_b/N_0)_0 \times \frac{L(BT, m)}{n \sin^2 \frac{\pi}{m}} \quad (2)$$

where $m \geq 4$

and $(E_b/N_0)_0$ is a reference value, equivalent to 11 dB for coherent phase detection and 2.5 dB for convolutional-encoding/sequential-decoding. By using these values for $(E_b/N_0)_0$ in equation 2, a quasi-continuous plot of E_b/N_0 versus B/r and E_b/N_0 versus B/r can be computed and these are shown on Figs. 4 and 5.

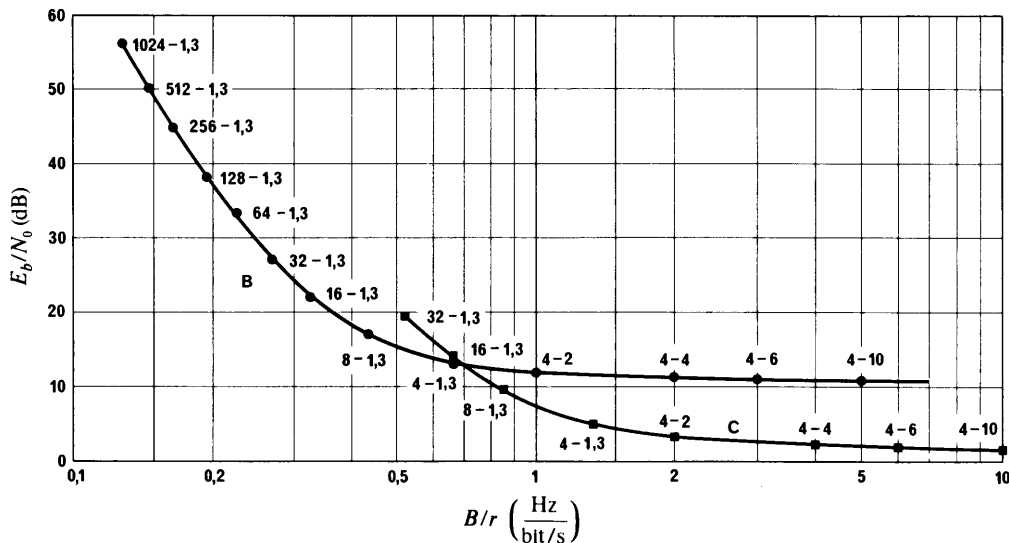


FIGURE 4 — E_b/N_0 versus B/r for digital modulation

B: Coherent phase detection reference; $E_b/N_0 = 11$ dB when BT is assumed to be infinite

C: Sequential decoding rate 1/2

The figures at each plotted point, such as 1024-1.3, identify the number of phases (1024) and the BT product (1.3)

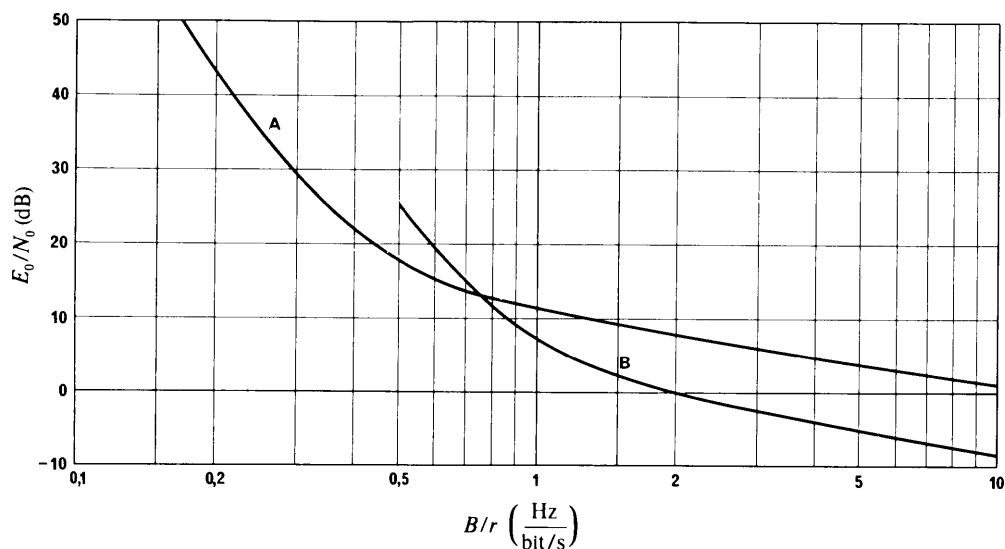


FIGURE 5 — E_0/N_0 versus B/r for digital modulation

A: $f(B/r)$ Coherent phase detection

B: $f(B/r)$ Sequential decoding rate 1/2

3. Functions describing the orbit utilization efficiency

In the case of a homogeneous set of satellites in orbit, the following functions can be used to describe the orbit utilization efficiency:

for analogue systems
$$U \sim \frac{f_m}{\theta \times B} \quad (3)$$

for digital systems
$$V \sim \frac{r}{\theta \times B} \quad (4)$$

where θ is the required angular spacing between satellites.

In homogeneous sets of equally-spaced satellites the following assumptions would appear to be reasonable:

- there is no correlation between the interference paths,
- the earth station transmit gain is 4 dB greater than the receive gain,
- the combination of thermal noise and interference noise behaves like thermal noise.

Then for analogue systems:

$$U = \frac{0.28^{\frac{1}{x}} (B/f_m)^{\frac{1}{x}-1} (B/f_m - 2)^{\frac{2}{x}}}{\left[\frac{64\,000}{3} \times G_R/G_0 \times N_0/I_0 \right]^{\frac{1}{x}}} \quad \frac{\text{Hz}}{\text{Hz-degree}} \quad (5)$$

and for digital systems,

$$V = \frac{0.28^{\frac{1}{x}}}{B/r \left[G_R/G_0 \times N_0/I_0 \right]^{\frac{1}{x}} \left[f\left(\frac{B}{r}\right) \right]^{\frac{1}{x}}} \quad \frac{\text{bit-rate}}{\text{Hz-degree}} \quad (6)$$

where

I_0 is interference noise density, part of N_0 , the total noise density (watts per HZ)

G_0 is the on-axis antenna gain

G_R is the antenna gain at 1° off-axis

x is the slope of the earth station antenna side-lobe envelope,

where $G(\theta) = \frac{G_R}{\theta^x}$,

$G(\theta)$ being the off-axis gain and G_R being the gain at $\theta = 1^\circ$

ANNEX II

THE EFFECT OF MODULATION INDEX ON ORBIT UTILIZATION EFFICIENCY FOR FREQUENCY-MODULATED CARRIERS

This Annex examines the effects of modulation index, m , on the efficiency of utilization of the geostationary-satellite orbit in systems carrying FDM/FM telephone traffic. It is assumed that the satellites are uniformly spaced, that the satellites are identical in bandwidth and available power capacity, and that the traffic each satellite handles is identical in the number of radio-frequency carriers, frequencies, modulation indices, telephone channel capacities and power, i.e. a homogeneous set of satellites. The earth stations are all considered to have the same figure of merit. Two values were examined: 40.7 dBK and 28 dBK.

An indication of efficient orbital utilization is the total number of telephone channels that may be handled by satellites in a fixed segment of orbit. The orbital capacity is expressed as the number of telephone channels per degree of orbit for a specified radio-frequency bandwidth. It is found that large modulation indices * give higher orbital capacities. An increase in the index from 2 to 10 provides an improvement of 40%.

The improvement is, however, obtained at the expense of the telephone channel capacity per satellite. Increasing the index from 2 to 10 reduces the telephone channel capacity for each satellite from 17 900 to 5000, a factor of 3.6. This reduction of channel capacity will also increase the number of required earth-station antennae in a system.

Large modulation indices require considerably less power from the satellite to meet the thermal noise requirement. A system using radio-frequency carriers with a modulation index of 10 requires 19.5 dB less power than one with an index of 2. This reduction in satellite power is achieved for both G/T ratios. An efficiency criterion which combines this economy in satellite power with orbital capacity is the orbital efficiency per watt of satellite e.i.r.p. As expected, large modulation indices give considerable improvement. The major percentage of the improvement is due to the saving in satellite power. This efficiency criterion shows that a large increase in satellite interference can be offset by a relatively small increase in satellite power.

The cost of the space segment is reduced if a large number of telephone channels can be accommodated in a fixed segment of orbit with as few satellites as possible. This implies using satellites with high telephone channel capacities and hence low modulation indices. The power required by a satellite also affects its cost. The choice of an optimum modulation index is determined by two conflicting demands: small values of m to obtain a high telephone channel capacity per satellite, and large values of m to achieve low satellite power.

* Modulation index m = multi-channel peak deviation/top baseband frequency with peak to r.m.s. value of four.

The telephone channel capacity of each satellite has a great bearing on the cost of the earth segment. With high modulation indices, the telephone channel capacity per satellite is low and hence a significant number of satellites may be required to handle the overall channel capacity of a communication system. Each earth-station antenna can operate with one satellite at a time so that several antenna systems will be required per site to obtain full access to all other sites in the system. For example, if the total one-way telephone channel requirement for a system is 50 000 channels, then ten satellites in orbit would be required using a modulation index of 10. For a complete communications capability, some sites might require in the extreme case ten operating antenna systems. If, however, a modulation index of 2 is employed, only three satellites will be needed to satisfy the traffic demand and no site would then require more than three operating antenna systems. This cost saving in the ground segment is more pronounced in systems with many sites. Therefore, for a system with a large number of sites and extensive interconnection, the cost trade-off favours the use of low modulation indices with higher power satellites.

The results of computations are summarized in Tables I and II for the two types of earth stations using the 4 and 6 GHz bands.

TABLE I
 $G/T = 40.7$ dBK (Antenna diameter 30 m)

	Interference level: 1000 pWp		
	$m = 2$	$m = 4$	$m = 10$
Number of radio-frequency carriers per satellite .	12	12	12
Satellite e.i.r.p. per carrier (dBW)	32.3	24.2	12.8
Number of telephone channels per satellite . . .	17 900	10 800	5000
Number of telephone channels per radio-frequency carrier	1 496	900	417
Telephone channels per degree of orbit	5 180	6 230	7270
Required satellite spacing (degrees) to meet noise objectives	3.4	1.7	0.7
Telephone channels per degree of orbit per watt of e.i.r.p.	0.25	1.95	31.5
Telephone channels per satellite per watt of e.i.r.p.	0.87	3.29	21.8

TABLE II
 $G/T = 28$ dBK (Antenna diameter 10 m)

	Interference level: 1000 pWp		
	$m = 2$	$m = 4$	$m = 10$
Number of radio-frequency carriers per satellite .	12	12	12
Satellite e.i.r.p. per carrier (dBW)	45.0	36.9	25.5
Number of telephone channels per satellite . . .	17 900	10 800	5000
Number of telephone channels per radio-frequency carrier	1 496	900	417
Telephone channels per degree of orbit	2 150	2 580	3020
Required satellite spacing (degrees) to meet noise objectives	8.4	4.2	1.7
Telephone channels per degree of orbit per watt of e.i.r.p.	0.0058	0.044	0.7
Telephone channels per satellite per watt of e.i.r.p.	0.047	0.182	1.17

REPORT 711

CRITERIA OF EFFICIENCY OF USE OF THE GEOSTATIONARY-SATELLITE ORBIT

(1978)

1. Introduction

The rapid development of fixed satellite and other satellite services raises the problem of efficiency in the use of the geostationary-satellite orbit. This orbit has limited potential possibilities and furthermore not all orbital arcs are equally suitable for the location of satellites. Some arcs are therefore occupied, or planned to be occupied, by a large number of satellites operating in different international or domestic systems, sharing the same frequency bands. Therefore, the efficient use of the geostationary-satellite orbit and the frequency spectrum in the Fixed Satellite Service is recognized as an important goal — but what constitutes efficient use of the orbit-spectrum resource is a complex question. It is generally agreed that a more quantitative approach to the work is desirable but the complexity of Earth-space geometry and the growing sophistication of radiocommunication-satellite systems may not make a simple answer possible. Insofar as the use of the radio spectrum is concerned, the constraints imposed by the shared use of certain parts of the spectrum by terrestrial services would also have to be taken into account. At the present time no simple comprehensive criteria have been developed to indicate whether or not satellite systems make efficient use of the geostationary-satellite orbit or of the radio-frequency spectrum. The possibility of finding some quantitative means of expressing the efficiency of orbit use and the efficiency of bandwidth use in a single formula, has received initial consideration [CCIR 1974-78a, b and c]. The terms involved require careful choice and precise definition and even when this is done, it may not be possible to reach a satisfactory method of expressing the efficiency of use of these resources in a meaningful and useful way. Nevertheless, it is generally considered that the subject requires continuing investigation. One of the new challenges which this study presents, is that it does not concern only the efficient use of bandwidth for a single transmission system. Instead, it involves the efficient use of bandwidth when a number of potentially interfering common-frequency systems using the geostationary-satellite orbit must also be taken into account.

The number of technical factors affecting geostationary-orbit utilization suggests the potential difficulties attending a comprehensive formulation of efficiency. The complexity of this subject is increased by the effect of non-technical considerations. That is, economic, social, and cultural factors are also important aspects. Progress in the technical area would be furthered by a careful separation and precise definition of concepts that have been previously used loosely and interchangeably. Such clarification might lead to better understanding of the concept of efficiency of orbit-spectrum utilization, and permit the adoption of Recommendations on the subject which would foster the efficient use of this resource. Consequently, § 2 addresses itself to the problem of definitions and § 3 considers the concept of “measure” of utilization of the geostationary orbit and the frequency spectrum. Annexes I and II present in more detail two possible, specific measures and the associated methods of calculation.

2. Concepts and definitions

2.1 *Criteria*

A criterion is a standard of desirableness against which actual use of the resource is to be measured. Although it would be desirable for it to be so, not very reasonable criterion may be amenable to measurement and some may not reflect all conceivable factors of interest. One of the practical difficulties of the concept of a generalized criterion is the likelihood that different users or different Administrations may well differ on the “preferred” criterion to be used.

2.2 *Efficiency*

Since the term efficiency has a widespread and generally accepted meaning, it should not be used less precisely in the present context. In broad terms:

$$\text{efficiency} = \frac{\text{actual performance}}{\text{ideal performance}}$$

In most scientific applications the ideal performance is easily identified, even if unattainable. However, in the present context, performance must be measured in terms of the operative criterion. When a criterion is qualitative, neither actual nor ideal performance is amenable to quantification. Even when a criterion is strictly technical, there are still great difficulties in computing efficiency. For although actual performance might be calculable, the meaning of efficiency implies the existence of a theoretical upper bound (i.e. the “ideal performance”) whose determination appears to be a very complex matter.

For this bound, if it is to be useful (and if it exists), must necessarily encompass within its domain of applicability every conceivable situation that could arise in terms of implementation. That is, it must be valid for any deployment of satellites and earth stations and cannot depend on any specific assumptions on the use of such techniques as reversed-frequency assignments, inter-satellite links, multibeam configurations, polarization diversity, etc. The formulation of a theoretical constraint in such a general setting is indeed a formidable problem.

If the governing criterion cannot be phrased in measurable terms, efficiency cannot be calculated and hence becomes useless in this context. However, even if performance can be well-defined, the identification of an upper bound on this performance, required by the definition of efficiency, is at this juncture an unsolved problem.

2.3 Measure (of orbit-spectrum utilization)

As discussed earlier there are difficulties in defining the efficiency of orbit-spectrum use. It is still important to quantify orbit-spectrum utilization in some manner. It seems that a purely technical context is necessary in order to achieve quantification.

A measure of orbit-spectrum utilization is simply a metric defined on all the relevant technical parameters and conditions belonging to a specified set of satellite networks. One possible metric, * for example, would be "telephone channels per degree of orbit and per MHz". Another method is based on the concept of social utility of satellite systems and is characterized by the equivalent terrestrial system. ** Still another metric might be "average intersatellite spacing". In any case it is clear that the numerical value of the measure will depend on the environment postulated. For example, when considering a particular network to be implemented, the metric considered will yield different numbers if a similar set of satellites is assumed (homogeneity), or some other set, or the actual environment itself into which the satellite is to be placed.

Of course, in order to make the notion of measure useful, it is necessary to select a particular one, and while it does not seem logical to select different measures for different classes of implementation, it is precisely this single measure which provides a meaningful distinction between these classes as to orbit-spectrum utilization. If these different classes represent different applications it may of course be possible to regard different values of the measure as "acceptable", depending on the application.

3. Measures of orbit-spectrum utilization

As discussed earlier, it would seem, barring a rigorous definition of efficiency, that the concept of "measure" is appropriate for assessing the way in which the orbit-spectrum resource is used.

As defined in § 2.3, a measure is a functional defined on the "space" of technical factors. Denote by T_f the set of relevant technical factors. Symbolically, a measure M can be expressed as:

$$M = F(T_f) \quad (1)$$

where $F(\cdot)$ is the functional in question. It is interesting also to define a generalized measure M_g as:

$$M_g = F_g(T_f, K_s, K_c) \quad (2)$$

where F_g is a generalized functional and K_s is a factor (or set of factors), reflecting social utility and K_c embodies cost factors which might comprise, e.g., initial costs, maintenance costs, revenues, etc. However, since we have defined measure as a technical concept we shall for the most part deal only with (1).

There are a number of possible measures, some of which are listed below:

- (a) The total data rate;
- (b) The average intersatellite spacing (equivalently, the number of satellites);
- (c) The number of space-Earth links;
- (d) The data rate per MHz;
- (e) The data rate per degree of orbit per MHz.

These measures reflect in one way or another the basic purpose of the resource and define the units in which orbit-spectrum utilization is to be counted. All the relevant technical factors contribute in some way to the rating that results.

* The term *metric* has been borrowed from mathematics where it is defined as a functional (with certain properties) which maps sets of points from one "space" into another. The most familiar metric, of course, is distance, which maps pairs of points into the real line. Our use of the term, therefore, implies the "mapping" of the "space" of technical characteristics into a single number preferably, or possibly, a set of numbers.

** By the term *equivalent terrestrial system*, is meant a terrestrial system which it would be necessary to implement in place of a satellite system in order to set up the same number of channels between the same points on the earth.

Another approach to the search for a measure would be to define a measure strictly as some mathematical function of the (relevant) technical parameters of the networks involved. As a purely hypothetical example, consider the function, μ , as follows:

$$\mu = P_t^{\alpha_1} G_t^{\alpha_2} \left(S(f) \right)^{\alpha_3} \left(\frac{G_r}{T_r} \right)^{\alpha_4} \left(\frac{1}{1 + \Delta N} \right)^{\alpha_5} \left(\frac{1}{1 + \Delta E} \right)^{\alpha_6} \quad (3)$$

where,

- G_t : on-axis transmit antenna gain,
- P_t : transmit power,
- $S(f)$: power spectral density averaged over a reference bandwidth,
- G_r : on-axis receive antenna gain,
- T_r : receiver noise temperature,
- ΔN : north-south station-keeping tolerance,
- ΔE : east-west station-keeping tolerance.

The exponents α_i reflect different degrees of importance. An equation such as (3) could be written for both up-path and down-path. The total measure of utilization over an arc of the orbit might be the average $\bar{\mu}$ over all networks. The motivation behind this type of measure is simplicity in the sense that (3) is a well-defined, straightforward function of the major technical factors that influence orbit-spectrum utilization. Another desirable feature of this method is that the measure is well-defined for an individual network, irrespective of its environment. This is a great advantage since one of the major difficulties with other approaches is the definition of a suitable environment for computational purposes. However, there are also disadvantages with this method that tend to render it less preferable than others. One difficulty is how to choose the relative values of the exponents α_i . A more basic difficulty is that, in fact, it is not always clear whether a factor actually tends to help or to hinder orbit-spectrum utilization. For some factors, such as G_r , it is clear what the trend is. But take P_t , for example. If all other things are fixed in equation (3) and P_t increases, the implication is that the bandwidth must increase (in order to keep $S(f)$ constant). Thus, greater capacity is achieved at the expense of bandwidth, and it is not possible in general, to say which of these changes will dominate. Of course, (3) is merely an example and it might be possible to find a formula that does not have the difficulties just mentioned. Even so, what is perhaps the main drawback with this type of measure is that it does not express utilization in terms of the resource itself and it is thus, difficult to appreciate the meaning of particular numbers resulting from its evaluation.

The fundamental purpose of the orbit-spectrum resource is the transmission of information. Thus it seems natural that a meaningful manner of measuring orbit-spectrum utilization is in terms of the amount of information transmitted relative to the amount of the resource "consumed" in order to transmit that information. Also of great importance is the cost necessary to establish the service as well as the social utility it renders. Equation (2) already reflects these ideas but in very general form. For computational purposes, one must specify a particular relationship among the variables involved. A particular form which seems sufficiently general and flexible for use as a generalized measure is as follows:

$$M_g = \frac{R \text{ (social utility)}^\alpha}{(\Delta\theta)^\nu (W)^\mu (\text{cost})^\delta} \quad (4)^*$$

where,

- $\Delta\theta$: orbital arc used
- W : occupied bandwidth
- R : data rate
- α, ν, μ, δ : relative weighting factors

As it stands, equation (4) is still not specific enough for computation. Two measures derived from somewhat different interpretations of (4) are discussed in some detail in Annexes I and II, respectively.

* It may be useful to observe that there could be external constraints in the evaluation of (4), for example, where bands are shared between terrestrial and space services.

3.1 Computing measures of orbit-spectrum utilization

Irrespective of the measure adopted the computational process must be standardized. One of the basic purposes of a measure is to provide guidance to satellite system designers on the utilization of orbit-spectrum of different prospective designs. Thus one would like a measure that can apply to a single specific network. Any measure into which satellite spacing enters necessarily requires another satellite with respect to which this spacing exists. Hence, for computational purposes at least one other satellite network must be defined. * There are many possible ways to do this, including:

- (a) Define another satellite network with a single satellite, identical to the satellite network considered.
- (b) Define a set of networks identical to the one being considered, i.e., the homogeneous case. (A measure that utilizes this method is discussed in Annex II.)
- (c) Define a reference satellite network which would serve as the basis for calculation with any network being considered. (A measure that utilizes this method is discussed in Annex I.)
- (d) Define a heterogeneous but tractable set of other networks to provide a more realistic context. For example, one could define a homogeneous ring of satellites identical to the one being considered, alternating with a second type of satellite.
- (e) One can make the computation for the actual environment in which the network under consideration would be implemented.

Method (e) is probably the most meaningful but also the most complicated. Its disadvantage, however, is that it does not consider future developments. It seems that either method (a) or method (c) might provide a relatively tractable basis for computing a measure. The main advantage of (a) is its relative simplicity and the fact that the measure would reflect only the parameters of the network under consideration since the other network would be identical. The main drawback of this method is the fact that it does not provide a common basis for different networks. This particular aspect is in fact the strong point of method (c) which, by providing the same reference for all networks, enables a more direct comparison of different networks. The disadvantage of the method is that a very general network must be defined in all relevant aspects to permit the appropriate calculations to be made. For example, if the network considered, transmits or receives signals in two different frequency bands the reference network must have corresponding properties. The reference system must be defined in such a way as to make calculations relatively straightforward without biasing the results unduly towards particular types of networks. This method, therefore, requires further study. Additional discussion of these methods is given in Annex III.

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[1974-78a]: a. 4/51 (United States of America); b. 4/55 (United States of America); c. 4/109 (U.S.S.R.).

ANNEX I

1. Introduction

In § 3, a general criterion for the effectiveness of use of the geostationary orbit was proposed, namely:

$$M_g = \frac{R \text{ (social utility)}^a}{(\Delta\theta)^v (W)^\mu (\text{cost})^\delta} \quad (5)$$

In this Annex a particular interpretation of (5) is put forward. In particular, an attempt at quantifying "social utility" in terms of an equivalent terrestrial system is made. Also a possible way of taking spot beams into account is developed. The numerical evaluation of (5) for a proposed system is accomplished by using the reference network method (§ 3.1, item (c)). A possible reference system which could prove useful is described in the last section of this Annex.

2. General development

Consider first the numerator of equation (5). The social utility of a planned satellite service depends on the distance between earth stations, the duration of the channel loading, types of messages — duplex or hub-mode transmitted information (i.e., directed at a large number of users simultaneously).

* This is not true in the case of measures such as are defined by equation (3) which are strictly functions of parameters of the network itself. However, as was mentioned in the preceding section, it is doubtful that such measures would prove useful.

To take account of all these factors, it is proposed that the useful traffic capacity of a communication-satellite system should be defined in terms of the terrestrial network which would be required to serve the same purpose as the satellite system, i.e. to set up the same number of channels between the same points on the surface of the Earth. Therefore, the numerator in (5) could be written:

$$(NL) \text{ eq. terr.} \times B \quad (6)$$

where,

(NL) eq. terr.: number of channel-kilometres of the equivalent terrestrial network;

B : factor characterizing the ratio of mean occupancy time T_o of a channel of a given system, to mean occupancy time of a trunk telephone channel T_{o0} .

According to (6) the value $T_{o0} \approx 2.5$ hours. Therefore,

$$B = T_o / T_{o0} \quad (7)$$

The factor B may be greater than 1 in telephone systems with demand-assigned circuits and also in radio and television broadcasting systems.

Now consider the denominator in equation (5). Difficulties in cost evaluation of the occupied orbit arc (i.e. of the necessary geostationary satellite separation) and the bandwidth, make it necessary to reject the consideration of the satellite-communication systems cost. At the same time equation (6) defining traffic capacity in terms of terrestrial network, reflects to a great extent an economic factor.

It is reasonable to assume values v and μ in formula (5) as equalling 1.

While determining $\Delta\theta$, we shall assume that in the vicinity of the geostationary satellite of the system in question, the reference geostationary satellite relating to a certain reference system should be located.

The reference system parameters could be selected in accordance with § 3 of this Annex.

It is evident that with a great enough separation between the reference geostationary satellite and the test geostationary satellite, mutual interference might not occur even in the case when onboard antennae are directed at the same sector of the Earth's surface. Obviously, to require satellite spacing ($\Delta\theta$) by such as an angle (θ_{max}), which virtually eliminates mutual interference, would be superfluous and wasteful.

To determine the degree of occupancy of a given point in a geostationary orbit arc, an arc utilization factor must be introduced:

$$D(\Delta\theta) = \frac{S_b}{S_v} \quad (8)$$

where,

S_b : surface of the Earth barred to radiation in this frequency band;

S_v : the Earth's surface visible from the geostationary satellite orbit.

Here S_v is defined as that part of the Earth's surface visible from the geostationary orbit which is calculated by the standard formula as the surface of a spherical segment subtending an angle of 150° . S_b is defined as an area on the Earth's surface whose irradiation by the interfering system causes an increase in the noise temperature, $\Delta T = y\Delta T_s + \Delta T_e$ in the reference satellite-communication system, which exceeds the permissible value. The increase in noise temperature is calculated by the standard method described in Report 454-2. Channel noise value specified in Recommendation 466-2 might serve as the interference unacceptability criteria.

For practical calculations we use a D value averaged for the whole occupied arc:

$$\bar{D} = \frac{1}{2\theta_{max}} \int_{-\theta_{max}}^{+\theta_{max}} D(\theta) d\theta \quad (9)$$

The calculations of the factor $\bar{D}$ assume a transmitter-receiving station of the "interfering" system (system under study) located at a sub-satellite point of the reference system (worst case).

Introducing formula (6) into (5) and replacing value $\Delta\theta$ by multiplication $\theta_{max} \bar{D}$:

$$M = \frac{[(NL) \text{ eq. terr.}] B}{\theta_{max} \bar{D} (W)} \left[\frac{\text{eq. terr. channel-km}}{\text{deg.} \times \text{MHz}} \right] \quad (10)$$

Methods of determining value M are given in [Kantor, 1976; Talyzin *et al.*, 1969; Talyzin *et al.*, 1970].

The geostationary orbit efficiency criteria defined in formula (10) requires further development.

3. **Parameters of one possible communication-satellite reference system used for evaluating efficiency in the use of the geostationary satellite orbit and the frequency spectrum**
 - 3.1 *Frequency range*: same as system under study.
 - 3.2 *Type of satellite*: geostationary-orbit satellite.
 - 3.3 *Up-path characteristics of system*:
 - (a) Maximum spectral power density at earth station antenna input, measured in the worst 4 kHz band:
 $P_e = -56 \text{ dB(W/Hz)}$.
 - (b) Transmitting antenna gain of earth station:
 $G_1 = 62 \text{ dB}$.
 Radiation pattern: $G(\theta) = 32 - 25 \log \theta$ dB
 - (c) Gain of satellite receiving antenna:
 $G_2 = 43 \text{ dB}$.
 Radiation pattern:
 $G(\varphi) = G_2 - [10.5 + 25 \log \varphi/\varphi_0]$, $\varphi_0 = 1^\circ$
 - (d) Noise temperature of receiving space station:
 $T = 3300 \text{ K}$.
 - (e) Working frequency band occupied with uniform spectral density.
 - 3.4 *Down-path system characteristics*:
 - (a) Maximum spectral power density at space station transmitting antenna input, measured in the worst 4 kHz band:
 $P_s = -66 \text{ dB(W/Hz)}$.
 - (b) Transmitting antenna gain of satellite:
 $G_3 = 43 \text{ dB}$.
 Radiation pattern:
 $G(\theta) = G_3 - [10.5 + 25 \log \varphi/\varphi_0]$, $\varphi_0 = 1$.
 - (c) Receiving antenna gain of earth station:
 $G_4 = 58.5 \text{ dB}$.
 Radiation pattern:
 $G(\theta) = 32 - 25 \log \theta$ dB.
 - (d) Working frequency band occupied with uniform spectral density.
 - 3.5 *Link parameters*:
 - (a) Transmission coefficient from repeater input to earth station receiver input:
 $\gamma = -9.5 \text{ dB}$.
 - (b) Link equivalent noise temperature:
 $T_{eq} = 80 \text{ K}$.
 - (c) Orientation of satellite receiving and transmitting antennae towards the sub-satellite point.
 - (d) Polarization — circular, right-hand and left-hand.
 - (e) Modulation — frequency; multiplexing — FDM.

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ANNEX II

METHODOLOGY FOR RELATING AN ORBIT-SPECTRUM
UTILIZATION MEASURE TO SYSTEM PARAMETERS

1. Introduction

This Annex presents a general methodology which may be used to derive numerical results relating one particular orbit-spectrum utilization measure to system parameters.

Equation (4) of the text presents one possible general formula to define orbit-spectrum measure. Because, however, of the difficulty of assessing factors other than the technical, it seems useful to consider a more restricted form of (4). In particular, setting $\alpha = \delta = 0$, one obtains the measure:

$$M = \frac{R}{(\Delta\theta)^v (W)^\mu} \quad (11)$$

where v and μ are exponents that might be used to express relative worth of orbital arc and bandwidth. Note that if $v = 0$, the measure reduces to measure (d) in § 3 and if $\mu = 0$ as well, it reduces to measure (a). Although equation (11) is simple enough in appearance, it could be simplified still further by setting the exponents to unity. It is felt that this would not materially detract from the meaningfulness of the measure and makes it easier to use. In addition, the problem of deciding the appropriate values of v and μ is removed. Thus, the formula:

$$M = \frac{R}{(\Delta\theta) (W)} \quad (12)$$

is suggested as a reasonable and meaningful measure of orbit-spectrum utilization.

It is worthwhile to discuss briefly to the meaning of (12) and avoid possible misinterpretation. In (12) no relationship whatever is assumed to exist between $\Delta\theta$ and W . In particular there is no implication of an inverse relationship. It is true that if $\Delta\theta$ is halved and W doubled (and R is constant) then M is unchanged. And if in fact in an actual case one were to double the bandwidth with the resultant effect that $\Delta\theta$ could be halved with R unaffected, then in that particular situation one could trade orbital arc for bandwidth. However this relationship would not be an a priori assumption, but merely a consequence of the system and parameter assumptions that had been made.

A similar kind of misunderstanding can result by asserting that (12) predicts a higher value of M by decreasing the bandwidth. Again, this assertion would be true if $\Delta\theta$ and R were unchanged. However, one cannot usually change any of these three parameters without affecting the other two. The basic point is that R , $\Delta\theta$, and W are not mutually independent variables, with a given set of other network parameters. Normally, R is a basic design specification. The bandwidth W can also be specified or it is constrained by the applicable allocations, or it is a consequence of R and the modulation index. With a given choice of antenna gains, modulation parameters, and interference allowance, $\Delta\theta$ is automatically determined. Thus the proper interpretation of (12) is that R , $\Delta\theta$, and W , form a consistent set of values resulting from the totality of design assumptions.

There are two main technical problems in numerically evaluating equation (12):

- the computation of wanted-to-unwanted carrier ratios given the geometry, e.i.r.p.s, antenna sizes, etc.; this is treated in detail in Report 455-2
- the computation of baseband noise given the carrier-to-interference and carrier-to-noise ratios. The relationship between baseband noise and radio frequency carrier-to-interference ratio is considered in Report 388-3.

The first step is independent of the modulation parameters, but the second represents a problem and depends on the method of modulation of wanted and unwanted carriers, the parameters thereof, and the type of signal. For brevity, therefore, this Annex considers only FDM-FM telephony.

2. Baseband noise due to thermal noise

The ratio of the test-tone to thermal noise in the top baseband channel may be written as:

$$\left(\frac{S}{N}\right)_t = \left(\frac{C}{N}\right) R_t \quad (13)$$

where,

C/N : total carrier-to-noise ratio at receiver input from down-path and up-path contributions;

R_t : a factor (sometimes called receiver transfer characteristics) representing the effects of modulation improvement and baseband processing; it may or may not include psophometric weighting and pre-emphasis as the case may be.

The baseband noise, N_t , is related to (13) through:

$$N_t = \frac{10^9}{S/N_t} \quad \text{pW} \quad (14)$$

and it may be shown that,

$$R_t = 380 M_{rms}^2 (\sqrt{\Lambda} M_{rms} + 1) \quad \text{for } n \geq 240 \quad (15a)$$

and,

$$R_t = 15 n^{0.6} M_{rms}^2 (\sqrt{\Lambda} M_{rms} + 1) \quad \text{for } 12 \leq n < 240 \quad (15b)$$

where,

M_{rms} : multichannel r.m.s. modulation index;

Λ : peak-to-average power in the baseband (generally, a function of n);

n : number of channels per carrier.

Equation (15) also includes a 4 dB pre-emphasis advantage as well as a 2.5 dB psophometric weighting, and was, further, based upon Carson's rule for FM bandwidth i.e.:

$$W = 8400 n (\sqrt{\Lambda} M_{rms} + 1) \quad \text{Hz} \quad (16)$$

3. Baseband noise due to interference

Consider K arbitrary interfering carriers. The ratio of the test-tone to the noise in the top channel of the wanted signal, due to the j th interfering carrier may be written as:

$$\left(\frac{S}{N}\right)_j = \left(\frac{C}{I}\right)_j R_j \quad (17)$$

where,

$(C/I)_j$: total carrier-to-interference ratio for the j th interfering carrier, from up-path and down-path contributions; *

R_j : receiver transfer characteristic for the j th interfering carrier: this may or may not include psophometric weighting and pre-emphasis advantage, as the case may be.

The values of $(C/I)_j$ will depend on the terminal parameters of wanted and unwanted systems: e.g., spacing between satellites, relative up- and down-path e.i.r.p. values, antenna size, etc. Complete expressions permitting the evaluation of $(C/I)_j$ are given in Report 455-2.

* This assumes that the wanted and unwanted carriers have the same translation frequencies at the satellite. If this is not the case, separate equations have to be written for up-path and down-path since different values of R_j will apply.

The values of R_j for any channel depend upon the modulation indices, the baseband bandwidths, the frequency separation, and the degree of pre-emphasis of the wanted and unwanted carriers. Report 388-3 may be used to compute the numerical values of R_j .

$$\text{Baseband noise } N_{lj} = 10^9 / (S/N)_j \quad \text{pW} \quad (18)$$

Since $(C/I)_j$ is directly related to the spacing between the wanted and unwanted satellites for a given set of system parameters, equation (18) can then be used to relate satellite spacing to the interference noise budget.

4. Total baseband noise

If the carrier-to-noise and carrier-to-interference ratios are sufficiently high, nominally above threshold, the total baseband noise may be obtained by simple addition of the individual contributions:

$$N_T = N_i + \sum_{j=1}^K N_{lj} \quad (19)$$

where K is the number of interference entries.

Using equations (13), (14), (17) and (18):

$$N_T = 10^9 \left\{ \frac{1}{(C/N) R_i} + \sum_{j=1}^K \frac{1}{(C/I)_j R_j} \right\} \quad \text{pW} \quad (20)$$

In the present context, N_T is conveniently described as the total baseband noise although it is the noise which arises only from thermal and interference sources. In practice, due allowance must be given to other potential contributions, such as radio-relay interference and equipment generated noise; such contributions, however, do not directly enter into orbit utilization trade-offs.

Equation (20) is quite general. For an arbitrary, given set of parameters such as bandwidth and satellite spacing, it may be used to compute the resulting system performance N_T . Conversely, given N_T , it allows the determination of those parameter values which satisfy the specification. Unfortunately, the latter process is difficult for a general situation and generally requires more restrictive constraints if it is to provide an easy solution.

5. Example : homogeneous case

In order to evaluate equation (12) in an orderly and systematic way, a "homogeneous" context is chosen (see § 3.1, item (b)). The assumptions collectively referred to as the homogeneous model are:

- a full ring of equally spaced satellites in the geostationary-satellite orbit;
- frequency modulation is used, with FDM telephony basebands of capacity not less than 240 channels;
- all satellites have earth coverage antennae, possess identical transmission and modulation parameters, and transmit the same type of signal on the same nominal carrier frequency (co-channel sharing);
- all earth stations are identical, with antenna side-lobe characteristics conforming to Recommendation 465-1;
- propagation conditions are clear weather.

Since telephony is being considered here, telephone channels is a more appropriate parameter than data rate. Hence we consider the equivalent measure:

$$\tilde{n} = \frac{n}{(\Delta\theta) (W)}$$

where $\tilde{n}$ is the number of telephone channels per carrier and W is the associated bandwidth, as in (16).

The assumption of homogeneity leads to R_j being the same for all networks; thus, it may be represented by R_0 , so that R_j in the summation of equation (20) may be replaced by a constant depending on M_{rms} . Using a numerical fit of the co-channel curve of Fig. 8-3-2 of Annex 8-3 of the Report of the CCIR Special Joint Meeting, Geneva, 1971, it can be shown that:

$$R_0 \approx 76 (1 + 9.5 M_{rms}^3) \text{ for } n \geq 240 \text{ channels} \quad (21a)$$

$$R_0 \approx 3n^{0.6} (1 + 9.5 M_{rms}^3) \text{ for } 12 \leq n < 240 \quad (21b)$$

The two equations include psophometric weighting and CCIR pre-emphasis.

Next, it is convenient to separate up-path and down-path contributions, as follows:

$$\left(\frac{C}{N}\right) = \left(\frac{C}{N}\right)_d \left(\frac{1}{1 + \alpha}\right) \quad (22)$$

where,

$(C/N)_d$: down-path carrier-to-noise ratio;

α : ratio of down-path to up-path carrier-to-noise ratios.

The relation of α and $(C/N)_d$ to the terminal parameters follows from elementary transmission theory.

For the interference:

$$\left(\frac{C}{I}\right)_j = \left(\frac{C}{I}\right)_{dj} \left(\frac{1}{1 + \alpha_j}\right) \quad (23)$$

where,

$(C/I)_{dj}$: ratio of the down-path carrier to the interference from the j th source;

α_j : a ratio of ratios: that of the carrier to the j th interfering carrier ratio in the down-path to the carrier to the j th interfering carrier ratio in the up-path.

From the assumptions that:

- all satellites have earth-coverage antennae,
- all earth-station antennae have side-lobe radiation patterns of the form given in Recommendation 465-1 namely:

$$G(\Delta\theta) = A/(\Delta\theta)^{2.5}; (A = 10^{3.2}) \quad (24) *$$

It may be shown, to a good approximation, that

$$\alpha_j = \alpha_0 \quad (25)$$

for all interfering entries where α_0 is the ratio of the down-path to the up-path gain of the earth station antenna.

The summation in (20) may then be written, using equations (21) and (25):

$$\sum_{j=1}^K \frac{1}{(C/I)_j R_j} = \frac{1 + \alpha_0}{R_0} \sum_{j=1}^K \frac{1}{(C/I)_{dj}} \quad (26)$$

and it may further be shown, for co-channel, co-polarized transmissions, that:

$$\sum_{j=1}^K \frac{1}{(C/I)_{dj}} \approx \frac{2A}{G_{0d} (\Delta\theta)^{2.5}} \sum_{k=1}^{\infty} k^{-2.5} \approx \frac{2.7 A}{G_{0d} (\Delta\theta)^{2.5}} \quad (27)$$

where G_{0d} = the on-axis, down-path gain of the earth station antenna. Using the relation

$$G_{0d} = \eta(\pi D/\lambda)^2$$

where η is the antenna efficiency and combining equations (22), (26) and (27) into equation (20) yields:

$$\frac{1}{\Delta\theta} = \left\{ \left(\frac{N_T}{10^9} - \frac{1 + \alpha}{(C/N)_d R_t} \right) \frac{R_0 \eta (\pi D/\lambda)^2}{2.7 A (1 + \alpha_0)} \right\}^{0.4} \quad (28)$$

* In principle $\Delta\theta$ is the topocentric angle, but since it approximates to the geocentric angle, these two angles are used interchangeably.

From equation (16)

$$\dot{n} = 119 / (\sqrt{\Lambda} M_{rms} + 1) \quad \text{channels / MHz}$$

and hence the quantity sought is,

$$\dot{n} = \frac{119}{(\sqrt{\Lambda} M_{rms} + 1) \Delta\theta} \quad \text{channels / degree / MHz.} \quad (29)$$

Introducing equation (28) into equation (29) gives an explicit equation relating a measure of orbit and spectrum utilization to all major system parameters. Fig. 1 is a graphical expression of this equation for the special case: $\alpha = \alpha_0 = 0$, $n \geq 240$ channels. $D/\lambda = 300$, $\eta = 0.5$, $N_T = 7500$, and assuming 2.5 dB psophometric weighting and CCIR pre-emphasis.

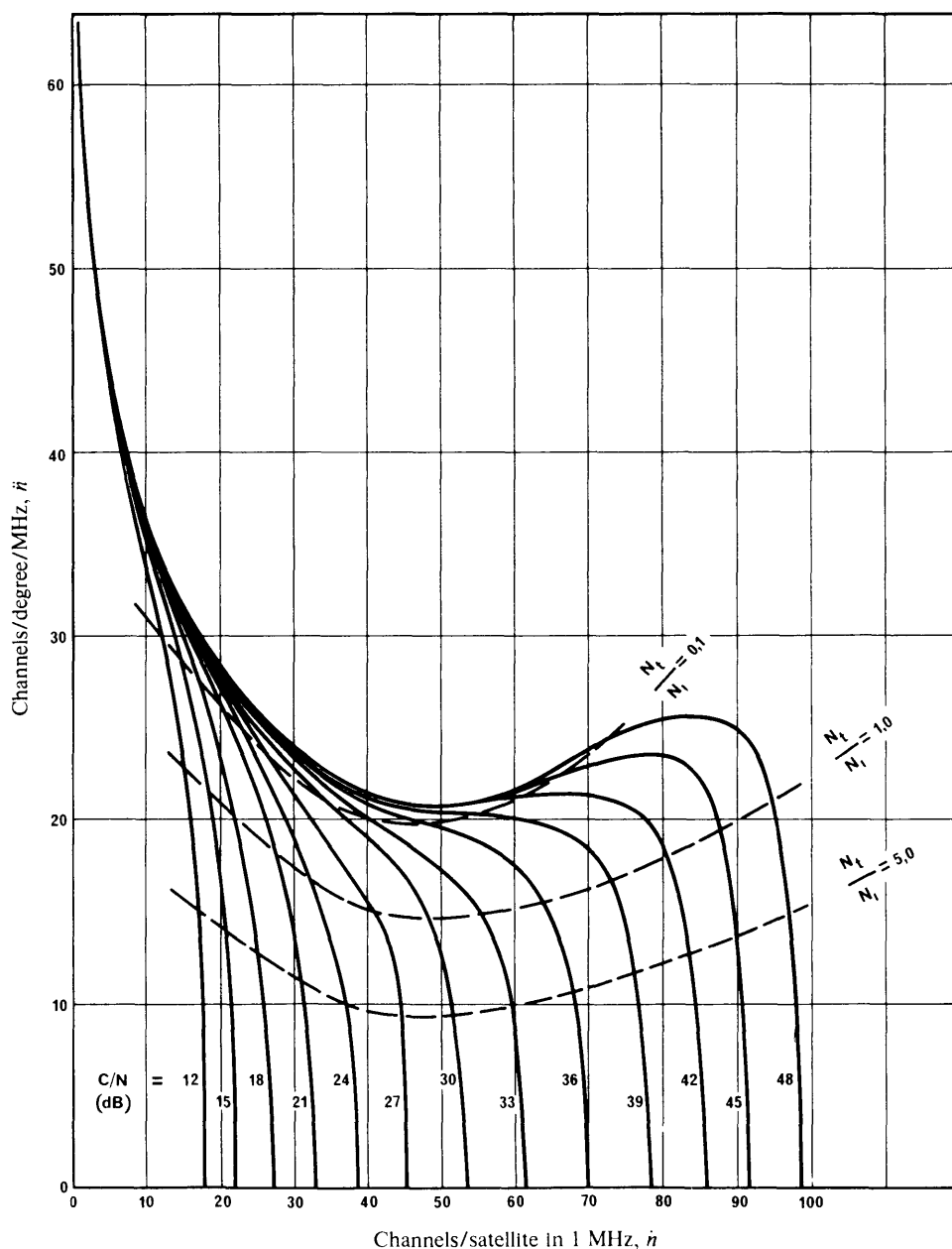


FIGURE 1 — Orbit-spectrum utilization as a function of channels per satellite

($D/\lambda = 300$, $N_T + N_I = 7500$)

(Interfering carriers are assumed to be co-channel)

ANNEX III

In § 3.1 of the text, several possible computational approaches are indicated for calculating measures of orbit-spectrum utilization. As indicated there, each method has advantages and disadvantages. This annex discusses in somewhat greater detail the problems that may arise in applying one method or another.

1. Spot beams

One of the major difficulties concerns the use of spot beams on satellites. Consider first method (a), the "identical pair" approach. If the subject satellite emits a spot beam, the question arises as to where the second satellite should point its beam. The answer will evidently affect the required separation $\Delta\theta$. If the second satellite is indeed identical, the beam placement perhaps most consistent with identicalness is on the same co-ordinates as the subject satellite. The resulting measure will therefore be unaffected by the narrowness of the beam. This is intuitively unsatisfying for one feels that spot beams do enhance orbit-spectrum utilization and this should somehow be reflected in the standardized procedure. Possibly, a satisfactory solution to this problem would be to assume that the beams intersect on the earth at the $-X$ dB contours, where X is to be further studied and would most likely be a function of the beamwidth.

A similar problem obtains with method (c), the reference network approach. If the latter has a spot beam, what should its beamwidth be, and where should it be pointed in relation to the subject satellite's beam? If the reference satellite has an earth-coverage beam, and if it is assumed that a receiving earth station can be anywhere within that beam, then the rating of whatever measure is used will be essentially unaffected by the width of the subject satellite's beam. As discussed above, this is not considered satisfactory. With this method it is not clear how to circumvent this problem.

2. Signal quality

Another technical issue concerns the signal quality to be assumed, either signal-to-noise ratio or the probability of error. Work to date has used standard CCIR quality for telephony channels and it is useful to maintain such a standard. Systems of higher quality would get no credit, while those of lower quality might have a penalty associated with a particular method of measure.

3. Bandwidth utilization

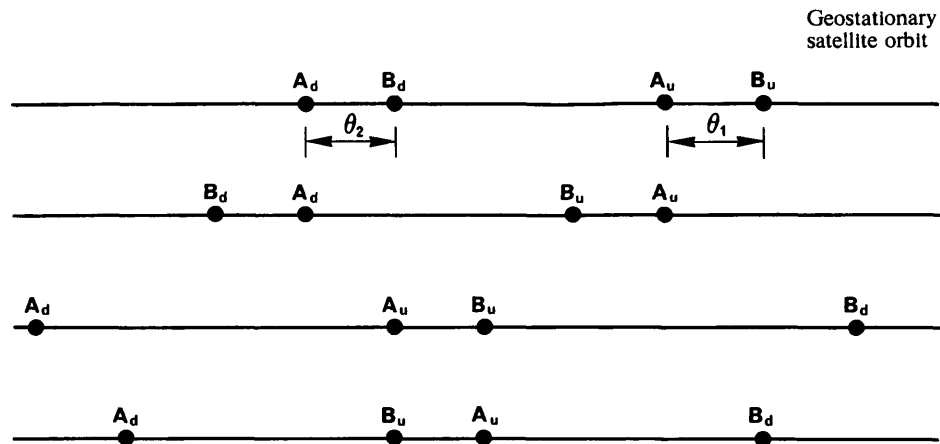
In the identical pair method, there is no difficulty in interpreting R , $\Delta\theta$, and W when computing a measure such as equation (4). $\Delta\theta$ is unambiguous and R can be taken as either the data rate per satellite or for both satellites, the difference being a factor of 2. Similarly W can be taken as the bandwidth jointly occupied by both satellites, or the sum of the individual bandwidths, again the difference being a factor of 2. As long as consistency is maintained there is no difficulty. If different parts of the bandwidth are used differently, the data rate per satellite is merely the sum of those in the different sub-bands.

With the reference network method there is a potential confusion in computing a measure such as (4). In general, the data rate of the reference and subject networks will not be the same, and the bandwidths of the two networks may also be different. Again, $\Delta\theta$ will be unambiguous. For R , it seems reasonable to use the sum of the data rates in all of the sub-bands in both networks. Similarly, for W , it seems reasonable to sum the bandwidths occupied by each network.

This latter approach also seems a reasonable one to use in a more general context. That is, it may be desirable to compute the measure associated with an actual set of networks whose satellites occupy a given arc of the orbit $\Delta\theta$. Here, the various networks may utilize the band in any way that is consistent with the Radio Regulations. Some satellites may use more than one pair (up-path and down-path) of frequency bands. In evaluating equation (4), for example, the value of $\Delta\theta$ used would be the total arc spanned by the satellites in question. The data rate would be the sum of the data rates achieved in each network, and the bandwidth would be the algebraic sum of the bandwidths occupied by each of the networks. This approach is unambiguous, the result can be interpreted as an average per network.

4. Inter-satellite links

Although inter-satellite links are not yet of great practical importance, an interesting issue is raised by them when attempting to apply the identical pair method. This method, as it has been discussed thus far, has been intended for application to networks. But where inter-satellite links are used, it is the system which has meaning as a communications entity. Thus, if for a part of that system an attempt to compute a measure of utilization is made, the question arises as to the meaning of that measure out of context of the whole system. The application of the identical pair method could be extended to an entire system. The definition of "identical", however, then runs into some difficulty. Consider a system that comprises two satellites A_u and A_d , the first receiving the up-path signal and transmitting it to the second, and the latter transmitting the down-path signal. Consider now another similar system with satellites B_u and B_d . Several possible configurations are possible, as sketched below.



All these placements satisfy a certain sense of symmetry, but which case is to be called "identical", and what arcs of the orbit are to be considered as occupied? Thus when inter-satellite links are considered and more generally arbitrary systems defining a single connectivity mode, more study is required to meaningfully evaluate a measure of orbit-spectrum utilization.

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**SECTION 4G: FREQUENCY SHARING BETWEEN NETWORKS
OF THE FIXED SATELLITE SERVICE
AND THOSE OF OTHER SPACE RADIOCOMMUNICATION SYSTEMS**

Reports

REPORT 560-1

**SHARING CRITERIA FOR THE PROTECTION OF SPACE STATIONS
IN THE FIXED SATELLITE SERVICE RECEIVING IN THE BAND 14.0 TO 14.4 GHz**

(Study Programme 2M/4)

(1974 - 1978)

1. Introduction

Study Programme 2M/4 requires the study of the criteria for frequency sharing between the Fixed Satellite Service (Earth-to-space) and the Radionavigation and Radionavigation Satellite Services at frequencies of the order of 14 GHz. This Report deals with those aspects concerning interference to geostationary space stations of the Fixed Satellite Service and derives provisional values for the limits to provide sufficient protection.

2. Protection of space station receivers in the Fixed Satellite Service against interference from radionavigation transmitters in the band 14 to 14.3 GHz

Since pulse-code modulation transmissions are likely to predominate in satellite systems working in the region of 14 GHz it would be appropriate to relate interference power to a bandwidth of 1 MHz. In accordance with previous studies of similar sharing problems, an interference power level not greater than 1/10 of the thermal noise at the satellite receiver input, is taken to be the objective.

A wide range of satellite antenna beamwidths, corresponding to various coverage requirements, is likely to be used in satellite systems in these bands. However, if the average geographical density of distribution of the interfering terrestrial stations, is the same for different coverage areas, it can be shown that the aggregate interference power at the satellite receiver input, is independent of the beamwidth of the satellite receiving antenna. The number of in-beam interfering transmitters will, in practice, vary with the size and location of the coverage area, and it is necessary to assume a typical beamwidth for the satellite antenna and make a suitable allowance for multiple interference entries.

In the following calculation a beamwidth of 1° has been assumed for the satellite antenna as a typical example.

TABLE 1 — *Calculation of permissible power flux-density of interference at the satellite*

Satellite receiver noise temperature	1500 K
Noise power in any 1 MHz band at receiver input	- 137 dBW
Permissible interference power at receiver input in any 1 MHz band	- 147 dBW
Satellite receiver antenna average gain relative to isotropic, for 1° beamwidth	43 dB
Effective aperture (S) of the antenna relative to 1 m^2	0.5
$10 \log S$	- 3
Permissible power flux-density of total interference at the satellite in any 1 MHz band	- 144 dB(W/m ²)
Allowance for multiple entries in any 1 MHz bandwidth	- 6 dB
Permissible power flux-density at the satellite from any single interfering transmitter in any 1 MHz bandwidth	- 150 dB(W/m ²)

In estimating the allowance to be made for multiple in-beam entries it is necessary to assume a model representing the future use of the band 14 to 14.3 GHz by the Radionavigation Service. Different types of radar transmitters are expected to use the band, including low-power FM or CW radars for distance and speed measurements. For these applications solid-state devices would be used with small antennae randomly oriented and having a beamwidth of a few degrees, and their use could become extensive. For other applications AM pulse radars with rotating beams might be used. As a guide in assessing the overall number of simultaneous in-beam interference entries into a geostationary satellite, a simple model has been assumed, in which the average density

of low-power FM radar transmitters is taken as one per 100 km², and the beamwidths as 6° randomly oriented in the horizontal plane. With these assumptions it is shown in Annex I that, in a 1 MHz bandwidth, a single satellite would, on average, be within the antenna beam of four such transmitters. This model is of course, highly simplified but is thought to justify provisionally an overall allowance of 6 dB, for multiple in-beam entries, bearing in mind that there will also be a large number of off-beam interference entries at lower level.

It is thus concluded that, to provide adequate protection to the Fixed Satellite Service, when the number of simultaneous interference entries is small, the peak value of power flux-density set up at any point on the geostationary-satellite orbit by any radionavigation transmitter in the band 14 to 14.3 GHz should not exceed –150 dB(W/m²) in any 1 MHz band.

3. Expression of power flux-density as a function of transmitter density

Although the limit derived in § 2 assumes only 4 simultaneous in-beam entries per MHz, it allows a reasonably high geographical density of simultaneously active transmitters when account is taken of the random distribution of their frequencies and antenna directions. However for some radionavigation applications it is possible that low-power devices may be used with much greater densities and in such cases the limiting power flux-density per transmitter would need to be reduced accordingly.

Assuming as before, that the radionavigation antennae are randomly oriented in the horizontal plane, the number of simultaneous in-beam interference entries in a 1 MHz band, received by a satellite antenna which is illuminating the earth at a low angle of elevation is given by:

$$n = DA \frac{\theta}{360}$$

where D is the average density per km² of the radionavigation transmitters simultaneously active within the 1 MHz band, A is the area of the Earth's surface covered by the satellite receiving antenna (in km²) and θ is a representative average value for the beamwidth in degrees of the radionavigation transmitting antennae.

Assuming as in § 2 and in Annex I, that the average value for θ is taken as 6°, and the coverage area A is 1.2×10^6 km²,

then,

$$n = D \times 2 \times 10^4$$

Thus, when n is greater than 4, the maximum value of peak power flux-density which any transmitter may produce at the geostationary-satellite orbit would be given by:

$$\begin{aligned} -150 - 10 \log n/4 & \quad \text{dB(W/m}^2\text{) in any 1 MHz band} \\ -187 - 10 \log D & \quad \text{dB(W/m}^2\text{) in any 1 MHz band.} \end{aligned}$$

Annex II gives an example calculation for a particular type of radar using this frequency band.

4. Protection of space station receivers of the Fixed Satellite Service against interference from satellites in the Radionavigation Satellite Service in the band 14.3 to 14.4 GHz

It is assumed that satellites in the Radionavigation Satellite Service employed in this band will be geostationary satellites providing the radio sextant type of system (see Recommendation 361-2). The permissible interference power at the fixed satellite receiver input will remain at –147 dBW in any 1 MHz band as shown in Table I, and to allow for four multiple entries a factor of 6 dB is appropriate. However, a different approach is required in applying this to the Radionavigation Satellite Service, since it is necessary to envisage co-ordination between these space services rather than a power flux-density limit. The criterion to be used in this procedure should therefore be that the interference power produced at the fixed satellite receiver input by any radionavigation satellite should not exceed –153 dBW in any 1 MHz band.

ANNEX I

ESTIMATE OF NUMBER OF SIMULTANEOUS INTERFERENCE ENTRIES FROM RADIONAVIGATION TRANSMITTERS

As a guide to estimating the allowance to be made for simultaneous interference entries from radionavigation transmitters, a simple model is assumed in which low-power FM radar transmitters operating on the same nominal frequency channel, are assumed to be distributed throughout the coverage area of the satellite antenna

beam. The radar antennae are randomly oriented in the horizontal plane. A derivation of the average number of simultaneous in-beam entries is as follows:

Radar antenna beamwidth	6°
Transmitter bandwidth	50 MHz
Average geographical density of transmitters within satellite coverage area	1 per 100 km ²
Approximate area covered by satellite antenna having 1° beamwidth	1.2×10^6 km ²
Number of transmitters within the coverage area	12×10^3
Number of radar antennae directed within $\pm 3^\circ$ of a geostationary satellite	$12 \times 10^3 \times 6/360 = 200$
Average number of radars within a 1 MHz band simultaneously pointing at a satellite	$200 \times 1/50 = 4$

ANNEX II

ESTIMATE OF THE POWER FLUX-DENSITY SET UP BY EQUIPMENT KNOWN AS "WHISTLER RADARS"

The Whistler radar is a portable device with a range of up to 3.7 km. Its main characteristics are the following:

Operating frequency band	14.0 to 14.03 GHz
Maximum antenna gain	25 dB
Beamwidths – Elevation	10°
Azimuth	3°
Power at antenna input	– 13 dBW
Modulating waveform	10 Hz triangular
FM deviation	± 7.5 MHz
Minimum detectable signal	– 150 dBW in a bandwidth of 150 Hz.

It is readily seen that the maximum e.i.r.p. of the device is 12 dBW and the resulting power flux-density at the geostationary orbit thus about -151 dB(W/m²) in 15 MHz, or about 10 dB less than stipulated in § 2 for the single entry; assuming main beam-to-main beam transmission (low elevation angle of the interfered-with space station).

REPORT 561-1 *

PROVISION OF EARTH-TO-SPACE CONNECTIONS TO SPACE STATIONS IN THE BROADCASTING-SATELLITE SERVICE

(Study Programme 2K-2/4)

(1974 – 1978)

1. Introduction

Frequency bands allocated to the Broadcasting-Satellite Service are, by definition, in the space-to-Earth direction. Connections to broadcasting satellites, operating in any frequency band (for example, in the bands 620 to 790 MHz, 2.5 to 2.69 GHz and 11.7 to 12.2 GHz (12.5 GHz in Region 1)), must, under the current provisions of the Radio Regulations, use the Earth-to-space allocations of the Fixed Satellite Service. For the purpose of this Report, the term "Fixed Satellite Service" is as defined in the Radio Regulations, but excludes up-links in the Broadcasting-Satellite Service.

If the up-link requirements of these services were small compared with those of the Fixed Satellite Service, they could be accommodated without causing problems or conflicts. However, requirements for broadcasting satellites are beginning to grow and have become especially large for systems which will utilize the 12 GHz band. The channel requirements set forth by Administrations prior to, and during, the 1977 Broadcasting-Satellite Conference, and the incorporation of those requirements in the Plan developed by the Conference, indicate that

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

the up-link requirements of broadcasting satellites will be significant compared with those of the Fixed Satellite Service, and large compared with any one of the up-link allocations of that service which are of main interest at this time.

This is illustrated by the situation in Region 1 where a total of 800 MHz has been allocated to the Broadcasting-Satellite Service and is not matched in bandwidth by any one Fixed Satellite Service Earth-to-space allocation.

Simultaneous use of the 14 GHz band for up-links for broadcasting-satellite networks operating in the 12 GHz band and fixed satellite networks operating in the 10.95 to 11.2 GHz and 11.45 to 11.7 GHz bands (space-to-Earth) will also be a problem in congested segments of the orbit arc.

In Region 2, the 11.7 to 12.2 GHz band is allocated to both the Fixed Satellite (space-to-Earth) and Broadcasting-Satellite Services; and under the current provisions, both services may wish to utilize the 14.0 to 14.5 GHz fixed satellite allocation for the up-links. In addition to individual and community type broadcasting-satellite services in the 12 GHz band, it is envisioned that interactive services (voice, data, and video) may be provided through the use of earth stations with small aperture antennae. This may place additional requirements and constraints on both services.

This Report evaluates the impact of sharing, associated with using fixed satellite allocations for up-link connection to broadcasting-satellites and examines alternative techniques and approaches to simultaneously providing the necessary up-links to the Broadcasting-Satellite Service and flexibility to the Fixed Satellite Service.

2. Technical and operational characteristics required for the up-link connections to broadcasting-satellites

2.1 General

This section presents some of the preferred characteristics of up-links in the Fixed Satellite Service from the point of view of broadcasting satellites.

The requirements placed on these up-links will vary from band to band. There are, however, certain requirements in satellite design which tend to limit the proximity of the up-link and the down-link frequencies. A balance must be chosen between the two frequencies so that they are neither too close nor too far apart; too small a frequency separation makes good filtering difficult to achieve, while too large a separation causes design problems.

Generally it is thought that the up-link contribution to the overall performance degradation of the link should be minimal. The apportionment of the total noise budget between the up-link and down-link will generally be different for each band pair.

Flexibility in locating the up-link earth station anywhere within the down-link service area will generally be desirable. In some cases, there may also be a requirement to provide up-links from outside the service area, especially in the case of large countries with several service areas from the same orbital location or regional broadcasting satellite services.

Such flexibility has an impact on the re-use of the up-link frequencies, and there are several approaches which could be used to reduce the amount of spectrum required.

If the up-link power flux-densities at the geostationary orbit were of a uniform level, the sharing situation would be eased. Such uniform up-link power flux-densities would result from the use of a standardized maximum gain satellite receiving antenna.

If the satellite receiving antenna could be of the highest directivity technically feasible, the possibility of re-using the up-link frequency channels would be increased, and the bandwidth requirements minimized. To take advantage of this possibility, the up-link transmitting earth station would have to be located near the boresight of the broadcasting satellite down-link service area, if the same satellite antenna were to be used for both transmitting and receiving.

If the up-link earth station location cannot be located near the boresight then special antenna techniques, or indeed separate antennae, might be required on the satellite. Either steerable receiving spot-beams or lower gain (wider beamwidth) antennae would be required in the case of a need to access the satellite from different locations in a time sequential order. If simultaneous up-links to the satellite were required, the use of narrow-beam, high-gain antennae might not be practicable.

2.2 Broadcasting-satellite systems operating in the 12 GHz band

The 1977 WARC-BS established certain technical standards which affect the up-link feeds. One important requirement is that the reduction in the quality in the down-link due to thermal noise in the up-link is taken to be equivalent to a degradation in the down-link C/N not exceeding 0.5 dB for 99% of the worst month. To limit the impairment to this value, the C/N on the up-link must be about 10 dB higher than that required for the down-link C/N , which in this case would mean a (C/N) of up to 24 dB, if the modulation indices were the same.

The Conference also established a value of 30 dB as the total protection ratio to which each broadcasting satellite transmission must be protected. Similarly, with the division of overall performance requirements, the total protection ratio of the up-path serving a broadcasting satellite may have to be of the order of 40 dB, with a single-entry protection ratio which may be as high as 45 dB. Standards for either of these two latter values have not yet been established.

Additionally the Conference decided that the Broadcasting-Satellite Service would use circular polarization and if the same antenna is used on the spacecraft for transmit and receive, then this may predetermine the type of up-link polarization.

Within the detailed orbit and frequency plan for Regions 1 and 3, the satellite orbital locations (nominal 6° spacing), and transmit beam characteristics, including polarization, were determined and set by agreement. The bandwidth from any orbital location can be greater than 800 MHz since both polarizations may be used from a given orbit position. The e.i.r.p.s of each beam were determined, which, in combination with other parameters and the maximum realizable transponder transfer gain, place further restrictions on the up-links.

While the Conference did not establish a detailed plan for Region 2, it did set aside orbital arcs specifically for the Broadcasting-Satellite Service. The Regional Conference of 1982 will determine a detailed plan and the problems will generally be similar, except for total bandwidth allocated and the individual channel bandwidth.

3. Up-link bandwidth requirements

3.1 Down-link allocations

The up-link bandwidth requirement has to be viewed in the context of the overall bandwidth allocated to the Broadcasting-Satellite Service. These are summarized in Table I.

TABLE I — *Bandwidth allocated to the broadcasting-satellite service*

Part of the spectrum	Amount of bandwidth (MHz)
700 MHz	170
2.5 GHz	190
12 GHz	500 (Regions 2 & 3)
	800 (Region 1)
22 GHz	500 (Region 3 only)
40 GHz	2000
85 GHz	2000

3.2 Reduction of bandwidth required for up-links to 12 GHz broadcasting satellites

Substantial bandwidth has been allocated to the Broadcasting-Satellite Service for its space-to-Earth links, and it is foreseen that these bands will ultimately be used extensively for television with frequency re-use obtained by means of high-gain satellite transmitting antennae and the use of cross-polarization techniques. A similar measure of frequency re-use will, no doubt, be obtained in the up-path direction by means of high-gain satellite receiving antennae, but it is doubtful whether this technique can provide a significantly greater degree of frequency re-use in the up-path than in the down-path, in parts of the world where broadcasting coverage areas are relatively small. The usage of the fixed satellite Earth-to-space bands for broadcasting-satellite up-paths, could be reduced if means could be found for a further measure of frequency re-use in the up-path. Four possible ways of achieving this have been identified:

3.2.1 Up-path frequency re-use using the higher directivity of the transmitting earth-station antenna, relative to broadcast receiving antennae

If the space segment of satellite-broadcasting systems serving a multi-national area of continental extent consisted of many satellites spaced at intervals of a few degrees over the geostationary satellite orbit, then the extent to which frequencies may be re-used at different positions in the orbit depends, in the case of Earth-to-space transmissions, on the off-beam discrimination of earth-station transmitting antennae and satellite receiving antennae. In the case of space-to-Earth transmissions, it depends on the off-beam discrimination of satellite transmitting antennae together with that of earth-station receiving antennae at the broadcasting receiving terminals. Since the off-beam discrimination of earth-station transmitting antennae will be considerably greater than that of the (necessarily) small broadcast receiving antennae, greater frequency re-use may be achievable on Earth-to-space transmissions. Consequently, the total bandwidth required on the up-path for broadcasting-satellite services can be less than on the down-path. One study of a satellite broadcasting scheme for 56 countries in a continental area [CCIR, 1970-74a] indicates that the up-path bandwidth required for a system providing four broadcast television channels for individual reception for each country, could be reduced from 720 MHz to 240 MHz in this way.

The plan adopted by the 1977 WARC-BS, as mentioned in § 2, would not enable the order of magnitude of bandwidth reduction for the up-path mentioned above. This is illustrated in another study of the efficient use of frequencies for the up-path in the 14 GHz band, which is to connect to broadcasting-satellites in the Western Pacific and Asian area, as established by the World Administrative Radio Conference on the Broadcasting-Satellite Service in the 12 GHz band [CCIR, 1974-78]. The results of this study are shown in Fig. 1. In this Figure inter-satellite spacing (ϕ) is taken as a parameter in calculating the carrier-to-interference ratio (C/I) in the up-paths between two satellite systems. In the case of $\phi = 0^\circ$, the value of C/I results in -3 dB for the worst and 49 dB for the best, in the orbital range 34° E to 158° E; but in most cases the value of C/I becomes less than 40 dB, which may be regarded as the required protection ratio for the up-path, so that use of different up-path frequencies is mostly needed for the satellites sharing the same orbital positions. In the case of $\phi = 6^\circ$, the value of C/I becomes greater than 40 dB even at the most interfered-with orbital positions around 74° E, when earth-station antennae greater than 4.5 m diameter are used. In the case of $\phi = 12^\circ$, the C/I becomes greater than 40 dB for the antennae having a diameter greater than 2.5 m ($D/\lambda > 117$ at 14 GHz) even at the most interfered-with orbital positions.

The C/I value of 40 dB in the study was assumed as the single entry value. However, as discussed in § 2.2, the value of 40 dB may perhaps be that corresponding to all entries of interference. Thus the desired single entry value of C/I might be as high as 45 dB.

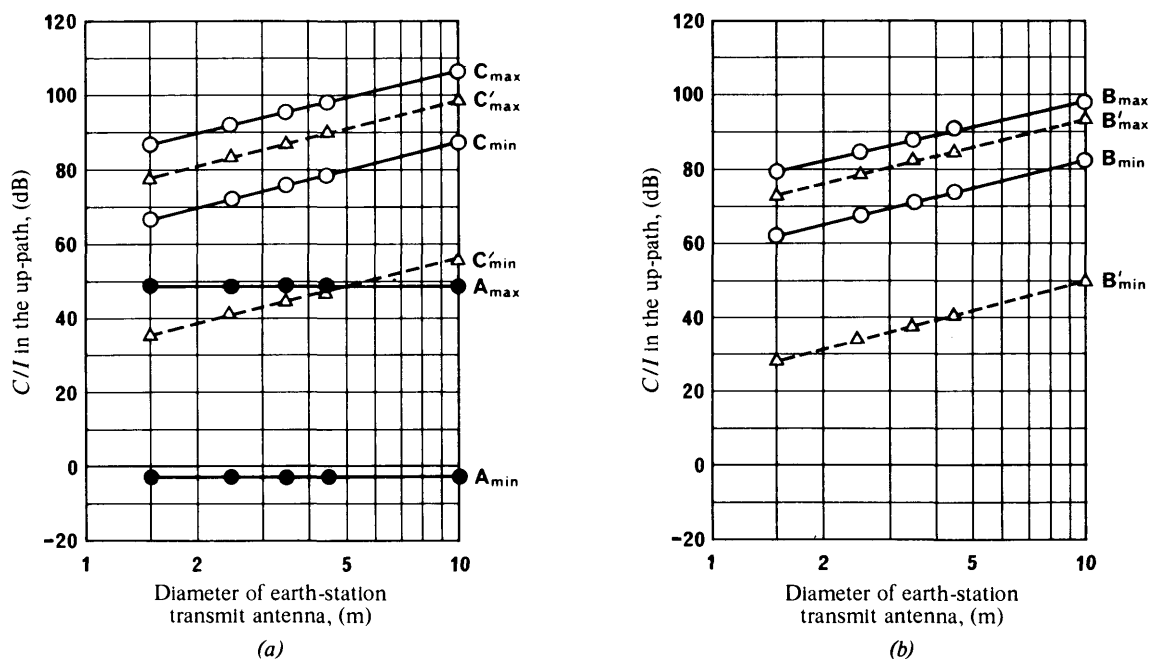


FIGURE 1 — Carrier-to-interference ratio in the connecting up-path for the broadcasting-satellite service in the 12 GHz band in the Western Pacific and Asian area, as established by the WARC (BS)

A_{max} : max. C/I for $\phi = 0^\circ$, at 140° E

A_{min} : min. C/I for $\phi = 0^\circ$, at 44° E

B_{max}, B_{min} : max. and min. C/I_s for $\phi = 6^\circ$, at 128° E

B'_{max}, B'_{min} : max. and min. C/I_s for $\phi = 6^\circ$, at 74° E

C_{max}, C_{min} : max. and min. C/I_s for $\phi = 12^\circ$, at 128° E

C'_{max}, C'_{min} : max. and min. C/I_s for $\phi = 12^\circ$, at 74° E

ϕ : inter-satellite spacing, C/I : for single interference entry

Note. — Orbital position, polarization, and satellite beam dimension are assumed to be the same as in the down-path, but station-keeping and antenna pointing errors are not taken into account in this calculation.

3.2.2 Polarization discrimination

In certain cases it is possible that the use of polarization discrimination would allow the frequency re-use in the up-link to be increased. The aspects which should be taken into account are described in Report 555-1. Further study is required to determine the overall up-link bandwidth required to provide connections to broadcasting satellites, in the Regions 1 and 3 Plan, taking into account the advantage to be gained from frequency re-use by means of polarization discrimination.

3.2.3 Alternative modulation methods for the up-path

An initial study has been made of the technique of reducing up-path bandwidth requirements by the use of narrow-band up-path modulation with modulation conversion in the satellite [Baker and Bolingbroke, 1975]. Substantial reductions in up-path bandwidth can be obtained, for example, by the use of low deviation frequency modulation, or multi-level PSK in conjunction with digital encoding and processing of the video signal. The use of low deviation frequency modulation would, however, involve signal processing at the satellite, and the use of digital encoding would involve demodulation, decoding and remodulation at the satellite.

The use of higher efficiency modulation in the up-path may require very high up-path protection ratios which are difficult to adhere to in practice. On the other hand, video signals contain a large amount of redundant elements, and techniques have been developed which would remove some of this redundancy at no loss in transmission quality. These techniques are known as "source coding". If source coding were applied to up-paths feeding broadcasting-satellites, substantial bandwidth savings would be possible with conventional modulation, and the up-path protection ratio would not have to be increased. The use of source coding, as that of higher-density modulation methods, would require processing in the satellite.

In general the disadvantage of alternative modulation methods for the up-path, is the consequent increase in satellite complexity, mass and cost, and some reduction in satellite reliability. The need to use such techniques may also delay the implementation of satellite broadcasting systems in some cases.

3.2.4 Integrated sound-vision systems

If the sound channel is time multiplexed within the video-signal (e.g. the sync. pulse interval), then a saving in the overall RF bandwidth of the modulated carrier can be achieved. The extent of the bandwidth saved and the extent of additional cost and complexity of the broadcast receivers needs further study.

4. Use of allocations to the Fixed Satellite Service (Earth-to-space) for up-links serving the Broadcasting-Satellite Service

4.1 Use of the 14 GHz band

An example is used to demonstrate interference by a Broadcasting-Satellite Service up-path transmission to a satellite with INTELSAT-V characteristics, and the reverse situation of interference by a Fixed-Satellite Service up-path transmission to a broadcasting satellite. The interfering signals are assumed to be co-frequency and co-polarized.

The following are the system assumptions made in the example for the two interfering signals:

Regarding the broadcasting-satellite up-path transmissions:

Satellite receive antennae beamwidths:	1°, 2°, 4°
Satellite receiving system noise temperature:	3000 K
Transmit earth station diameter:	2, 4, 8 metres
Up-path carrier/noise ratio:	25 dB
RF bandwidth:	27 MHz

These assumptions result in the following consequential system parameters (at 14 GHz):

Satellite receiving system		Transmit earth station			
Antenna beamwidth	Beam edge G/T (T expressed in K)	e.i.r.p.	Power into antenna		
			2 m	4 m	8 m
1°	6 dB	72.7 dBW	380 W	97 W	24 W
2°	0 dB	78.7 dBW	1500 W	380 W	97 W
4°	-6 dB	84.7 dBW	6000 W	1500 W	380 W

Regarding the INTELSAT system, three representative transmission types will be assumed, with the following characteristics:

Type	Modulation	Capacity	e.i.r.p.	Protection ratio
A	FDM/FM	24 ch.	69 dBW	31 dB ⁽¹⁾
B	FDM/FM	972 ch.	81 dBW	35 dB ⁽¹⁾
C	Q-CPSK TDMA	120 Mbit/s	82 dBW	32 dB ⁽²⁾

(¹) To produce 400 pW0p of noise power in the worst channel due to interference from an analogue FM TV transmission.

(²) Minimum permissible for a single entry from any high power transmission contained within the occupied band of 72 MHz.

Assuming coincident or overlapping, 14 GHz space station receive antenna coverages of both a broadcasting-satellite and an INTELSAT-V, and assuming further that the earth stations transmitting to the broadcasting-satellite meet the CCIR reference earth station antenna pattern; compliance with the required protection ratios given above would necessitate the following geocentric angular separations between the broadcasting-satellite and an INTELSAT-V:

Characteristics of the broadcasting-satellite system		Spacings for interfered-with satellites INTELSAT carrier types		
		A	B	C
Satellite antenna receive beamwidth	Transmitting earth station antenna diameter	24 ch. FDM/FM	972 ch. FDM/FM	Q-CPSK 120 Mbit/s
1°	2 m	6.0°	2.9°	2.0°
	4 m	3.5°	1.7°	1.1°
	8 m	2.0°	1.0°	< 1.0°
2°	2 m	10.4°	5.0°	3.5°
	4 m	6.0°	2.9°	2.0°
	8 m	3.4°	1.7°	1.1°
4°	2 m	18.2°	8.7°	6.0°
	4 m	10.5°	5.0°	3.5°
	8 m	6.0°	2.9°	2.0°

The advantages of decreased broadcasting-satellite receiving antenna beamwidth in reducing interference conditions are clearly shown; however, the reduced coverage could prevent transmission to the broadcasting satellite from anywhere within the boundaries of the service area, or from outside the service area.

Present INTELSAT planning provides for an appreciable number of FDM/FM carriers of only 24 channels capacity with numerous FDM/FM carriers having capacities anywhere between 24 and 972 channels. The geocentric angular separations required between a broadcasting satellite and an INTELSAT-V are, for such carriers, appreciable. They might be achievable if broadcasting-satellites were spaced from each other by twice the above angles, but that would result in only just one fixed service satellite location alternating with one broadcasting-satellite location. Where a ratio of n fixed service satellites to one broadcasting satellite would be desirable, the broadcasting-satellite spacing would have to be further increased by $n - 1$ times the spacing required between the fixed service satellites.

One could, with the INTELSAT system, take advantage of the fact that it provides only limited up-path (14 GHz) coverage and use for broadcasting-satellite up-paths, satellite receive beams of less than 1° beamwidth, and transmit earth stations of greater than 8 metre antenna diameter to alleviate the problem; but this could be a severe constraint on the broadcasting-satellite service and may not be acceptable. Alternatively, one might align carrier frequency plans between broadcasting up-path assignments and INTELSAT-V carriers; or attempt to realize some up-path polarization discrimination.

However, no matter which solution is pursued, the fact remains that systems in the Fixed-Satellite Service would somehow have to subject their planning to that adopted for broadcasting-satellites by the 1977 Conference, since the co-ordination procedure of Report 454-2 would not be relevant to this situation. This would impose severe constraints on both services operating in the same frequency bands.

In the other direction, interference from Fixed Satellite Service earth stations into broadcasting satellites is far from negligible. With the parameters for the INTELSAT 972-channel carrier and an assumed required single entry protection ratio of 45 dB in the Broadcasting-Satellite Service up-path, the following geocentric satellite separations would be required at 14 GHz:

Broadcasting-satellite received beamwidth	Satellite spacings for different INTELSAT transmit earth station diameters		
	8 metres	12 metres	16 metres
1°	11.6°	8.8°	6.8°
2°	6.7°	5.0°	4.0°
4°	3.8°	3.0°	2.3°

The system parameters given in this Section for the Fixed Satellite Service are those of INTELSAT-V. Other systems in the Fixed-Satellite Service, particularly those intended for domestic and regional service, may require greater spacings than those indicated in the Tables.

In this case, increase in sensitivity of the broadcasting-satellite receiver correspondingly increases its sensitivity to interference from transmissions of earth stations in the Fixed Satellite Service, and may result in increased satellite spacing requirements.

It may be concluded that co-direction up-path use by the Fixed Satellite Service and the Broadcasting-Satellite Service would impose severe constraints upon both services operating in the same frequency band.

4.2 Use of higher frequency bands

It would ease the impact on the Fixed Satellite Service to provide broadcasting-satellite up-link connections in a higher frequency band such as 30 GHz, allocated, but not actually in use for the Fixed-Satellite Service.

There are substantial technical difficulties associated with the use of such bands, for example:

At 30 GHz it would probably be necessary to take special steps, such as the use of site diversity, at many earth station locations, to overcome the effects of precipitation attenuation, since a 30 GHz up-path might otherwise be interrupted for a significantly greater percentage of the time than the 12 GHz down-path, and reasonable overall link reliability would be difficult to achieve [CCIR, 1970-74b]. Preliminary studies show that significant diversity advantage could be achieved by using two up-path transmitters separated by about 15 km (Report 564-1).

5. Use of allocations to the Fixed Satellite Service (space-to-Earth) for up-links serving the Broadcasting-Satellite Service

If it were decided to use the reverse-direction approach, i.e., broadcasting up-path assignments to be made in a space-to-Earth band allocated to the Fixed Satellite Service, the following interference modes would ensue:

- (a) interference from Fixed Satellite Service space stations into space stations of the Broadcasting-Satellite Service, and
- (b) interference from earth stations transmitting to broadcasting-satellites into earth stations receiving from fixed service satellites.

For interference condition (a) above, one may assume the previously introduced parameters for a broadcasting-satellite up-path which led to a wanted carrier power at the broadcasting-satellite receiver of about -95 dBW. Assuming that a single-entry up-path protection ratio of 45 dB would be required, the interference power at the broadcasting-satellite receiver input must not exceed a level of -140 dBW. The net attenuation between the output of an interfering fixed-satellite space station transmitter and the broadcasting-satellite receiver, is the free space loss A between the two space stations, less the sum of the antenna gains ΣG (transmit antenna

gain of the fixed satellite; receive antenna gain of the broadcasting-satellite) of the two kinds of space stations in the direction of each other, i.e., their respective antenna gains at an angle of no less than about 70° off their respective main beam directions. The following inequality applied:

$$P_{FS} + \Sigma G(70^\circ) - A(\varphi) \leq -140 \text{ dBW} \quad (1)$$

which, with

$$A = 90 + 20 \log f_{\text{MHz}} + 20 \log \varphi^\circ \quad \text{dB} \quad (2)$$

and the assumption of $f = 11\,000$ MHz yields an equation for the minimum value of the satellite separation angle φ with the two variables P_{FS} (available carrier power at the transmit antenna terminal of the fixed satellite) and ΣG ; as follows:

$$\log \varphi = \frac{P_{FS} + \Sigma G - 31}{20} \quad (3)$$

The Table below shows the relationship between φ (in degrees), P_{FS} (in dBW) and ΣG (in dB).

$P_{FS}(\text{dBW})$	$\Sigma G(\text{dB})$		
	0	10	20
0	0.03°	0.09°	0.3°
5	0.05°	0.16°	0.5°
10	0.09°	0.3°	0.9°
15	0.16°	0.5°	1.6°
20	0.3°	0.9°	2.8°

It can be seen that even with 100 watts (20 dBW) of available fixed satellite carrier power and 20 dB of total joint antenna gain an inter-satellite spacing of less than 3° would be required.

As an example, INTELSAT-V has an available carrier power of 10 watts (10 dBW), and it should readily be possible to maintain the joint antenna gain between two space stations to less than about 10 dB, so that inter-satellite spacings of about 3/10 of a degree would be feasible. This corresponds to a linear distance of about 230 kilometres. Since differences in orbit altitude between two space stations may from time to time be appreciable (perhaps up to 75 kilometres), one would in practice have to maintain a sufficiently large spacing so as not to produce unfavourable relative geometries between the spacecraft, which, for certain periods of time, might place one of the space stations into a somewhat higher gain location on the other's antenna pattern; however, a minimum spacing of about 0.3° appears to be safe.

As regards potential interference from earth stations transmitting to broadcasting satellites into Fixed Satellite Service receiving earth stations, it is obvious that the two types of earth stations could not be co-located. One would also, in general, choose their relative locations in such a way that they would not be situated on each other's main beam azimuths; this would be easy in countries at low latitudes and only very moderately restrictive in high-latitude countries. It should, in all cases, be possible to hold each station's horizon antenna gain in the direction of the other station at levels 10 dB below isotropic and so avoid main beam intersections in the troposphere.

Considering again the three carrier types used previously for the INTELSAT-V system and stipulating that, for 0.01% of the time the applicable protection ratios could be reduced by 10 dB, one obtains, with the further assumptions of a 150 K INTELSAT earth station receiving system noise temperature and a nominal required down-path carrier/thermal noise ratio of 19 dB for FDM/FM carriers, and of 25 dB for TDMA, the following values for required basic transmission loss (in dB) between the two sites, exceeded for all but 0.01% of the time, for various broadcasting-satellite up-path earth station transmitter powers:

INTELSAT carrier type	Broadcasting-satellite earth station transmitter power				
	22 W	90 W	350 W	1400 W	5600 W
24 ch. FDM/FM	140 dB	146 dB	152 dB	158 dB	164 dB
972 ch. FDM/FM	131 dB	137 dB	143 dB	149 dB	155 dB
120 Mbit/s Q-CPSK	119 dB	125 dB	131 dB	137 dB	143 dB

From Fig. 2 of CCIR Report 382-3 it can be seen that nearly all these values for the required attenuation (0.01% of the time) would result in site separation distances of less than 100 km, in some cases much less. If, in addition, site shielding were available to provide additional isolation between the sites, even shorter separation distances would be necessary.

Further study is required on the potential effects on radio-relay systems of proposals for both up-links and down-links of space systems operating in bands shared with terrestrial services. In addition, it must be studied as to whether this mode of utilization produces operational constraints on up-links to broadcasting-satellites.

6. Up-links in bands not now allocated to the Fixed Satellite Service

A future possibility is the use of up-links in bands not shared with the Fixed Satellite Service. This could be through the exclusive use of bands by broadcasting satellite up-links or by the shared use of bands with other Radiocommunication Services. Further study is required in respect of the latter possibility to evaluate the feasibility and necessary constraints.

7. Conclusions

This Report has shown that the accommodation of all or a substantial part of the up-path requirements of the Broadcasting-Satellite Service, and the Broadcasting-Satellite Plan in particular, in one of the existing Earth-to-space allocations to the Fixed Satellite Service may result in severe mutual constraints of the two services upon each other since:

- the up-path requirements for the Plan have to match those of the down-path, the number of required up-path channels is of the same order of magnitude as that for down-paths, but may be greater, and orbital positions are not subject to choice;
- protection ratio requirements in up-paths to broadcasting-satellites may be high, and inter-satellite spacing may have to be appreciable;
- certain orbit locations and/or certain radio-frequency channels may be unavailable to either of these two services;
- inter-network co-ordination procedures currently in force in the Fixed Satellite Service may not be fully applied to the up-links of broadcasting-satellites in the Plan.

As a consequence it appears necessary to give consideration to technical solutions which would alleviate or avoid the problems; with due regard to current or near future limitations upon implementing such solutions. Two major objectives have been identified as worth being pursued:

- consideration of techniques which would allow the total up-path bandwidth requirements to be minimized;
- consideration of strategies or techniques which would allow the up-path requirements of the Broadcasting-Satellite Service to be wholly or partly accommodated in usable frequency bands other than those allocated to the Fixed Satellite Service in the Earth-to-space direction.

Among the bandwidth minimization techniques, the following have been identified:

- spectrum compression through the use of high density transmission modes in the up-path (low-index modulation and/or source coding). These techniques require signal processing in the satellite and will have an impact on spacecraft complexity, and system reliability and cost.
- increased spectrum re-use through the careful use of improved isolation techniques, such as polarization isolation and/or earth and space station antenna gain and side-lobe control. The cost impact is believed to be moderate when only one or a very few antenna systems would be involved.

Among the strategies and techniques of reducing the impact on Earth-to-space allocations to the Fixed Satellite Service, the following are worthy of consideration:

- sharing with services other than the Fixed Satellite Service. The relatively simple frequency plan of the Broadcasting-Satellite Plan may allow favourable sharing conditions to be found in frequency bands allocated to a variety of services;
- sharing with the Fixed Satellite Service in frequency bands allocated to the latter in the space-to-Earth direction. However, where such bands are also allocated to terrestrial services, a relatively large number of interference interfaces would exist. Further study is required for the development of appropriate sharing criteria;

- consideration of the conditions under which sharing is effectively avoided; i.e., in an exclusive frequency band, or a band in which earth and terrestrial stations would, within a given service area, not operate on the same frequencies. For certain systems in the Broadcasting-Satellite Service there may be a need to access the space station in the Earth-to-space direction without the requirement of co-ordination of transmitting earth stations.

It may well be desirable that provisions for the concurrent use of several, or all, of the above techniques be made, to offer a choice to individual system operators and to minimize the impact on the Fixed Satellite Service in general within the constraints of the current use of the radio-frequency spectrum in the range of interest.

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REPORT 712

FACTORS CONCERNING THE PROTECTION OF FIXED SATELLITE EARTH STATIONS OPERATING IN ADJACENT FREQUENCY BAND ALLOCATIONS AGAINST SPURIOUS EMISSIONS FROM 12 GHz BROADCASTING SATELLITES

(1978)

1. General

The high space station e.i.r.p. required for individual reception in the broadcasting-satellite service may lead to substantial levels of spurious emissions at frequencies outside the channel occupied by the broadcasting-satellite emission. For the broadcasting-satellite channels closest to the edges of the 12 GHz band, i.e. 11.7 to 12.2 GHz (12.5 GHz in Region 1), these spurious emissions may set up power flux-densities in the direction of a fixed satellite earth station operating near the edges of the adjacent fixed satellite bands, which may greatly exceed the levels of interference acceptable to the earth station.

Whether or not such levels of spurious emissions cause unacceptable interference to fixed satellite earth stations depends on a number of factors including:

- the orbital spacing between the broadcasting-satellite and the fixed satellite and the corresponding fixed satellite earth station antenna discrimination that may be achieved,
- the level of filtering in the broadcasting-satellite transmitter and the earth station receiver that may be realized in practice,
- the frequency separation between channels on either side of and closest to the band edge,
- the interference criterion used in defining the permissible maximum spectral power flux-density, and
- additional factors providing isolation, such as satellite antenna discrimination.

2. Estimated levels of spurious emissions from 12 GHz broadcasting satellites

Report 807 discusses the various sources of spurious emissions from 12 GHz broadcasting satellites. Fig. 1 reproduces two curves from this Report which can be used to estimate the worst-case levels of spectral power flux-density produced by such emissions, as a function of the frequency difference from the centre of a

broadcasting-satellite channel. The levels of spectral power flux-density given in Fig. 1 correspond to a beam-centre e.i.r.p., from the broadcasting-satellite, of 69 dBW. The values of e.i.r.p. associated with approximately 90% of the frequency assignments made in the broadcasting-satellite plan for Regions 1 and 3, lie in the range of 64 ± 1.5 dBW. This fact should be kept in mind when interpreting the data presented in Figs. 4 to 7 and the examples of orbit spacing and frequency separation presented in § 5. More study is required to establish which curve between the two shown, may appropriately represent the operational conditions. The signal used in the calculation of curve A in Fig. 1 consisted of 100 per cent saturated colour bars. Such a signal is not used in normal broadcasting.

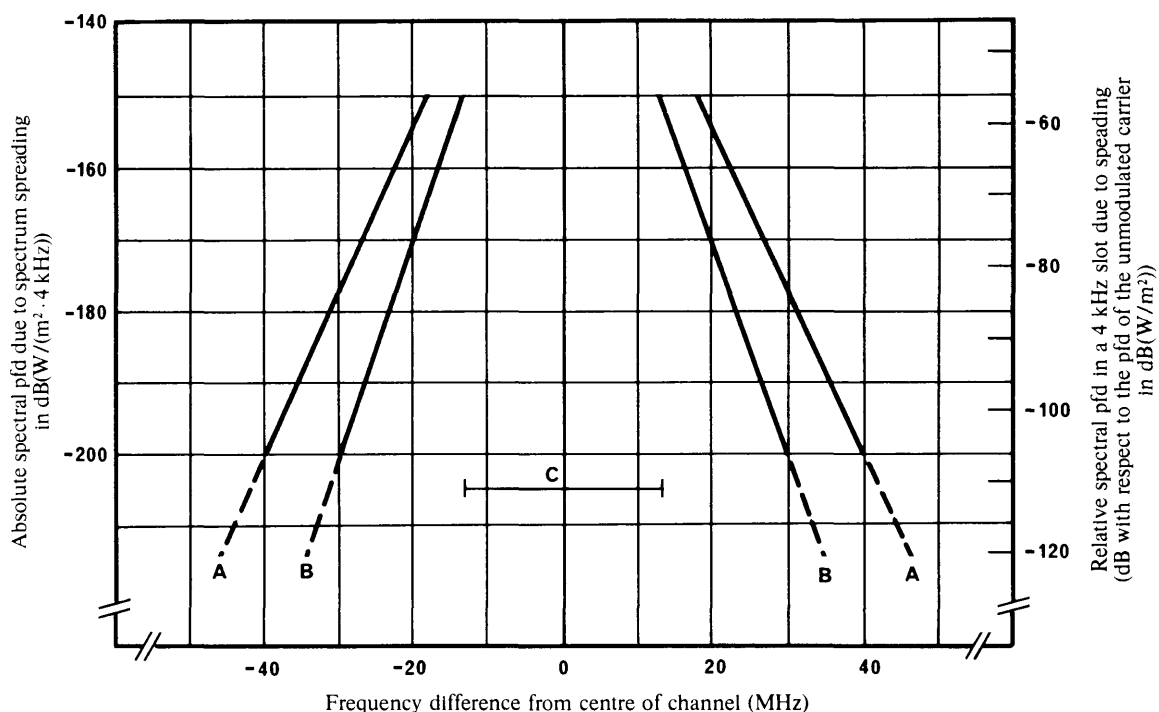


FIGURE 1 — Typical out-of-band envelopes of the radio-frequency spectrum radiated by a TV broadcasting-satellite

- A: Envelope for 100 per cent colour-bar baseband signal, modulator AC coupled
 B: Envelope for line 330 insertion test signal, modulator AC coupled
 C: Nominal channel bandwidth (27 MHz)

Note 1. — For the left-hand scale, it is assumed that the satellite e.i.r.p. corresponds to a pfd of -94 dB(W/m²) at the centre of the beam for an unmodulated carrier.

Note 2. — Minimum energy dispersal of ± 7.9 kHz is assumed.

Note 3. — Pre-emphasis according to CCIR Recommendation 405-1 is assumed.

3. Worst-case maximum permissible levels of spectral power flux-density at the interfered-with receivers

Examples of fixed satellite systems using the bands adjacent to the 11.7 to 12.5 GHz band are given in Table I, along with calculations of the worst-case maximum permissible pfd at the interfered-with receiver. The criterion used in these calculations was that the overall interference due to spurious emissions should be at a level 10 dB below the thermal noise level of the interfered-with system. The possible benefit of antenna directivity has not been included in the calculations. Moreover, no account was taken of the spectral shape of either the spurious emissions, nor of the interfered-with received signal. Under these conservative assumptions, the maximum permissible spectral power flux-density of spurious emissions in the band below 11.7 GHz is seen to be about -200 dB(W/(m² · 4 kHz)) for a narrow-band fixed satellite signal and -195 dB(W/(m² · 4 kHz)) for a maritime satellite. In the band above 12.5 GHz, the limit is -171 dB(W/(m² · 4 kHz)) for a narrow-band data link. The frequency at which the maximum power flux-density from the broadcasting satellite is specified will be called the "protected frequency". For narrow-band signals it will be the centre frequency of the narrow-band fixed satellite channel in question.

When considering the use of narrow-band signals in the upper part of the 11.45 to 11.7 GHz band, the foregoing maximum permissible spectral power flux-densities apply directly. However, when wide-band carriers are used in the upper part of the 11.45 to 11.7 GHz band, the relatively rapid roll-off characteristics of out-of-band emissions from broadcasting-satellite space stations will tend to reduce the effect of interference on such carriers.

TABLE 1 — *Examples of systems in the 11.45 to 11.7 GHz and 12.5 to 12.75 GHz bands and the maximum pfd limits of spurious emissions from broadcasting satellites to protect them*

Parameter	System		
	11.45 - 11.7 GHz		12.5 - 12.75 GHz
	Maritime satellite to earth station link	Fixed satellite to earth station link	Fixed satellite to earth station link (Data carrier)
Boltzmann's constant in dB(W/(Hz·K))	- 228.6	- 228.6	- 228.6
Receive noise temperature (K)	300	100	2610 (°)
Receive thermal noise level (°) (dB(W/4 kHz))	- 167.6	- 172.6	- 158.4
Maximum interference level in a 4 kHz bandwidth into receiver in dB(W/4 kHz)	- 177.6	- 182.6	- 168.4
Gain of receive antenna (dB)	60	60	45.8
Effective maximum allowable pfd at the interfered-with receiver in dB(W/(m ² ·4 kHz))	- 194.6	- 199.6	- 171.2

(°) A level of interference of 10 dB below thermal noise level is assumed.

(°) This assumes a relatively intensive small earth terminal application.

As an example of a broadband system in the 11.45 to 11.7 GHz band, some calculations have been made for a 20 MHz 612 channel carrier used in the INTELSAT system.

For the calculations it was assumed that an effective single entry interference noise contribution of about 500 pW0p should be tolerable due to out-of-band interference.

Taking the worst case, where the interference spectrum is represented by curve A of Fig. 1, the required carrier-interference ratio for the example considered, was found to be 25.6 dB. Then, taking an average e.i.r.p. density of 16.4 dB(W/MHz) for the INTELSAT system, together with the relationship between cumulative interference e.i.r.p. and band-edge power flux-density given in Fig. 2, the values of maximum permissible unwanted band-edge spectral density may be derived. The results are given in Fig. 3 as a function of the bandwidth of the wanted carrier.

For the particular case of the 20 MHz 612 channel carrier instanced above, it may be seen that the maximum permissible band-edge pfd would be about -177 dB(W/(m² · 4 kHz)). It is considered that a standard of protection based on this 20 MHz carrier would afford reasonable protection for most other carrier sizes, apart from narrow-band carriers. Thus by avoiding the use of narrow-band carriers in the upper portion of the 11.45 to 11.7 GHz band a reasonable beam-edge out-of-band interference pfd, would appear to be -177 dB(W/(m² · 4 kHz)). Further study is required on other broad-band fixed satellite systems in the 11.45 to 11.7 GHz band.

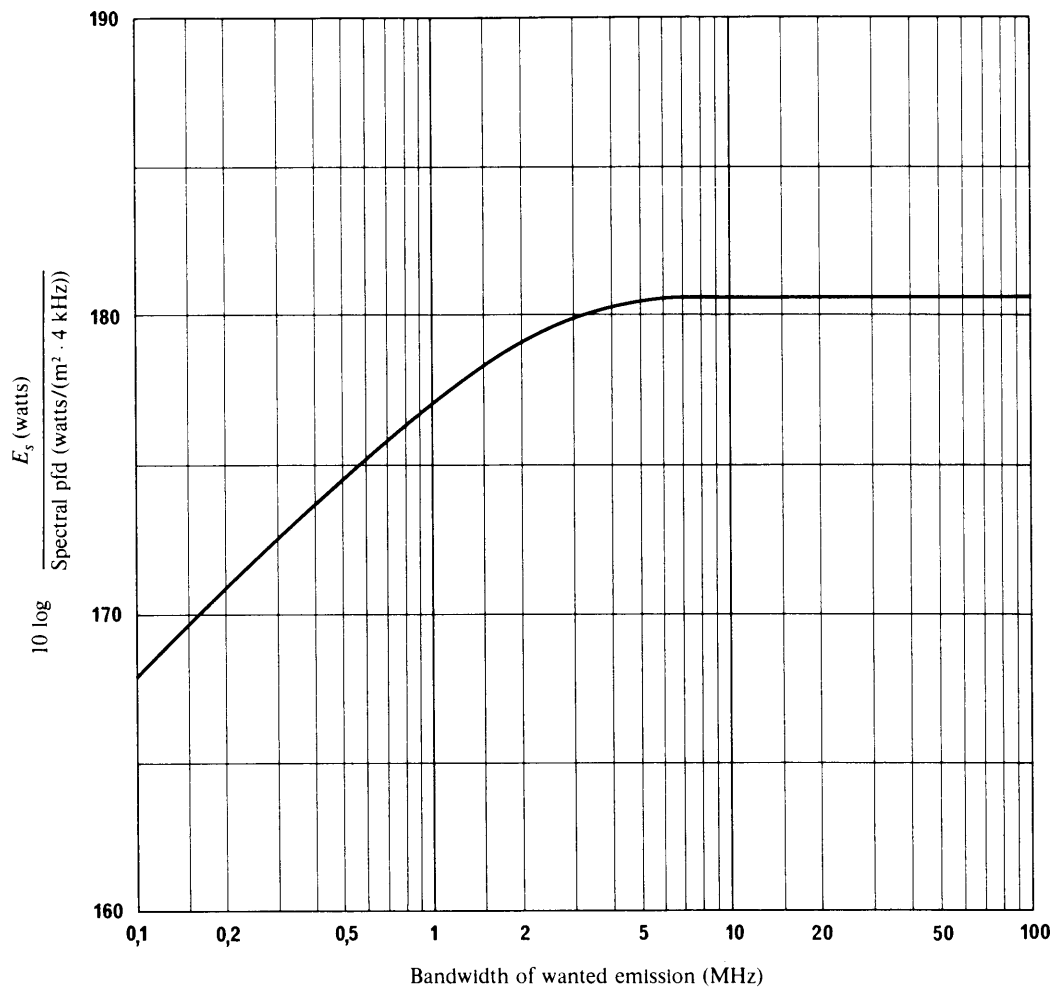


FIGURE 2 — *The ratio of E_s to the interference spectral pfd at the edge of the broadcasting-satellite frequency allocation, as a function of the wanted carrier bandwidth, where*

E_s : The maximum permissible cumulative interference e.i.r.p. within the bandwidth of the wanted carrier, which is located at the edge of the band occupied by the fixed-satellite service, a guard-band of 4 MHz being allowed

Note. — This Curve corresponds to Curve A of Fig. 1.

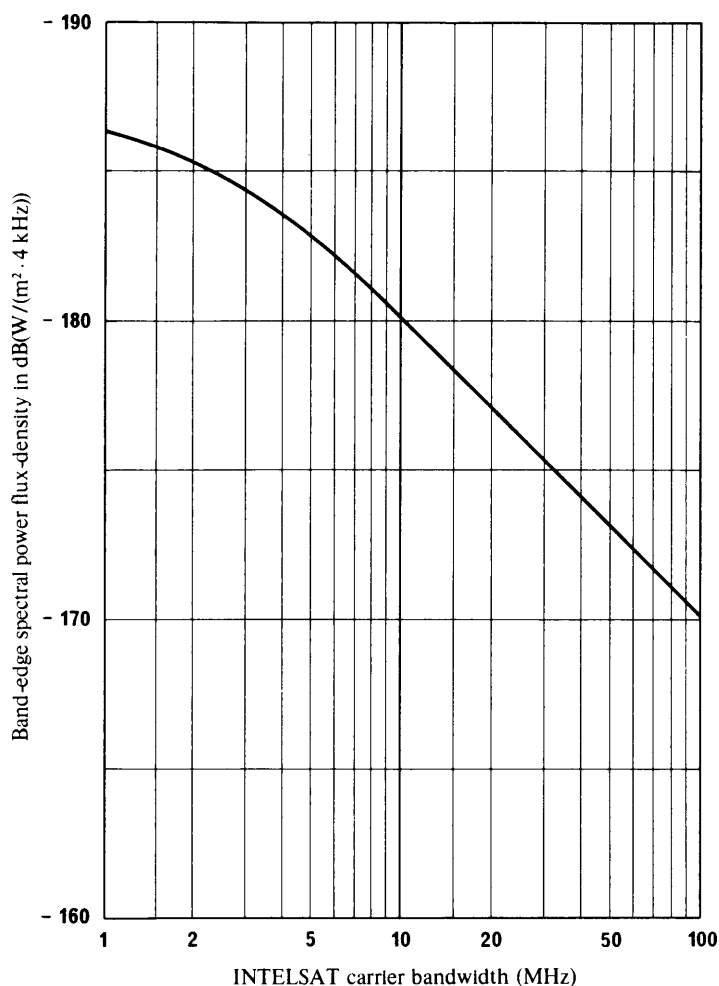


FIGURE 3 — *Maximum permissible band-edge spectral power flux-density due to spurious out-of-band emissions as a function of carrier bandwidth in the INTELSAT-V system (base) on a single entry producing 500 pW0p of interference noise power and assuming a guard band 4 MHz wide between the edge of the allocated band and the band-edge of the wanted emission)*

Note. — This Curve corresponds to Curve A of Fig. 1.

4. Approaches to protecting fixed satellite earth stations

To achieve compatibility between spurious emissions from broadcasting-satellite space stations and permissible levels of interference in the fixed satellite earth stations, a combination of the following provisions may have to be made:

- 4.1 Provide for adequate angular separation between the orbit location of satellites in the Broadcasting-Satellite Service and the Fixed Satellite Service;
- 4.2 Provide adequate output filtering in the transmitter of the broadcasting-satellite space stations or in the receivers of the fixed satellite earth stations; or both;
- 4.3 Provide adequate frequency separation between the centre of the lowest channel occupied by an emission from a broadcasting-satellite space station and the previously defined protected frequency of the Fixed Satellite Service.

In the interests of minimizing *a priori* constraints on system design in both services, it may be undesirable or impractical to rely on filtering requirements alone, as outlined under item 4.2 above; however, a relationship between pertinent system parameters including orbit spacing between satellite locations and frequency separation between "protected frequency" and channel centre frequency, as outlined in items 4.1 and 4.3 above, can be developed.

This relationship is shown in Fig. 4 where the required satellite spacing is plotted versus the power flux-density of spurious emission at the protected frequency of the fixed satellite earth station, with frequency separation as a parameter. The curves were derived from information regarding spurious emissions from broadcasting-satellite space stations as given by curves A and B of Fig. 1 for a broadcasting-satellite channel with a channel bandwidth of 27 MHz.

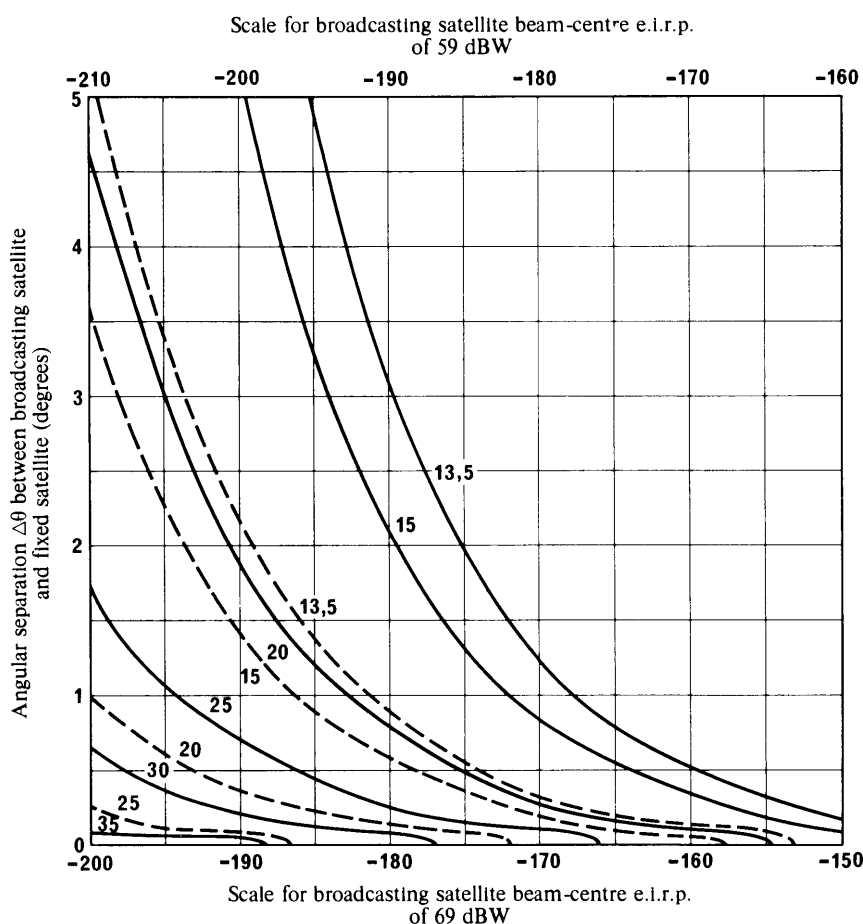


FIGURE 4 — Angular spacing and frequency separation to protect fixed satellite earth stations from spurious emissions from adjacent-band broadcasting satellites

Spectral power flux-density of spurious emissions at the fixed satellite earth station in $\text{dB}(\text{W}/(\text{m}^2 \cdot 4 \text{ kHz}))$

Note 1. — Channel bandwidth of broadcasting satellite signal is 27 MHz.

Note 2. — Numbers on curves indicate Δf = frequency separation between fixed satellite protected-frequency and broadcasting-satellite channel centre frequency (MHz).

Note 3. — Solid curves based on curve A of Fig. 1. Dashed curves based on curve B of Fig. 1.

The absolute level of the spurious emissions at the fixed satellite earth station depends, of course, upon the e.i.r.p. of the broadcasting satellite. Separate abscissa scales are given in the figure for e.i.r.p.s of 69 dBW and 59 dBW corresponding to clear weather power-flux densities of about $-94 \text{ dB(W/m}^2\text{)}$ and $-104 \text{ dB(W/m}^2\text{)}$, respectively, at the centre of the Broadcasting-Satellite Service area.

The level of spurious emissions also depends on the type of television signal carried by the broadcasting-satellite space station, on the location of the fixed satellite earth station, relative to the broadcasting-satellite service area, and on the gain and side-lobe pattern of the earth station receiving antenna. The solid curves in Fig. 4 were drawn for the worst-case situation in which the broadcasting-satellite signal was modulated by 100 per cent colour-bar baseband (see curve A in Fig. 1). The dashed curves were drawn for the case in which the broadcasting-satellite signal is modulated by a line-330 insertion test signal (see curve B in Fig. 1). In both cases, it was assumed that the fixed satellite earth location is located at the centre of the Broadcasting-Satellite Service area. The earth station antenna gain was assumed to be 60 dB and its sidelobe pattern to be given by $32 - 25 \log \phi$. If the earth station is located outside the coverage area of the broadcasting-satellite, additional interference protection is realized from the angular discrimination of the broadcasting-satellite space station transmitting antenna.

5. Examples of compatible satellite spacing and/or frequency separation (co-coverage)

5.1 Case 1: Both orbit spacing and frequency separation

Using the curves of Fig. 4, it is possible to calculate the combinations of orbital spacing $\Delta\theta$ and frequency separation Δf that will reduce the levels of spurious emission from a broadcasting-satellite to the maximum permissible level at the protected frequency. The results of such calculations are displayed in Fig. 5 where $\Delta\theta$ is plotted versus Δf for values of maximum permissible pfd ranging from -210 to $-160 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$. Separate families of curves, labelled A and B, are given for the two types of broadcasting-satellite test signals corresponding to curves A and B, respectively, in Fig. 1.

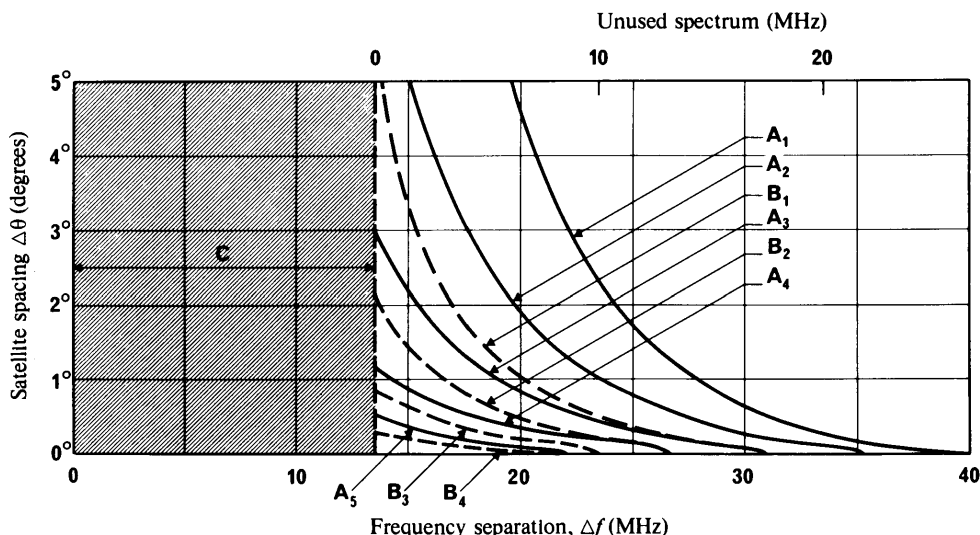


FIGURE 5 — Tradeoff between satellite spacing ($\Delta\theta$) and frequency separation (Δf) for various maximum permissible pfds

- A: 100 per cent modulated colour-bars (solid curves)
- B: Line 330 insertion test signal (dashed curves)
- 1: 269, e.g. pfd = $-200 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ from a 69 dBW satellite
- 2: 259, e.g. pfd = $-200 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ from a 59 dBW satellite
- 3: 249
- 4: 239
- 5: 229
- C: Half-bandwidth of broadcasting-satellite channel (13.5 MHz)

Note. — The letter and number on a curve respectively identify the type of baseband signal assumed for the broadcasting-satellite emission and the difference, $E_s - \text{pfd}$, between the satellite e.i.r.p., E_s , in dBW and the resultant spurious emission level, pfd, in $\text{dB(W/(m}^2 \cdot 4 \text{ kHz))}$ at the fixed satellite earth station.

For example, to keep the spurious emissions from a 69 dBW e.i.r.p. broadcasting-satellite to a maximum level of $-200 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ at a fixed satellite earth station, curve A1 indicates that the following combinations of $\Delta\theta$ and Δf may be used, if it is assumed that the broadcasting-satellite signal is modulated by 100 per cent modulated colour bars.

$\Delta\theta$ (deg)	0	1	2	3	4	5
Δf (MHz)	40	28	24.5	22	20.6	18.6
Unused spectrum (MHz)	26.5	14.5	11	8.5	7.1	5.1

Thus the required separation between the protected frequency and the centre of the broadcasting satellite channel decreases from 40 MHz for co-located satellites ($\Delta\theta = 0$) to 18.6 MHz for a 5 degree satellite spacing. Note that about 13.5 MHz of the required frequency separation (half of the bandwidth assumed for the broadcasting satellite channel) is required for the essential spectrum of the broadcasting-satellite; the remainder is unused spectrum lying between the protected frequency in the fixed satellite band and the edge of the television channel in the broadcasting-satellite band. Note also that with a 59 dBW e.i.r.p. broadcasting-satellite, the same combinations of $\Delta\theta$ and Δf would keep spurious emissions at the earth station below $-210 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$.

For the same satellite e.i.r.p. and maximum permissible pfd, much smaller satellite spacings and/or frequency separations are required if it is assumed that the broadcasting-satellite signal carries a line-330 insertion test signal. In this case, curve B1 of Fig. 5 shows that the following combinations of $\Delta\theta$ and Δf may be used:

$\Delta\theta$ (degrees)	0	1	2	3	4	5
Δf (MHz)	30	20	17	15.5	14.5	14
Unused spectrum (MHz)	16.5	6.5	3.5	2	1	0.5

For a fixed satellite carrying a 20 MHz bandwidth carrier, the maximum permissible pfd at the (band-edge) protected frequency was cited in § 3 as about $-177 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$. To achieve this level of spurious emission at the earth station with a 69 dBW e.i.r.p. broadcasting-satellite, the interpolation between curves A3 and A4 in Fig. 5 shows that for the worst case test signal corresponding to curve A in Fig. 1 the following combination of $\Delta\theta$ and Δf may be used:

$\Delta\theta$ (deg)	0	1	2
Δf (MHz)	30	18	14
Unused spectrum (MHz)	16.5	4.5	0.5

Note that for satellite spacings of more than 2 degrees, the required frequency separation is less than half the bandwidth of the broadcasting-satellite, and there is no unused spectrum. With a 59 dBW e.i.r.p. satellite, a maximum separation of about 1 degree would suffice to reduce the unused spectrum to zero.

If the line-330 insertion test signal corresponding to curve B in Fig. 1 is assumed, interpolation between curves B3 and B4 in Fig. 5 shows that for any given value of $\Delta\theta$ the required frequency separation will in all cases be reduced from 8 to 10 MHz.

5.2 Case 2: co-located satellites ($\Delta\theta = 0$)

If, in order to avoid placing any constraints on either service in the location of its satellites, the possibility of co-located satellites is assumed, the reduction of spurious emission to the permissible values may have to be achieved by frequency separation alone. In this case, the values of maximum permissible power flux-density mentioned in § 3, together with the curves given in Fig. 1, can be used directly to deduce the frequency separation between the centre frequency of the bottom (or top) channels in the broadcasting-satellite band and the fixed satellite protected frequency. For convenience, these curves are reproduced in Fig. 6a, from which the following observations can be made:

- The example of a fixed satellite (data) requiring protection to $-171 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ in the band 12.5 to 12.75 GHz leads to a frequency separation of about 20 MHz and 28 MHz for curves B and A respectively. As previously noted, this frequency separation is not all unused frequency spectrum, since about 13.5 MHz of it contains some of the essential spectrum of the broadcasting-satellite emission.
- The example of a narrow-band fixed satellite transmission requiring protection to about $-200 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ in the band 11.45 to 11.7 GHz leads to a frequency separation according to curves B and A, of about 30 MHz and 40 MHz respectively. Again, about 13.5 MHz of this can be considered to include essential spectrum of the broadcasting-satellite emission.
- The example of a wide-band fixed satellite requiring a protection of $-177 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ at band-edge in the band 11.45 to 11.7 GHz leads to a frequency separation of about 22 MHz and 30 MHz for curves B and A respectively.

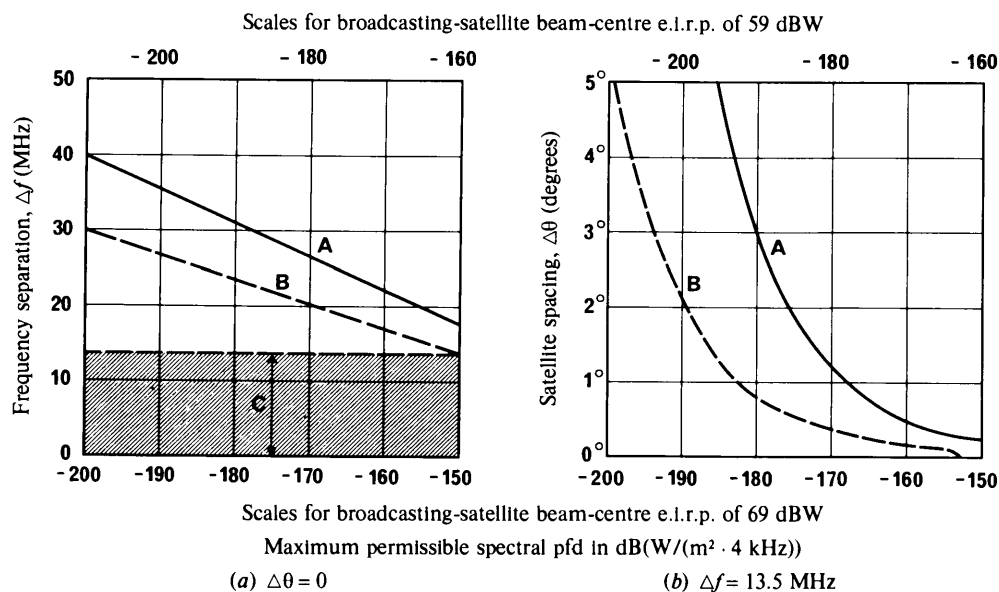


FIGURE 6 — Frequency separation for special cases of co-located satellites ($\Delta\theta = 0$) and zero unused spectrum ($\Delta f = 13.5 \text{ MHz}$)

C: Half-bandwidth of broadcasting satellite channel (13.5 MHz)

Note. — The letters on the curves have the same meaning as in Fig. 5.

5.3 Case 3: No unused spectrum ($\Delta f = 13.5$ MHz)

In many cases, uplink interference problems will preclude the co-location of 12 GHz broadcasting-satellites and fixed satellites in the adjacent bands. Moreover, in Regions 2, where the 12 GHz band includes only 500 MHz of spectrum (compared with 800 MHz in Region 1) and must accommodate fixed satellites as well as broadcasting-satellites; it is desirable to minimize the amount of unused spectrum near the band-edge. For these reasons it is of interest to consider the other special case in which the reduction of spurious emissions to the permissible levels is achieved by orbital spacing alone.

The curves for this case corresponding to the two test signals previously discussed are shown in Fig. 6b and may be read directly. For example to protect a fixed satellite earth station receiving a 20 MHz carrier just below the upper edge of the 11.45 to 11.7 GHz band, against a 69 dBW broadcasting-satellite just above band-edge, requires a satellite spacing of about 2 degrees. For a 59 dBW broadcasting-satellite, the spacing drops to about 0.8 degrees.

Both these examples correspond to the worst case 100 per cent colour bar test pattern signal corresponding to curve A spurious emission in Fig. 1. With the line-330 test pattern the spacings are reduced significantly as shown by curve B in Fig. 6b. In this case, spacings of about 0.7 and 0.3 degrees may suffice for broadcasting satellite e.i.r.p.'s of 69 dBW and 59 dBW, respectively.

5.4 Discussion

A consequence of the results presented above is that a set of broadcasting-satellites in the geostationary orbit would make certain orbital arcs unusable by satellites in the Fixed Satellite Service operating in adjacent bands, depending on the frequency separation between the closest channel used by the broadcasting-satellite and the protected frequency of the fixed satellite. This point is illustrated in Fig. 7. An array of broadcasting-satellites is shown in the 11.70 to 12.5 GHz band at a spacing of 7.5 degrees. At each point shown the full 800 MHz is radiated (different channels being received by different countries). Thus from each point the lowest and highest channels are radiated. The separation between broadcasting-satellites is purely illustrative but may be regarded as typical separation determined by inter-broadcasting satellite interference considerations when adjacent broadcasting satellites employ opposite polarizations. If opposite polarizations are not used, the required spacing between broadcasting-satellites will be approximately doubled and the percentages of orbit usable by the Fixed Satellite Service will be significantly increased. The curves shown in Fig. 7 are based on Fig. 5 but the vertical axis gives the percentage of orbit available to the Fixed Satellite Service in the 11.45 to 11.70 GHz band, relative to all the orbit being available. Depending on the relative positions of the Fixed Service and the Broadcasting-Service satellites, these additional separation requirements will not necessarily lead to the inability to find a location for another particular Fixed Service Satellite.

The implications of Fig. 7 will need to be assessed for the different parts of the geostationary orbit in the 11.45 to 11.70 GHz band. For example, in those parts where a high density of fixed satellites is anticipated, orbital separation, as shown in Figs. 5 and 6b, may not be feasible for all cases. It may then be necessary to assume no orbital separation as the general case for broadcasting-satellites in this part of the orbit.

A solution to this problem, from practical considerations, may have to take into account that it would be generally unacceptable to reposition a broadcasting-satellite whose signals are intended for individual reception.

6. Some technical observations concerning frequency band allocations

Based on the frequency study on spurious emissions, particularly difficult technical problems arise when a Broadcasting-Satellite Service frequency allocation (in which individual reception is permitted) and a fixed satellite service allocation (in which systems are developed employing global beam, large diameter earth station antennae, sensitive low noise amplifiers and/or narrow-band modulation techniques) are adjacent to each other in the Table of Frequency Allocations.

Fixed Satellite Service earth stations located in the service area of a Broadcasting-Satellite Service will be subjected to high-power emissions from the Broadcasting-Satellite Service space stations. These emissions, which are in the band adjacent to the Fixed Satellite Service, if received unattenuated, could cause overloading of the Fixed Satellite Service earth station low-noise receiver and a consequent increase in the effective system noise temperature. Therefore, attention must be given to this possible situation during the design phase of the Fixed Satellite Service earth station.

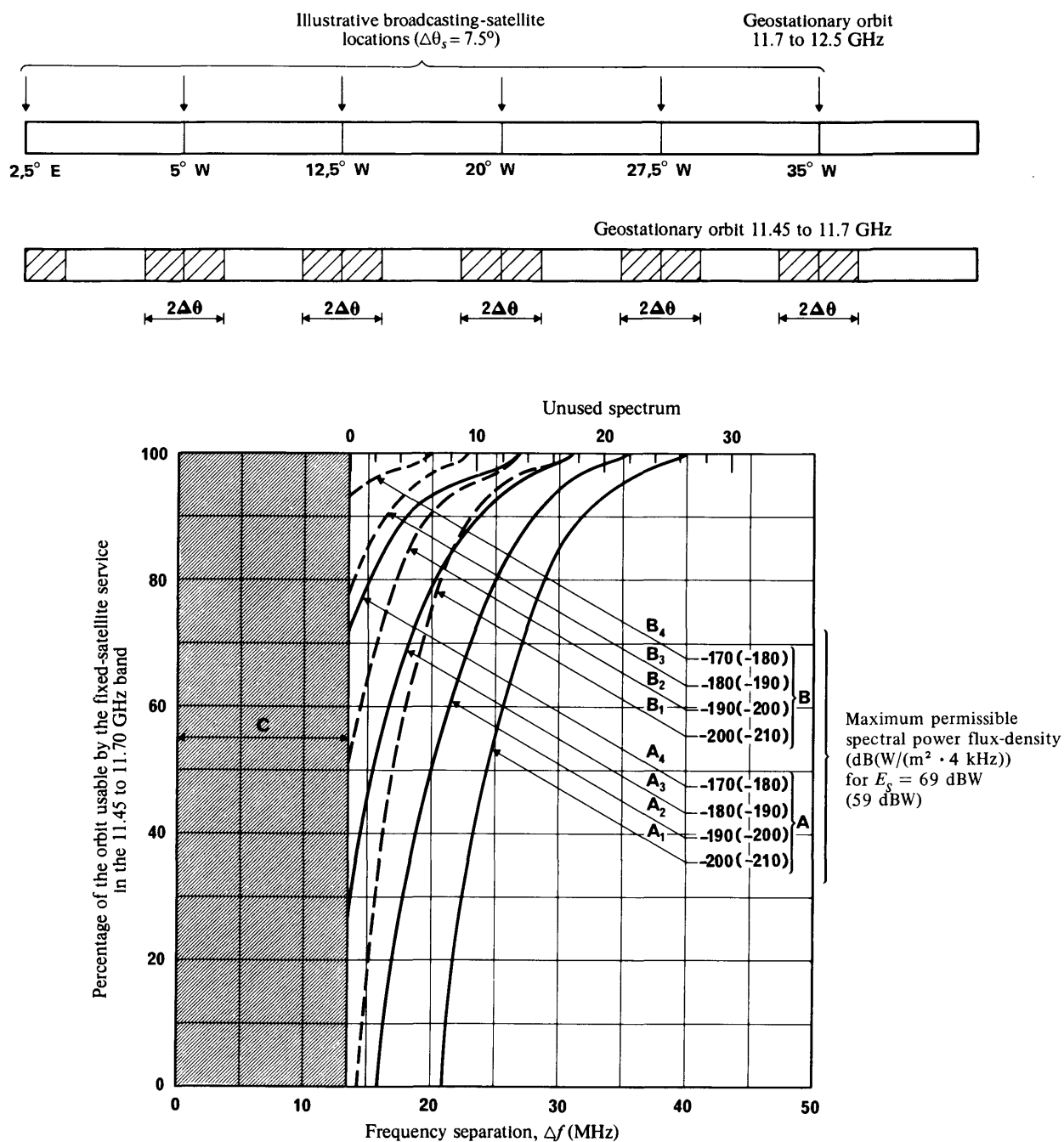
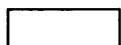
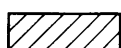


FIGURE 7 — Illustrative example of possible effect of spurious emissions from 12 GHz broadcasting-satellites on the orbital arc usable by fixed satellites in adjacent bands

C: Half bandwidth of broadcasting satellite channel

-  Orbit usable by fixed satellites
-  Orbit not usable by fixed satellites

Note. — The curves have the same designation as those of Fig. 5.

REPORT 713

**THE RADIATION OF SPURIOUS EMISSIONS FROM EARTH STATIONS
AND SPACE STATIONS OF THE FIXED SATELLITE SERVICE**

(1978)

1. Introduction

Spurious emissions from space stations of the Fixed Satellite Service could cause interference at earth stations and terrestrial stations, and in particular, at stations designed to receive very weak signals. This interference could be particularly objectionable at frequencies in bands allocated to the Radioastronomy Service. The Radio Regulations do not, at present, define limits of spurious radiation for transmitters operating at frequencies higher than 235 MHz.

Spurious emissions from earth stations in the Fixed Satellite Service might also cause interference. Such cases of interference from spurious emissions that do arise might often be dealt with on an ad hoc basis. However, the number of earth stations in the Fixed Satellite Service is increasing rapidly and the geographical separation between earth stations obtained in the past may not be obtained in the future. Accordingly, it seems desirable to study the problem of spurious emissions from earth and space stations in the Fixed Satellite Service.

2. The nature and possible power level of spurious emissions radiated from earth and space stations

Little information is available as to the power level of spurious emissions from earth and space stations and without such information it is difficult to discuss the problem on a realistic basis. In order to provide a starting-point for discussion, a very approximate forecast of the order of magnitude of the power of these emissions and their approximate frequency is made in this section. In the following discussion PD_{WE} and F_{WE} represent the power density and frequency of the wanted emission at the input to the earth station antenna, whilst PD_{WS} and F_{WS} represent the e.i.r.p. density and frequency of the wanted emission of the satellite.

Spurious emissions are typically of the following types:

- harmonics and images of the wanted emission,
- fundamentals and harmonics of oscillators used in the frequency conversion process,
- parasitic oscillations,
- intermodulation products arising from non-linear amplification and perhaps from the presence of non-linearities caused by inhomogenities in conductors in the waveguide/filter/antenna-feed chain, following the final amplifier.

There may, however, be other significant sources of spurious emission.

Harmonics of the wanted emission will have a spectral power distribution similar to that of the wanted emission. Their frequencies will be multiples of F_w , and their maximum power density level might be $(PD_{WE} - 80)$ dB(W/MHz) or $(PD_{WS} - 50)$ dB(W/MHz).

Since the lowest frequency allocated to the Fixed Satellite Service for transmissions from space is 2.5 GHz, harmonic radiation will be at 5 GHz or above. These emissions are likely to be spread over a bandwidth of many megahertz and their power density levels might fall in the range of -70 to -60 dB(W/MHz) for earth stations or an e.i.r.p. density of -10 to -30 dB(W/MHz) in the case of emissions from satellites.

Image signals will be broadly similar, but their power is likely to have been reduced by band-pass filters in the transmitter, to a level of the order of -90 dB(W/MHz) for earth stations and about -60 dB(W/MHz) for space stations.

Fundamentals and harmonics of earth station local oscillators can be expected to be of the order of -50 dBW, whilst in the case of emissions from satellites a maximum e.i.r.p. of the order of -60 dBW can be expected. However, the actual power level radiated in any particular case will depend greatly on details of design. Furthermore, these spurious emissions, being unmodulated, may cause significant interference in sensitive narrow-band systems even though the absolute value of the interfering emission may be very low. The effects of parasitic oscillations may be similar in nature but more unpredictable in frequency and more severe in degree.

Earth station intermodulation products will have spectral distributions similar to those of the wanted emissions, usually widely spread, and they tend to be concentrated close to F_w . At the edges of the occupied frequency band the level of intermodulation products may be of the order of $(PD_{WE} - 30)$ dB(W/MHz), giving an absolute value of about -20 to -10 dB(W/MHz).

Satellite intermodulation products will also have spectral distributions similar to those of the wanted emissions. At the edges of the frequency band occupied by the transponders of the satellite, the level of intermodulation products may be of the order of $(PD_{WS} - 20)$ dB(W/MHz) giving an absolute value of about 0 to -20 dB(W/MHz).

These levels should decline considerably at frequencies several times the width of the occupied band away from the band edge.

Signal spectrum components due to modulation but lying just outside the necessary bandwidth are excluded by definition from the term "spurious emission", but these too, may be a source of interference, particularly when the carrier frequency is close to the edge of the allocated frequency band.

For earth stations the estimates quoted above are of spurious emission power at the input to the antenna of a transmitting earth station. The e.i.r.p. from the antenna will then depend upon the radiation pattern at the frequency of interest. As a first approximation it is assumed here that the earth station antenna gain in a given direction for spurious emissions is the same as for the wanted emission. In most interference situations of interest, it may be assumed that the spurious emission signal is radiated in a direction far removed from the earth station antennae main lobe. A gain of 0 dB has been assumed in this Report.

3. Levels of permissible interference at a receiving station

Before limits could be determined, of the power of spurious radiation by earth stations, it would be necessary to relate the power of such emissions to the level of interference that they would cause at typical receiving stations of the various services likely to be affected. These levels of interference and the percentages of time for which they occur must in turn be related to levels of permissible interference from all sources. The determination of these total interference levels and the percentage that may comprise spurious radiation must, of course, take place in the Study Groups responsible for the Services concerned. The task is a substantial one, since existing limits on spurious emissions recommended by the CCIR apply only below 960 MHz (Recommendation 329-3). These studies would need to take into account:

- the probable number of simultaneous interference entries due to spurious emissions from stations of all services;
- the effect that the spectrum of the interfering signal would have on the affected service compared with the equivalent amount of thermal noise;
- the most appropriate bandwidth in which to refer levels of interference;
- the sensitivity to interference of the services within the band and
- in shared bands, the amount of interference that already arises as a result of the sharing of the frequency band.

In order to gain some understanding of the problem, this Report has assumed the simplified situation of a service receiving spurious emissions solely from stations of the Fixed Satellite Service. Levels of permissible interference have been derived from Reports and Recommendations of the appropriate CCIR Study Groups where they exist. It has been generally assumed that the spurious component should be 10 to 20 dB below the level of the permissible in-band interference. This range of values of interference resulting from spurious emission is given for illustration only and should be reviewed as the work continues towards answering Question 25/4. However for the sake of simplicity the value of 20 dB only has been used in the examples that follow.

3.1 *Interference to radio-relay stations from earth stations*

Earlier studies by CCIR Study Groups 4 and 9, in the context of the determination of interference potential between earth stations and terrestrial stations, have determined values of permissible interference powers. Report 448-2 provides the long term permissible levels for radio-relay systems operating at frequencies between 1 and 40 GHz. Typical values of the long term permissible level, for each entry of interference, are –151 dB(W/4 kHz) for analogue modulated systems operating at 6 GHz and –134 dB(W/MHz) for digitally modulated systems operating at 30 GHz, these values being applicable when the interference is present continuously.

A limit corresponding to 20 dB below these values might be of the order needed to define a reasonable allocation of this interference allowance to spurious emissions from earth stations of the Fixed Satellite Service, which would give values around –171 dB(W/4 kHz) at 6 GHz and –154 dB(W/MHz) at 30 GHz.

With these assumptions, and also assuming that the source of interference is in the direction of maximum sensitivity of the radio-relay station antenna, spurious radiations of which the e.i.r.p. did not exceed –80 dB(W/4 kHz) at 6 GHz or –54 dB(W/MHz) at 30 GHz should not cause more than the permitted level of interference in a radio-relay station receiver situated 25 km away; free-space propagation conditions being assumed.

3.2 *Interference to radio-relay stations from space stations*

Earlier studies by CCIR Study Groups 4 and 9 have determined maximum levels of power flux-density (pfd) set up by the carriers emitted by satellites of the Fixed Satellite Service working in all frequency bands shared with the terrestrial Fixed Service. Permissible values of power flux-densities are given in Recommendation 358-2. For angles of arrival of above 25°, these pfd values range from –144 dB(W/(m² · 4 kHz)) at 2 GHz to –138 dB(W/(m² · 4 kHz)) at 13 GHz; at 20 GHz the corresponding value is –150 dB(W/(m² · MHz)). An e.i.r.p. density limit corresponding to 20 dB below these pfd limits might be of the order needed to define a reasonable allocation of this interference noise allowance to spurious emissions from a geostationary satellite of the Fixed Satellite Service, giving values of –2 dB(W/4 kHz) at 2 GHz and 37 dB(W/MHz) at 20 GHz. This assumes that the antenna pattern of the space station antenna at the frequencies of the spurious radiation is similar to that at the fundamental frequency.

3.3 *Interference to “trans-horizon” stations from earth stations*

As in the case of line-of-sight radio-relay systems, Report 448-2 gives values of permissible interference for trans-horizon systems. Assuming that the level of the spurious component may be 20 dB below the level of the permissible interference, a reasonable limit for interference from spurious emission is of the order of -160 dB(W/4 kHz) for 0.01% of the time. With this assumption, the limit on spurious emission e.i.r.p. density from an earth station, required to avoid exceeding permissible interference values at a trans-horizon station receiver 100 km distant overland, would be -74 dB(W/4 kHz). The corresponding value for 250 km separation is -48 dB(W/4 kHz).

The propagation data used in this calculation and in the other examples of long-distance terrestrial path interference quoted in this Report are given in Report 569-1, the following parameters being assumed:

degree of terrain irregularity: $\Delta H = 25$ m,

gradient of atmospheric refractive index: $\Delta N = 40$ to 55 .

3.4 *Interference to “trans-horizon” stations from space stations*

The Radio Regulations, No. 470NGA, require the interference power from a space station at the input of the receiver of a trans-horizon station not to exceed -168 dB(W/4 kHz). Such an interfering signal level would be set up if there is direct entry of a signal from a transmitter in a satellite of the Fixed Satellite Service with a pfd of -189 dB(W/(m² · 4 kHz)) into the main lobe of the trans-horizon system antenna. It is suggested that a pfd limit of 20 dB below that value would be a reasonable allocation for the aggregate of all satellite spurious emissions. A small further reduction would be necessary to reach an acceptable value for the spurious emissions from any one satellite, to allow for multiple entries, leading to an e.i.r.p. density limit of about -50 dB(W/4 kHz).

3.5 *Interference to fixed-satellite earth stations from earth stations*

Report 448-2 contains sufficient information for the calculation of permissible input powers for interference from all sources, with the exception of values for the earth station noise temperature. Making reasonable assumptions for the noise temperature, a value of permissible interference power of about -146 dB(W/MHz) is found for frequencies between 1 and 10 GHz, increasing to -140 dB(W/MHz) for systems operating in the 15 to 40 GHz range, these figures being applicable, for example, to 0.01% of the time. A limit of 20 dB below these values would seem to be a reasonable allocation for spurious emissions. With these assumptions, spurious radiations with an e.i.r.p. density not exceeding the following values should not cause more than the permitted level of interference at another earth station at a distance of 100 km overland:

for frequencies around 4 GHz: -35 dB(W/MHz),

for frequencies around 12 GHz: -29 dB(W/MHz),

for frequencies around 30 GHz: -6 dB(W/MHz).

3.6 *Interference to fixed-satellite earth stations from space stations of any Service*

Earth stations operating in the Fixed-Satellite Service may receive spurious emissions from other satellites over the following transmission paths:

- (a) directly from unwanted satellites;
- (b) indirectly from unwanted satellites after retransmission by the wanted satellite;
- (c) indirectly from earth stations of other networks or terrestrial stations after retransmission by the wanted satellite;
- (d) from the wanted satellite, the spurious emissions having originated either in the wanted satellite or in other earth stations of the same network.

It may be assumed that (c) will be small and that (d) may be disregarded. Furthermore, an examination indicates that the probability of significant interference arriving at an earth station via path (b) is very small; therefore interference limits obtained in considering case (a) should also be acceptable for case (b) (See Annex I).

In exceptional cases it may be necessary to co-ordinate the location of satellites to control interference from predictable high-level spurious emissions. One such case is band-edge interference from broadcasting satellites. In the general case, however, it is desirable that the level of interference should be so low that it can be tolerated without co-ordination. Thus it is suggested that an arbitrary allocation be made of 5% of the total inter-network interference budget to cover normal cases (a) and (b) above, i.e., 50 pWp for FDM/FM. No Recommendation has been made yet for permissible interference to digital emissions, furthermore, it is unlikely that spurious emissions would enter a single wanted channel by both routes (a) and (b), so each may be allocated the 5% share.

Since interference from spurious emissions can arise from a satellite which does not use the same frequency bands as the wanted satellite, the normal processes of co-ordination cannot be assumed to prevent the entry of spurious emission interference in the main beam of the earth station. However, if the level of spurious emission pfd at the Earth's surface is so low that an in-beam entry can be tolerated at an earth station with a high-gain antenna, it may be assumed that any other spurious emissions which are similarly low in strength will have a negligible effect if they enter via side-lobes. Likewise, it is unlikely that a high-gain earth station antenna would suffer direct entry spurious emissions from more than one interfering satellite at a time. Earth stations with low gain may suffer more than one direct entry, but this will not matter if the acceptable level is determined by the protection of high-gain antennae.

3.6.1 *Direct entry from the interfering satellite (Case (a))*

For a first approach to the calculation of acceptable levels of spurious emission, it would be convenient to follow the pattern set by Recommendation 358-2, and to divide the spectrum at 15.4 GHz. Below 15.4 GHz the characteristics of existing earth stations receiving FDM/FM signals at 4 GHz might be assumed, the maximum acceptable level of interference spectral pfd being calculated in a bandwidth of 4 kHz. Above 15.4 GHz it would be necessary to make assumptions as to the characteristics of future earth stations receiving at 19 GHz, the limiting spectral pfd being calculated in a bandwidth of 1 MHz.

For a direct entry into a high-gain earth station antenna, such as INTELSAT Standards A and C, receiving FDM/FM signals, the interference spectral pfd should not exceed $-221 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ below 15.4 GHz. Above 15.4 GHz the limit might be $-182 \text{ dB(W/(m}^2 \cdot \text{MHz))}$. See Annex I for the justification of these figures.

3.6.2 *Indirect entry from an interfering satellite via the wanted satellite (Case (b))*

The gain of a satellite antenna at angles well removed from the main beam can be assumed to be 0 dB relative to isotropic. This assumption is probably valid for interference received at one satellite from another satellite, provided that orbital eccentricity is kept to a minimum.

With this assumption, a spurious emission conforming to the limits in § 3.1 might set up 50 pWp of interference in a wanted channel if it entered the earth station indirectly via the wanted satellite; and if the separation between the two satellites was about 4 km. See Annex 1. This corresponds to the extremely small separation angle of 0.006° . The probability that two satellites would be so close for more than a brief period of time is small. Thus the pfd limit obtained via Case (a) is also acceptable for Case (b).

3.7 *Interference to radioastronomy stations from earth stations*

Report 224-4 examines the problem of interference into radioastronomy earth stations. Report 224-4 offers as a target the reduction of interference to the point at which uncertainties due to the interfering signal are not more than 10% of the uncertainties due to the statistical fluctuation of the astronomical signal when both are integrated over 2000 s and an appropriate bandwidth. Recommendation 314-4 considerations, are also relevant. Applying this criterion, the limiting interfering power at the receiver input in typical cases is given approximately as follows:

- for measurements of the continuous part of the spectrum, -207 dBW in a bandwidth of 10 MHz at 2.7 GHz, increasing to -192 dBW in a bandwidth of 400 MHz at 24 GHz;
- for spectral line measurements, -222 dBW in 10 kHz at 1.7 GHz, increasing to -209 dBW in 100 kHz at 22 GHz.

If it is assumed that the gain of the radioastronomy antenna in the direction of the interfering source is 0 dB, then spurious radiations with an e.i.r.p. density not greater than the following values should not cause these permitted levels to be exceeded for more than 0.01% of the time in the typical cases mentioned above, when the stations are separated by 100 km (or 250 km) overland:

- for measurement of the continuous part of the spectrum, -75 (or -50) dB(W/10 MHz) at 100 km (or 250 km) at 2.7 GHz and -36 (or -2) dB(W/400 MHz) at 100 km (or 250 km) at 24 GHz;
- for spectral line measurements: -96 (or -71) dB(W/10 kHz) at 100 km (or 250 km) at 1.7 GHz and -53 (or -19) dB(W/100 kHz) at 100 km (or 250 km) at 22 GHz.

3.8 *Interference to radioastronomy stations from space stations*

As in § 3.7 the interference criteria of Report 224-4 are relevant. For many interference situations it has been agreed that protection needs to be provided to the required standards only when the interference is incidental on the side-lobes of the radioastronomy antenna with an assumed gain of 0 dBi. With this criterion the power flux-density of an interfering signal should not exceed the following values in the two radioastronomy bands which are taken as examples:

2700 MHz	$-247 \text{ dB(W/(m}^2 \cdot \text{Hz))}$
15.4 GHz	$-233 \text{ dB(W/(m}^2 \cdot \text{Hz))}$

Values for other frequencies can be obtained from Report 224-4. These values are specified as being necessary for the protection of measurements in the continuous part of the spectrum; they can be relaxed by 10 to 15 dB for measurements of spectral lines when the same integration time is used, but the common use of much longer integration times for line work reduces the difference.

Now, taking as an example a fixed-satellite transmitter at 4 GHz, the maximum pfd at the ground is $-142 \text{ dB(W/m}^2\text{)}$ in any 4 kHz band for elevation angles above 25° , this limit being imposed for the protection of terrestrial services in shared bands (No. 470NM of the Radio Regulations). Since the recommended protection level for radioastronomy at 2700 MHz, for example, corresponds to $-211 \text{ dB(W(m}^2 \cdot 4 \text{ kHz))}$ for continuum measurements, the protection criteria are met if spurious radiations in the radioastronomy band are 69 dB below the maximum permitted flux-density of the wanted signal.

It must be pointed out, however, that while the criteria in Report 224-4 are acceptable for interference from a terrestrial transmitter and even for a single interfering source in the sky, the possible incidence of interference from a series of satellites distributed around the geostationary satellite orbit, creates a new situation. Using the recommended antenna pattern of Recommendation 465-1, it may be deduced that if the individual satellites just meet the criteria of Report 224-4, radioastronomy observations of the area of the sky within $\pm 20^\circ$ of the geostationary satellite orbit, would suffer harmful interference continuously. It would clearly be of great value to radioastronomy if a more stringent protection criterion could be met. A reduction of the spurious radiation by 10 dB from the value of -69 dB relative to the main signal would reduce the prohibited region to $\pm 8^\circ$, and a further reduction of 10 dB would reduce it to $\pm 3^\circ$. There is an evident need to study the practicability of achieving the minimum spurious radiation compatible with the proper functioning of the fixed satellite operations.

3.9 *Interference to space research earth stations from earth stations*

For earth stations used for deep-space research, Recommendation 365-3 proposes an interference limit of -220 dB(W/Hz) at frequencies above 1 GHz, this value not to be exceeded for more than 5 min in any day. This is usually interpreted as protection for 0.001% of the time. If an interfering signal has an approximately uniform spectrum over a 4 kHz band, the limit becomes -184 dB(W/4 kHz) . At 100 km the radiated power of a potential source of interference should therefore, for example, be less than -56 dB(W/4 kHz) at a working frequency of about 2 GHz.

For reception of signals from near-earth satellites, the same interference can normally be accepted for 0.1% of the time; this would allow the interfering e.i.r.p. to be increased by about 3 dB, (Recommendation 364-3). However, for manned missions the additional safety margins that are required necessitate the same degree of protection as for deep-space missions (Recommendation 364-3).

3.10 *Interference to space research earth stations from space stations*

There is little information in CCIR texts on which to base an assessment of the levels of interference which might be acceptable from satellites. Report 536-1 indicates that the thermal noise level of a deep-space receiving station would be of the order of -214 dB(W/Hz) . If continual interference into such a station is to be no greater than, say, 20 dB below thermal noise, then the interference e.i.r.p. radiated by a geostationary satellite should not exceed about -104 dB(W/Hz) . This assumes a receiving antenna operating at about 2 GHz with a main beam gain of 60 dB.

4. **Form of presentation of limits**

It must be decided in what form any limits should be expressed. There appear to be three possibilities:

- 4.1 Defining the maximum permissible power of any spurious emission in absolute terms.
- 4.2 Defining the maximum permissible power of any spurious emission relative to the power of the fundamental.
- 4.3 Defining the maximum permissible power of any spurious emission relative to the fundamental power and that the spurious level in absolute terms should not exceed given values.

Method 4.1 would permit low-power transmitters to radiate disproportionately high levels of spurious emissions relative to the power of the fundamental. Method 4.2 has the disadvantage that if a compromise value of suppression is adopted, it is likely to be unduly stringent for lower-powered transmitters and inadequate for higher-powered transmitters. Method 4.3 appears to be a reasonable compromise but this requires further study.

The following comments from Study Group 2 are also relevant.

Study Group 2 considers that when a spurious emission has been identified as falling within a radioastronomy band, the latter service can be protected only by limiting the emissions to an absolute value which will enable agreed criteria to be met. It is suggested that Study Groups 2 and 4 should collaborate on the determination of the compromise criteria which would enable radioastronomers to carry out observations at a small angular distance from the geostationary satellite orbit without introducing unacceptable difficulties to the reducing of spurious emissions from satellites.

5. Conclusions

5.1 *Spurious emissions from space stations of the Fixed Satellite Service*

The following very tentative conclusions are drawn from this preliminary examination.

The probability of interference to terrestrial radio relay stations by spurious emission from space stations of the Fixed Satellite Service does not appear to be high, but further examination of radiation levels and their aggregate effects should be made.

It may be necessary to limit the emission by satellites of inter-modulation products in the immediate neighbourhood of the occupied band to prevent significant interference to fixed-service earth stations using a nearby satellite and occupying an adjacent band; the same may apply when trans-horizon services use an adjacent frequency band. However, it seems probable that severe interference will be suffered by radioastronomy stations from direct entries of harmonic radiation and possibly image signals, local oscillator harmonics and parasitic emissions from fixed-satellite space stations and also from intermodulation emissions in cases where the Radioastronomy and the Fixed Satellite Services have adjacent frequency band allocations. Interference entering in the far side-lobes of the antennae of radioastronomy stations may also be a cause of serious difficulty, but in these cases the problem is perhaps more open to solution.

5.2 *Spurious emissions from earth stations of the Fixed Satellite Service*

Interference in excess of levels thought likely to be permissible may arise at various kinds of receiving stations due to spurious radiations from earth stations of the Fixed Satellite Service, depending, among other factors, upon the distance between the stations, causing and suffering the interference. For example, interference may be significant at distances of a few tens of kilometres at radio-relay receiving stations and at distances of a few hundreds of kilometres at trans-horizon receiving stations and radioastronomy stations; other earth stations of the fixed-satellite stations are intermediate in susceptibility to interference. Other services using very sensitive stations, not considered in this Document, may also need to be considered.

5.3 *General*

Before it is possible to draw up Recommendations limiting spurious radiations from space and earth stations of the Fixed Satellite Service, further studies in the appropriate Study Groups will be needed:

3.1 to identify all services with stations likely to be susceptible to interference from these emissions and to determine, with sufficient precision, the levels of interference that may be permitted and the relevant frequency ranges, having regard to the possible interference from other sources and to such factors as the percentage of time that the interference is present, and the bandwidth and time over which interference should be integrated,

5.3.2 to determine what level of spurious radiation would arise in the various frequency bands from space and earth stations of the Fixed Satellite Service and the e.i.r.p. densities of spurious emissions from earth stations, particularly in the direction of the horizon,

5.3.3 to consider the limits of spurious radiation as a function of frequency separation especially as applied to adjacent frequency bands,

5.3.4 to consider whether it is necessary and if so, to what extent it is technically and economically feasible, to improve on the levels identified in 5.3.2 in general, at all frequencies. Alternatively, it may be desirable to identify more stringent limits on spurious emissions in frequency bands which are allocated to Services which use particularly sensitive receivers, with more relaxed limits applied at other frequencies,

5.3.5 to consider the best form for the expression of the recommended maximum levels of spurious emissions from space and earth stations.

It may also be desirable to consider provisions for limiting the level of out-of-band spectral components, in particular, those due to the modulation process.

ANNEX I

1. Derivation of values of acceptable power flux-density

The following assumptions have been made in the derivation of values of acceptable power flux-density:

- To protect fixed-satellite bands below 15.4 GHz, pfd values are calculated for 4 GHz. For the protection of fixed-satellite bands above 15.4 GHz, pfd values are calculated for 19 GHz.
- The wanted satellite network employs FDM/FM telephony transmission with a down-path thermal noise contribution of 5000 pW0p.
- The maximum acceptable interference in a telephone channel from spurious emissions is 50 pW0p.
- The earth station antenna gain (G_e) is 60 dB at 4 GHz and 64 dB at 19 GHz.
- The earth station system noise temperature (T_s) is 60 K at 4 GHz and 250 K at 19 GHz.
- The reference bandwidth (B) is 4 kHz at 4 GHz and 1 MHz at 19 GHz.

Then with these assumptions, the maximum acceptable interference pdf_i due to a spurious emission is given by:

$$pdf_i = 10 \log kT_S B + 10 \log \frac{50}{5000} - G_e - 10 \log \frac{\lambda^2}{4\pi}$$

$$= -221 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz)) at 4 GHz}$$

$$\text{and } -181.6 \text{ dB(W/(m}^2 \cdot \text{MHz)) at 19 GHz.}$$

2. Spacing required between two geostationary satellites

From § 1 above the interference spectral pfd should not exceed $-221 \text{ dB(W/(m}^2 \cdot 4 \text{ kHz))}$ at 4 GHz. This corresponds to an interference spectral power density at the earth station receiver input of -195 dB(W/4 kHz) and an interference e.i.r.p. from a geostationary satellite of -58 dB(W/4 kHz) .

The following assumptions are made, in addition to those made for § 1:

- The gain of the wanted satellite antenna in the direction of the interfering satellite is 0 dB relative to isotropic.
- The transmission gain of the wanted system from satellite receiver input to earth station antenna output is -20 dB .
- The spectral e.i.r.p. density of the spurious emission at the frequency received by the wanted satellite is -58 dB(W/4 kHz) .

The path loss between the two satellites equals $20 \log 4\pi d/\lambda$.

Then, if the interference power density at the earth station receiver input may not exceed -195 dB(W/4 kHz) ,

$$-195 \leq -58 - 20 - 20 \log \frac{4\pi d}{\lambda}$$

therefore, $d \geq 4 \text{ km}$.

The corresponding geocentric separation angle is 5.7×10^{-3} degrees. At 19 GHz the minimum satellite separation distances would be less.

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SECTION 4H: FREQUENCY SHARING WITH TERRESTRIAL RADIOCOMMUNICATION SYSTEMS

Recommendations and Reports

Recommendations and Reports concerning the sharing of frequency bands with the terrestrial radiocommunication systems will be found in Volume IX.

Recommendations

- Rec. 355-2 Frequency sharing between systems in the Fixed Satellite Service and terrestrial radio services in the same frequency bands.
- Rec. 356-4 Maximum allowable values of interference from line-of-sight radio-relay systems in a telephone channel of a system in the Fixed Satellite Service employing frequency modulation, when the same frequency bands are shared by both systems.
- Rec. 357-3 Maximum allowable values of interference in a telephone channel of an analogue angle-modulated radio-relay system sharing the same frequency bands as systems in the Fixed Satellite Service.
- Rec. 358-2 Maximum permissible values of power flux-density at the surface of the Earth produced by satellites in the Fixed Satellite Service using the same frequency bands above 1 GHz as line-of-sight radio-relay systems.
- Rec. 359-4 Determination of the coordination area of earth stations in the Fixed Satellite Service using the same frequency bands as the systems in the Fixed Terrestrial Service.
- Rec. 406-4 Maximum equivalent isotropically radiated power of line-of-sight radio-relay system transmitters operating in the frequency bands shared with the Fixed Satellite Service.
- Rec. 558 Maximum allowable values of interference from terrestrial radio links to systems in the Fixed Satellite Service employing 8-bit PCM encoded telephony and sharing the same frequency bands.

Reports

- Report 209-3 Frequency sharing between systems in the Fixed Satellite Service and terrestrial radio services.
 - Report 382-3 Determination of co-ordination area.
 - Report 386-2 Determination of the power in any 4 kHz band radiated toward the horizon by earth stations of the Fixed Satellite Service sharing frequency bands with the terrestrial services.
 - Report 387-3 Protection of terrestrial line-of-sight radio-relay systems against interference due to emissions from space stations in the Fixed Satellite Service in shared frequency bands between 1 and 23 GHz.
 - Report 388-3 Methods for determining interference in terrestrial radio-relay systems and systems in the Fixed Satellite Service.
 - Report 393-3 Intersections of radio-relay antenna beams with orbits used by space stations in the Fixed Satellite Service.
 - Report 448-2 Determination of the interference potential between earth Stations and terrestrial stations.
 - Report 449-1 Measured interference into frequency-modulation television systems using frequencies shared within systems in the Fixed Satellite Service between these systems and terrestrial systems.
 - Report 790 E.i.r.p. and power limits for terrestrial radio-relay transmitters sharing with digital satellite systems in bands between 11 to 14 GHz and around 30 GHz.
 - Report 791 Inter-satellite service sharing with the fixed and mobile services.
 - Report 792 Calculation of the maximum power density averaged over 4 kHz of an angle-modulated carrier.
 - Report 793 Derivation of interference criteria for digital systems in the Fixed Satellite Service sharing bands with terrestrial systems.
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QUESTIONS AND STUDY PROGRAMMES, DECISIONS, RESOLUTIONS AND OPINIONS

QUESTION 1-2/4

ANTENNAE FOR SYSTEMS IN THE FIXED SATELLITE SERVICE

(1961 - 1963 - 1970 - 1974)

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 atmospheric effects and techniques of fabrication influence the maximum gain and minimum beamwidths achievable;
- (c) that interference is an important problem particularly with respect to efficiency of utilization of the geostationary-satellite orbit and the sharing of frequency bands with terrestrial systems;
- (d) that frequency re-use in space telecommunications systems would be of significant value for the efficient utilization of the radio spectrum;
- (e) that little is known of the radiation fields close to earth-station antennae, or how such fields are affected by nearby terrain or pits used for shielding;
- (f) that satellite antennae beam shaping is known to be of particular importance in the effective use of the available radio-frequency power, frequency spectrum and the geostationary orbit,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the influences of the atmosphere and techniques of fabrication on achievable antenna beamwidth and gain;
2. what is the state of development in the design and fabrication of antennae particularly with improved side- and back-lobe characteristics;
3. what are the polarization characteristics of antennae, particularly in the side-lobe regions and in planes other than the principal planes;
4. what pointing accuracy is reasonably attainable with antennae of various sizes and types;
5. what are the required technical characteristics of antenna systems which are capable of simultaneous utilization of the same frequencies twice or more at any given location;
6. how can these various antenna characteristics be measured;
7. what are the radiation characteristics close to earth-station antennae, particularly outside the main beam and in the presence of terrain obstacles or pits used for shielding;
8. what are the technical characteristics of satellite antenna systems which employ beam shaping, either along the propagation axis or perpendicular to that axis?

Note. — See Report 390-3.

STUDY PROGRAMME 1A-1/4

REFERENCE RADIATION DIAGRAM OF ANTENNAE AT EARTH STATIONS
IN THE FIXED SATELLITE SERVICE

(1972 - 1974)

The CCIR,

CONSIDERING

- (a) that the side-lobe characteristics of antennae for earth stations will affect the level of interference between the fixed satellite services and terrestrial systems in shared frequency bands and also the efficiency of utilization of the geostationary-satellite orbit;
- (b) that the majority of earth stations in the existing satellite services employ antennae of large diameter to wavelength ratio (D/λ) and that important but incomplete data concerning such antenna radiation patterns are already available;

(c) that in the future earth stations in the fixed satellite service systems may employ antennae of relatively small D/λ ,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of a reference radiation pattern for coordination studies and the calculation of interference between fixed satellite systems, and between earth stations of such systems and stations of other services (Note 1);
2. determination of a design objective for new antennae with side-lobe levels as low as practicable (Note 2).

Note 1. — To do this in a statistically significant and convincing manner a great deal of information on antenna far field side-lobes is needed. This information should cover a representative range of antenna types over a wide range of D/λ and operating frequencies. Measurement conditions and uncertainties should be stated.

Note 2. — Since one of the main aims is to improve utilization of the geostationary-satellite orbit a high degree of suppression of radiation a few degrees off-beam is of particular importance. The design objective should be based on:

- the analysis of measurements of the side-lobe peaks of new earth-station antennae, where these show a high degree of side-lobe suppression; these measurements should be made in the far field with adequate ground clearance. The uncertainty associated with the measurements should be stated;
- the analysis of available studies for proposed antenna types where these aim at a high degree of side-lobe suppression.

Note 3. — See Recommendation 465-1 and Report 391-3.

STUDY PROGRAMME 1B/4

RADIATION CHARACTERISTICS OF SATELLITE ANTENNAE IN THE FIXED SATELLITE SERVICE

(1974)

The CCIR,

CONSIDERING

- (a) that the efficient utilization of the frequency spectrum and the geostationary-satellite orbit is dependent on the performance of the antenna system;
- (b) that antenna systems capable of the simultaneous utilization of the same frequencies twice or more at the same location or from the same service area are necessary for frequency re-use;
- (c) that multi-beam antennae may be utilized for different service areas and may also involve frequency re-use;
- (d) that frequency re-use might be achieved with orthogonally polarized signals;
- (e) that more effective utilization of satellite power can be made if beam shaping is employed;
- (f) that the performance of such antenna systems should be evaluated by practical means prior to their use,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the orthogonal polarization performance in all angular regions, with particular regard to the antenna type;
2. determination of the coupling between antennae in close proximity and between beams of multi-beam antennae;
3. determination of techniques for beam shaping both along the axis of propagation and perpendicular to that axis;
4. determination of the minimum achievable beamwidth, taking into account factors such as, physical size, realizable geometrical antenna tolerances in orbit and spacecraft antenna orientation accuracy;
5. determination of the minimum usable beamwidth, taking into account the environmental effects in orbit, such as, heating, and atmosphere effects in the transmission path;
6. determination of techniques for evaluation of these antenna characteristics.

Note. — See Reports 555-1 and 558-1.

STUDY PROGRAMME 1C-1/4

CHARACTERISTICS OF ANTENNAE AT EARTH STATIONS
IN THE FIXED SATELLITE SERVICE

(1974 – 1978)

The CCIR,

CONSIDERING

- (a) that the radiation fields close to antennae will affect the level of coupling between earth-station antennae in the fixed satellite services and nearby antennae using the same frequency bands;
- (b) that the radiation fields of antennae may also be affected by the use of pit shielding;
- (c) that earth-station antennae with more than one beam are feasible, and that the use of such antennae may be preferable to employing several single-beam antennae at an earth station;
- (d) that frequency re-use might be achieved with orthogonally polarized signals;
- (e) that the precision of satellite station-keeping and attitude control may improve as a result of the development of more advanced control techniques in the satellite subsystems,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the relationship between near and far field patterns of earth stations in the fixed satellite service and other stations using the same frequency bands;
 2. determination of coupling between antennae close to one another;
 3. determination of the effectiveness of pits or other devices for providing shielding;
 4. determination of the radiation characteristics of each beam of multi-beam antennae;
 5. determination of the limitations on the number of beams that can be generated by a single antenna, and the determination of the minimum achievable angular separation between the beams;
 6. determination of the polarization discrimination performance of antenna systems in all angular regions with particular regard to the antenna type;
 7. determination of the desirable limits of steerability of earth station antennae for geostationary satellites.
- Note.* — See Reports 555-1 and 709.

QUESTION 2-3/4

TECHNICAL CHARACTERISTICS OF SYSTEMS IN THE
FIXED SATELLITE SERVICE

(1963 – 1970 – 1974 – 1978)

The CCIR,

CONSIDERING

- (a) that systems in the fixed satellite service are an important means for fixed and mobile communication, both regional and global;
- (b) that the frequency bands to be used by such systems should be the subject of international agreement, not only to facilitate the setting up of communication links between earth stations in different countries, but also to avoid interference to and from other space systems and terrestrial systems which may share the same frequency bands;
- (c) that the choice of preferred frequency bands for such systems is determined by a number of factors including the characteristics of wave propagation, radio noise levels, the feasibility of frequency sharing with terrestrial services, the beamwidths and size of antennae, tracking considerations and pay-load limitations;
- (d) that the extensive frequency requirements of such systems may necessitate the use of frequency bands other than those considered to be the optimum from a technical point of view;
- (e) that, usually, at least two frequency bands are required at an earth or a space station (one for transmission, the other for reception); and that additional bands for transmission and reception may be required at a space station when inter-satellite relays are used;
- (f) that the scope for development and future application of such systems will depend to a great extent upon the feasibility of sharing frequency bands used by terrestrial services, without mutual interference;

- (g) that it may not in all cases be possible for such systems to share frequency bands with terrestrial services, because of considerations of mutual interference;
- (h) that the efficiency of spectrum utilization in such systems will be determined in part by the technical characteristics employed, such as modulation methods and parameters, frequency re-use techniques or the arrangement of radio-frequency carriers;
- (j) that the establishment of such systems would require international agreement on the technical characteristics to be employed, including the baseband, modulation and radio-frequency characteristics;
- (k) that the noise permissible in a system in the fixed satellite service may be expected to depend upon the system configuration and specific system design factors, and that it may be desirable for design purposes, to specify hypothetical reference circuits,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the preferred types of orbit and characteristics for systems in the fixed satellite service for the following applications:
 - 1.1 fixed services for multi-channel telephony, television, sound, telegraphy and data transmission;
 - 1.2 mobile services providing telegraphy, telephony and data transmission between fixed earth stations and space stations serving also mobile stations;
 2. what are the technical considerations in the selection of frequency bands for these applications;
 3. under what conditions and to what extent is it feasible for space stations in the fixed satellite service, operating in the same system or operating in different systems, to share these preferred frequency bands;
 4. under what conditions and to what extent would it be feasible for systems in the fixed satellite service to share these preferred frequency bands with terrestrial services;
 5. to what extent would it be feasible for systems in the fixed satellite service to use frequency bands other than those considered as optimum, in particular, frequency bands above 10 GHz;
 6. to what extent would the choice of system characteristics such as modulation methods, frequency re-use techniques or radio-frequency channelling arrangements, influence the efficiency of spectrum utilization for systems in the fixed satellite service for the applications referred to in § 1 above;
 7. what are the preferred baseband and modulation characteristics for these applications, including such characteristics as frequency deviation and pre-emphasis most suited to broadcasting satellites, taking into account the operational constraints of the down-path;
 8. what hypothetical reference circuits are appropriate for the design of systems in the fixed satellite service including those which might contain inter-satellite relays?
- Note.* — See Recommendations 352-3, 353-3, 354-2, 355-2, 358-2 and Reports 205-4, 206-3, 207-4, 208-4, 209-3, 386-2 and 393-3.

STUDY PROGRAMME 2A-3/4

FEASIBILITY OF FREQUENCY SHARING BETWEEN SYSTEMS IN THE FIXED SATELLITE SERVICE AND TERRESTRIAL SERVICES

(1965 – 1966 – 1970 – 1974 – 1978)

The CCIR,

CONSIDERING

- (a) that the use of systems in the fixed satellite service will require extensive occupation of the radio-frequency spectrum;
- (b) that for systems in the fixed satellite service, in the interest of spectrum conservation, the spectrum should be shared with terrestrial services to the extent practicable;
- (c) that the feasibility of sharing spectrum space with radio-relay systems should be investigated;
- (d) that particular attention should be paid to the feasibility of frequency sharing between inter-satellite links in the fixed satellite service and terrestrial links,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the criteria which affect the selection of sites for earth stations in a system in the fixed satellite service, taking into account the various portions of the radio-frequency spectrum used;
2. 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 radio services;

3. the criteria which affect the determination of the maximum power, in a reference bandwidth, which may be radiated in the horizontal plane by an earth station;
4. the criteria which affect the determination of the minimum angle of elevation, which should be employed at the locations of the earth stations;
5. the degree to which physical modification of terminal sites will provide electromagnetic shielding between earth stations and stations in other radio services;
6. the criteria which affect the selection of satellite power in frequency bands shared with other radio services;
7. the criteria which affect the determination of the minimum practicable separation between the transmitting and receiving locations of radio-relay systems and the receiving and transmitting locations of earth stations in systems in the fixed satellite service, where either system uses any type of modulation;
8. the criteria which affect the maximum permissible power flux-density in a reference bandwidth which may be produced at the surface of the Earth by emissions from satellites in the fixed satellite service;
9. the criteria for frequency sharing between inter-satellite links in the fixed satellite service and terrestrial links.

Note. — See Recommendations 356-4, 357-3, 359-4, 406-4, 558, and Reports 382-3, 385-1, 387-3, 388-3, 448-2, 449-1, 790, 791, 792, 793.

STUDY PROGRAMME 2D-1/4

PREFERRED MODULATION CHARACTERISTICS AND ENERGY DISPERSAL IN THE FIXED SATELLITE SERVICE

(1961 – 1963 – 1970 – 1974)

The CCIR,

CONSIDERING

- (a) that the increasing use of communication satellites will place heavy demands on the radio-frequency spectrum;
- (b) that the extent to which these demands can be met will depend on the efficiency of use of the available frequency bandwidth in conveying information, and on the extent to which this bandwidth can be shared between different systems in the fixed satellite and terrestrial services having regard to the possibilities of frequency re-use techniques;
- (c) that the efficiency of use of the bandwidth and the feasibility of frequency sharing are determined in part by the modulation methods and parameters;
- (d) that the determination of the feasibility of frequency sharing, as described in Reports 209-3 and 382-3, depends on the availability of appropriate values for the protection ratios between wanted and unwanted signal powers at the receiver input for specified grades of service;
- (e) that wanted-to-unwanted signal ratios are required between each type of wanted signal and each type of unwanted signal, for appropriate modulation and fading conditions;
- (f) that Recommendation Spa2-15 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, in RECOMMENDS 2.5, requests that the CCIR continue to study the criteria of permissible interference;
- (g) that the feasibility of frequency sharing may be greatly increased by ensuring that the energy of sharing systems is uniformly dispersed over the occupied band;
- (h) that by the use of energy dispersal of frequency-modulated and digital signals, the peak energy density may be minimized and made substantially independent of the content of the modulating signal;
- (j) that any such techniques of energy dispersal should be designed so as not unduly to increase the total system noise, distortion of the signal, or complexity of design and operation of the system,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of preferred modulation characteristics for transmission from Earth-to-Space and from space-to-Earth in systems in the fixed satellite service;
2. determination of the extent to which signal compression or signal processing techniques can be employed to use bandwidth as efficiently as is practicable to convey information, having regard to the possibilities of frequency re-use techniques and the preferred characteristics which should be employed when such techniques are used;

3. theoretical and experimental determination of the wanted-to-unwanted signal ratios required for specific grades of service for various types of wanted and unwanted signals, for appropriate modulation conditions and for various kinds of fading;
4. investigation of techniques of transmission, reception and modulation which will minimize the wanted-to-unwanted signal ratios required for a specific grade of service;
5. a theoretical and experimental assessment of the manner in which the radio-frequency spectral energy density of a frequency-modulated multi-channel telephony transmission, a frequency-modulated television transmission and a digital modulation system can be kept sensibly constant and uniformly low, irrespective of the content of the modulating signal, and also an evaluation of the reduction in the maximum power density obtained using this technique.

Note. — See Recommendations 446-2, 464 and Reports 212-3, 384-3, 559, 708.

STUDY PROGRAMME 2E-1/4

PREFERRED MULTIPLE-ACCESS CHARACTERISTICS IN THE FIXED SATELLITE SERVICE

(1965 – 1966 – 1970 – 1974)

The CCIR,

CONSIDERING

- (a) that satellites in the fixed satellite service are simultaneously used by many earth stations at different locations;
- (b) that various multiple access methods including time division-multiple access (TDMA) are already used or planned by various Administrations;
- (c) that, in order to ensure the efficient use of frequency spectrum and orbits, it may be desirable to determine the optimum multiple-access characteristics;
- (d) that recommendation of certain system characteristics may be desirable;
- (e) that the transmission characteristics of multiple-access systems, especially TDMA systems, may be of importance in their interaction one with another,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the preferred multiple-access methods taking into account in particular the nature of the network, the modulation methods and the different system characteristics used in the fixed satellite service;
2. identification of characteristics of multiple-access systems, in particular of TDMA systems, which might usefully be recommended as preferred and, if appropriate, the determination of such characteristics.

Note. — See Report 708.

STUDY PROGRAMME 2H-2/4

USE OF FREQUENCY BANDS ABOVE 10 GHz IN THE FIXED SATELLITE SERVICE

(1968 – 1970 – 1974)

The CCIR,

CONSIDERING

- (a) that wide frequency bands are needed for systems in the fixed satellite service, both regional and global;
- (b) that the technical feasibility of using frequency bands above 10 GHz for systems in the fixed satellite service should be considered;
- (c) that the use of frequency bands above 10 GHz for these systems would introduce special technical problems, such as the effects of cloud and precipitation, on system performance and reliability,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the technical problems associated with the use of frequency bands above 10 GHz for systems in the fixed satellite service;

2. the special techniques (such as diversity and adaptive * transmission techniques) which could be used to overcome these problems;
3. the conditions under which the use of these techniques would be appropriate;
4. the conditions under which it may be feasible for systems in the fixed satellite service to share frequency bands above 10 GHz with terrestrial services, and the extent to which such sharing might be possible.

Note. — See Report 552-1.

STUDY PROGRAMME 2J-2/4

TECHNICAL FACTORS INFLUENCING THE EFFICIENCY OF USE OF THE GEOSTATIONARY-SATELLITE ORBIT BY RADIOCOMMUNICATION SATELLITE NETWORKS SHARING FREQUENCY BANDS ALLOCATED TO THE FIXED SATELLITE SERVICE

(1968 - 1970 - 1974 - 1978)

The CCIR,

CONSIDERING

- (a) that, for radiocommunication satellite networks, the geostationary-satellite orbit is particularly valuable;
- (b) that this orbit can accommodate only a finite number of radiocommunication satellite networks sharing the same frequency band and certain arcs of this orbit may be in great demand;
- (c) that the service requirements are not uniform and may result in different system characteristics;
- (d) that the spacing between such satellites is determined by the need to control interference and that, where the characteristics of the satellites are different, the number that can be accommodated in a given arc depends also on how they are arranged;
- (e) that interference can arise in both the up- and down-paths and in direct paths between satellites and is dependent on a number of technical factors;
- (f) that the factors involved are interrelated and it is necessary to define the relationship between them so as to establish appropriate criteria providing for the orderly development and most effective use of the geostationary-satellite orbit;
- (g) that the effectiveness of use of the geostationary-satellite orbit will be further improved to the extent that it may be possible to use the same frequencies more than once within a single radiocommunication satellite;
- (h) that the effectiveness of the use of the geostationary-satellite orbit and the frequency spectrum may also be improved if up-path and down-path frequency bands are used in satellite networks systematically in pairs;
- (j) that Recommendation No. Spa2 - 15 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, calls upon the CCIR to give priority to studies on these subjects,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the technical characteristics of radiocommunication satellite systems using fixed satellite frequency bands which affect the utilization of the geostationary-satellite orbit, and the interrelationships between them, some of which are as follows:
 - 1.1 the preferred technical characteristics of transmitting and receiving antennae for earth and space stations, including the purity of polarization (circular and linear) attainable in all relevant parts of the radiation patterns, and the direction of the planes of polarization in the case of linear polarization, from the standpoint of frequency sharing within the same satellite network and with other networks;
 - 1.2 the optimum range of powers to be employed by satellite and by earth-station transmitters, to facilitate frequency sharing among networks;
 - 1.3 the effects of baseband and modulation characteristics on frequency sharing among networks;
 - 1.4 the extent to which it is feasible and useful to reduce errors in satellite station-keeping and the pointing direction of satellite antenna beams;
 - 1.5 the technical means by which the service arc of a satellite can be maximized;

* "Adaptive", in this sense, means changing the information rate or radiated power over a transmission link to compensate for changes in path attenuation.

2. the technical criteria that should be used to ensure an orderly development aiming at the most efficient and effective use of the geostationary-satellite orbit;
3. the extent to which it may be feasible and desirable to adopt preferred technical characteristics for different geostationary radiocommunication satellites and earth stations, to improve the overall effectiveness of the use of the orbit;
4. the technical characteristics and utilization principles that should be recommended for application to single geostationary-satellites providing for up-paths and down-paths in more than one pair of frequency bands (including the case of satellites used for multiple services) to improve the efficiency of use of the geostationary-satellite orbit;
5. the extent to which it may be desirable to pair the frequency bands allocated for Earth-to-space and space-to-Earth links for the fixed satellite service and, if found desirable, to recommend preferred pairing to improve the overall effectiveness of use of both the frequency spectrum and the geostationary orbit. This study should take into account the various applications and the different frequency allocations in the three ITU Regions;
6. the ways in which it will be feasible to increase the efficiency of use of the geostationary-satellite orbit and of the frequency spectrum, by permitting a total interference-noise contribution from other satellite networks substantially in excess of the values recommended in Recommendation 466-2. This study should take account of the possibility that a higher total interference-noise contribution might, if necessary, be limited to networks using satellites in congested parts of the orbit; the study should also include both the feasibility of overcoming problems of interference which result from inhomogeneous network parameters and the impact of external interference on satellite networks in which frequency reuse is practised;
7. the factors affecting the multiple use of the same frequencies within a radiocommunication satellite;
8. the sharing criteria that will permit the operation of networks using geostationary and non-geostationary satellites without unacceptable interference.

Note. — See Recommendations 466-2, 483-1, 484-1, 523 and 524, and Reports 388-3, 453-2, 454-2, 455-2, 556-1, 557, 558-1, 559, 710, 711.

STUDY PROGRAMME 2K-2/4

CHARACTERISTICS OF AN EARTH-TO-SPACE PATH USED FOR THE CONNECTION OF A SPACE STATION IN THE BROADCASTING-SATELLITE SERVICE IN A FREQUENCY BAND ALLOCATED TO THE FIXED SATELLITE SERVICE

(1972 - 1974 - 1978)

The CCIR,

CONSIDERING

- (a) that under the Radio Regulations the Earth-to-space path used for the connection of a satellite in the broadcasting service is part of the fixed satellite service;
- (b) that the frequency and technical characteristics of this path may depend on the technical characteristics of the broadcasting satellite, but that risks of interference with satellites in the fixed satellite service providing links between specified points on the Earth should also be taken into account;
- (c) that certain frequency bands are allocated to the fixed satellite service in both the Earth-to-space and the space-to-Earth directions;
- (d) that the system constraints of the satellite broadcasting service may affect the efficiency with which the fixed satellite service frequency bands are used for links between fixed stations,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the frequency bands allocated to the fixed satellite service (Earth-to-space) that should preferably be used for the connection of broadcasting satellites, taking into account the frequency band in which these satellites send their emissions, and where applicable, determination of the recommended frequencies in these bands;

2. the technical characteristics, e.g. frequency deviation and pre-emphasis consideration, and utilization principles to be recommended for these paths, taking into account the special requirements of the broadcasting satellite-service;

3. the extent to which paths for the connection of broadcasting satellites (i.e. Earth-to-space path) can share a frequency band with other Earth-to-space or space-to-Earth paths of the fixed satellite service, taking into account the requirements and constraints arising in the two types of systems, and determination of the sharing conditions.

Note 1. — This Study Programme is brought to the attention of Study Groups 1, 10 and 11, and the results of any such studies should also be presented to these Study Groups.

Note 2. — See Reports 561-1 and 712.

STUDY PROGRAMME 2L/4

FREQUENCY SHARING BETWEEN THE RADIONAVIGATION SERVICE AND THE RADIONAVIGATION SATELLITE SERVICE ON THE ONE HAND AND THE FIXED SATELLITE SERVICE ON THE OTHER HAND OPERATING AT FREQUENCIES OF THE ORDER OF 14 GHz

(1972)

The CCIR,

CONSIDERING

§ 2.14 of Recommendation No. Spa2-15 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971,

UNANIMOUSLY DECIDES that the following studies should be carried out:

the criteria for frequency sharing between the radionavigation service and the fixed satellite service (Earth-to-Space) in the frequency band 14.0 to 14.3 GHz and also between the radionavigation satellite service and the fixed satellite service (Earth-to-Space) in the frequency band 14.3 to 14.4 GHz.

Note. — This subject is also dealt with by Study Group 8 under Study Programme 17D/8.

STUDY PROGRAMME 2M/4 *

CHARACTERISTICS OF UP-PATHS AND DOWN-PATHS IN THE FIXED SATELLITE SERVICE USED FOR THE CONNECTION OF SATELLITES IN THE MARITIME MOBILE-SATELLITE SERVICE

(1974)

The CCIR,

CONSIDERING

(a) that under the Radio Regulations the up-paths and down-paths used for connections between earth coast stations and a satellite in the maritime mobile-satellite service may belong to the fixed satellite service;

(b) that it is highly probable that frequency bands allocated to the fixed satellite service will be used for these connections in view of the narrowness of the frequency bands allocated to the maritime mobile-satellite service;

(c) that the frequencies and technical characteristics of such paths may depend on the technical characteristics of networks in the maritime mobile-satellite service but that the risks of interference with fixed satellite networks providing links between fixed points on the surface of the Earth must also be taken into account;

(d) that the system constraints of the maritime mobile-satellite service may affect the efficiency with which the fixed satellite frequency bands are used for communication between fixed stations,

* This Study Programme is brought to the attention of Study Group 8.

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the frequency bands allocated to the fixed satellite service (up-path and down-path) to be used for preference for satellite links in the maritime mobile-satellite service and, if necessary, determination of the frequencies within these bands which are recommended for this purpose;
2. determination of the technical characteristics and, if necessary, of the principles recommended for the use of these paths, having regard to the special requirements of the maritime mobile-satellite service;
3. the extent to which a frequency band can be shared between paths for satellite links in the maritime mobile-satellite service and other paths of the fixed satellite service, having regard to the requirements of, and the constraints upon, the two types of systems, and determination of the conditions of such frequency sharing.

Note. — See Report 560-1.

STUDY PROGRAMME 2N/4

INTERFACE CHARACTERISTICS FOR INTERNATIONAL DIGITAL TRANSMISSION LINKS IN THE FIXED SATELLITE SERVICE

(1976)

The CCIR,

CONSIDERING

- (a) that the CCITT suggests a demarcation line between the study of the CCITT Study Group XVIII and the CCIR Study Group 4 concerning international digital links between two countries using different primary multiplexes;
- (b) that the Digital Speech Interpolation (DSI) technique is a relevant feature of digital satellite transmission, for example, time division multiple access (TDMA), which has not been considered by the CCITT, in the study of the international digital links;
- (c) that the CCITT has established a series of interface parameters for primary and higher order multiplex systems (Recommendations G.732, G.733, G.742, G.743, G.751 and G.752);
- (d) that digital satellite links should be part of the recommended plesiochronous international digital network;
- (e) that, for a quasi-geostationary satellite, the transmission time from end-to-end of the hypothetical reference circuit may vary significantly over any interval of 12 to 24 hours and over longer periods of time due to movement of the satellite relative to the Earth,

UNANIMOUSLY DECIDES that the following studies should be carried out:

for the case in which a terrestrial digital path exists between the earth station and the transit centre:

1. determination of the best way of implementing DSI techniques with a direct digital interface;
2. determination of the location of the interface, taking into account the various possible types of transmission techniques (e.g. TDMA, TDMA/DSI, SCPC/PSK, TDM/PSK/FDMA);
3. determination of the types of higher order multiplex signals which might be transmitted on satellite links in addition to primary multiplex signals;
4. determination of quality and availability criteria (e.g. phase jitter, slips, bunched digital errors) at the relevant interfaces; and what coding/decoding techniques for error correction, if any, may be needed to meet the quality criteria for data transmission;
5. determination as to whether, for transparency and/or energy dispersal, there is a need for scrambling methods and what kind of methods may be adequate;
6. determination as to whether there is a need for coding/decoding and multiplexing/demultiplexing of signals and what methods should be used;
7. determination as to whether there is a need for "stuffing" techniques and what would be the relevant parameters (e.g. how many justification service digits would be needed);
8. determination as to whether there is a need for elastic buffering (variable time delay) to compensate time delay variations due to satellite movement and if such elastic buffering could be combined with the TDMA buffer storage;
9. determination of the type of frame structure of the direct digital interface equipment which might be adequate for primary PCM and higher order multiplex systems.

Note. — See Recommendations 521, 522, Report 707 and Opinion 56.

STUDY PROGRAMME 2P/4

CHARACTERISTICS OF INTER-SATELLITE LINKS AND THEIR EFFECT
ON CIRCUITS USED IN THE FIXED SATELLITE SERVICE

(1978)

The CCIR,

CONSIDERING

- (a) that inter-satellite links may be used extensively in the fixed satellite service;
- (b) that the use of inter-satellite links may facilitate and improve the interconnection of earth stations in the fixed satellite service, particularly in cases where it might be difficult or impossible to achieve mutual visibility with a single satellite in the geostationary satellite orbit;
- (c) that the presence of an inter-satellite link should be taken into account in the consideration of overall earth station-to-earth station performance and availability objectives, and in the design of the Earth-to-space and space-to-Earth transmission paths;
- (d) that interference is an important consideration particularly with respect to efficiency of utilization of the geostationary satellite orbit and the sharing of frequency bands with terrestrial systems;
- (e) that the satellite station-keeping and attitude tolerances and the characteristics of antenna patterns for inter-satellite links affect the level of interference between the inter-satellite links of different satellite networks in the fixed satellite service which use the same frequencies,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the purposes and conditions under which it might be necessary or desirable to employ inter-satellite links;
2. the technically preferred frequencies for inter-satellite links;
3. the modification, if any, necessary in the hypothetical reference circuit of Recommendation 352-3 to take into account the possible use of inter-satellite links;
4. the modification, if any, necessary in the circuit quality criteria of Recommendations 353-3 and 354-2 to take into account the possible use of inter-satellite links;
5. determination of the effects on transmission system characteristics of the additional transmission delay and delay variations introduced by an inter-satellite link;
6. determination of the objectives applicable to circuit availability with respect to transmission systems which include an intersatellite link;
7. criteria which affect frequency sharing between satellite networks employing inter-satellite links operating at the same frequencies;
8. determination of the extent to which the presence of an inter-satellite link affects the characteristics of the associated space-to-Earth and Earth-to-space transmission paths and consequently, the extent to which the sharing criteria with terrestrial systems and/or other satellite systems are in any way affected;
9. the optimum technique of modulation, including possible regeneration or other processing of signals in the satellites of systems employing inter-satellite links;
10. the manner in which the presence of inter-satellite links may be taken into account in assessing the efficiency of utilization of the geostationary satellite orbit.

Note. - See Report 451-2.

STUDY PROGRAMME 2Q/4 *

INTEGRATION OF SATELLITE SYSTEMS IN DATA TRANSMISSION NETWORKS

(1978)

The CCIR,

CONSIDERING

- (a) that digital satellite links should form part of the international plesiochronous digital network recommended by the CCITT;
- (b) that the transmission delay from one end of the link to the other can have a considerable effect on the transmission performance of a data network if unsuitable error-correction techniques are adopted;

* Studies carried out under this Study Programme should be co-ordinated with the work of Study Groups VII and XVII of the CCITT.

(c) that allowance should be made for the special characteristics of satellite systems in designing new international data networks,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the determination of satellite system characteristics significant for data transmission and the similarities with and differences from terrestrial networks;
2. the impact on current data networks or services of the new factors related to satellite systems, and particularly the transmission delay;
3. solutions which might offset the potential unfavourable effects of satellite systems on existing data services;
4. error-correction systems better suited to data transmission by satellite (co-ordination with CCITT Study Group XVII, Question 7/XVII is required);
5. advantages and drawbacks of satellite systems from the standpoint of interconnection with national data networks;
6. means of integrating satellite systems into international data networks;
7. high-speed services that can be provided by satellite and a comparison with the facilities offered by terrestrial networks;
8. the effect of multi-destination and multiple access satellite characteristics on data network topology.

QUESTION 7-1/4

BASEBAND TRANSMISSION VARIABILITY, DELAY, ECHOES AND SWITCHING DISCONTINUITIES IN SYSTEMS IN THE FIXED SATELLITE SERVICE

(1962 - 1963 - 1970 - 1974)

The CCIR,

CONSIDERING

- (a) that satellites at various altitudes may be used for communication purposes;
- (b) that, due to the distances to be traversed by the signals and the finite velocity of radio waves, the use of satellites for communication purposes will introduce transmission delay;
- (c) that echoes, e.g. due to impedance mismatch at 4-wire/2-wire terminations external to the satellite link, may also be present;
- (d) that transmission discontinuities, due to the switching of signals from satellite to satellite in non-synchronous satellite systems, may cause difficulties for the transmission of telephony, telegraphy, television and other signals, if the discontinuities are excessive or too frequent;
- (e) that the permissible overall transmission delays, levels of echoes, switching discontinuities, attenuation variations, frequency variations arising from Doppler and other effects, are matters for the CCITT (in the case of television, for the CMTT) to decide;
- (f) that the permissible values of transmission delay may have a marked effect on the costs of establishing and maintaining fixed satellite systems;
- (g) that, whereas high altitude satellites offer increased coverage with fewer satellites, the transmission delay would be greater than if low altitude satellites were used,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what transmission delays and switching discontinuities are to be expected in the various types of fixed satellite system;
2. what methods, within the satellite system itself, could be used to minimize or avoid transmission-delay variations and switching discontinuities in non-synchronous satellite systems;
3. what attenuation variations and residual frequency variations are to be expected in the baseband for various types of systems in the fixed satellite service;
4. which orbits are most suitable for fixed satellite systems, as regards the maximum permissible values of the transmission delay, level of echo signals and switching discontinuities for telephony, telegraphy, television and other signals, taking account of the views of the CCITT and CMTT, as appropriate?

Note. — See Reports 214-3 and 383-3.

QUESTION 13-1/4

CONTRIBUTIONS TO THE NOISE TEMPERATURE
ON AN EARTH-STATION RECEIVING ANTENNA

(1965 – 1970 – 1974)

The CCIR,

CONSIDERING

- (a) that the noise temperature of an earth-station receiving antenna includes contributions associated with atmospheric constituents such as water vapour, clouds, and precipitation;
- (b) that the use of a radome can introduce additional components into the antenna noise temperature;
- (c) that these effects can be isolated and examined when proper account is taken of all sources of receiving system noise temperature, such as solar and cosmic noise, the ground and other features of the antenna environment, man-made noise and unwanted signals, and thermal noise generated by the receiving system or noise measuring system and referred back to the antenna terminals;
- (d) that all the above contributions will be a function of frequency and elevation angle,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what contributions to the noise temperature of typical earth-station receiving antennae, with or without radomes, are introduced by:
 - 1.1 water vapour in the atmosphere,
 - 1.2 clouds,
 - 1.3 precipitation,
 - 1.4 other atmospheric constituents,
 - 1.5 the Earth,
 - 1.6 solar and cosmic noise;
2. how do these contributions vary diurnally and seasonally;
3. how do they vary with the receiving pattern of the antenna and with direction, especially with angle of elevation;
4. how can those variations of noise temperature, which are related to meteorological factors, be expressed statistically;
5. what additional contributions to the noise are caused, typically, by the use of radome, when wet and when dry, taking into account both its absorbing and its scattering properties, and also the possibility of ice accretion both with and without other matter;
6. how are these contributions expected to depend on frequency?

Note. – See Report 390-3.

QUESTION 20-1/4

OPERATION AND MAINTENANCE OF EARTH STATIONS

(1970 – 1974)

The CCIR,

CONSIDERING

- (a) that the rapid strides made in international communications via satellites have resulted in the building of earth stations in various countries;
- (b) that it would be useful to ask the international organizations, recognized private operating agencies and scientific or industrial organizations connected with satellite communications to contribute their experience to the studies to be made;
- (c) that the work so far done on this subject by the various international seminars is no doubt the most valuable initial contribution to be taken into consideration;

(d) that a comparative study of methods of measurement and remote control is desirable, in particular, to facilitate the introduction of automatic systems,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what test procedures are appropriate for the operation and maintenance of an earth station;
2. what types of test equipment are necessary to carry out these procedures;
3. what might be the characteristics of automatic measuring and remote control equipments?

Note. — See Recommendation 481-1 and Report 553-1.

QUESTION 22-1/4 *

USE OF SYSTEMS IN THE FIXED SATELLITE SERVICE IN THE EVENT OF NATURAL DISASTERS, EPIDEMICS, FAMINES AND SIMILAR EMERGENCIES FOR WARNING AND RELIEF OPERATIONS

(1972 – 1978)

The CCIR,

CONSIDERING

- (a) that rapid and reliable telecommunications are essential for relief operations in the event of natural disasters, epidemics, famines and similar emergencies;
- (b) that geostationary satellite systems can provide telecommunication services to help minimize losses resulting from these emergencies;
- (c) that, through damage or from other causes, the normal telecommunications facilities in disaster areas are often inadequate for relief operations and cannot be restored or supplemented quickly through local resources;
- (d) that the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, has adopted Recommendation No. Spa2 – 13;
- (e) that use of space radiocommunication systems is one of the means by which rapid and reliable telecommunications could be provided for relief operations;
- (f) that the cost of the equipment needed for this purpose should be minimal, but that the equipment might perform a variety of functions including voice disaster warning, field reporting, data collection and co-ordination of relief operations,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the preferred characteristics and frequency bands for transportable earth stations in the fixed satellite service to provide relief telecommunications;
2. what are the criteria to ensure compatibility between stations in the fixed satellite service and stations for relief telecommunications which might be provided by the mobile satellite service or by terrestrial radiocommunications?

Note. — See Report 554-1.

* See also Questions 22/3, 22/8 and 20/9.

QUESTION 23/4

LOW CAPACITY EARTH STATIONS AND ASSOCIATED SATELLITE SYSTEMS

(1974)

The CCIR,

CONSIDERING

- (a) Resolution 18 of the Plenipotentiary Conference, Malaga-Torremolinos, 1973;
- (b) the urgent needs of developing countries and the needs of various Administrations for the use of low capacity earth stations and associated systems;
- (c) the need to incorporate low capacity systems in the international telecommunication network;
- (d) that more information on technical and operational matters is necessary to assist in the development of economical low capacity earth stations and associated systems;
- (e) that such systems may operate in the frequency bands allocated to the fixed satellite service,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the preferred frequency bands and modulation methods for low capacity systems;
2. what are the preferred performance characteristics of earth stations and space stations for such systems;
3. what systems criteria must be defined to ensure compatibility between low capacity systems; and between future low capacity systems and existing systems in the fixed satellite service, including those for:
 - facilitating interconnection in the international telecommunication network,
 - frequency sharing and making most effective use of the geostationary-satellite orbit?

QUESTION 24/4

FIXED SATELLITE SERVICE FOR TELEPHONY AND TELEVISION

Circuit availability

(1974)

The CCIR,

CONSIDERING

- (a) that the existing Recommendations provide no objectives for circuit availability within the fixed satellite service;
- (b) that circuit availability is related to interruptions of traffic due to all causes, including those due to noise increase and attenuation due to hydrometeors;
- (c) that the degree of circuit availability has a major bearing on system design, the cost of its provision, operation and maintenance;
- (d) that protection arrangements may be used to improve circuit availability,

UNANIMOUSLY DECIDES that the following question should be studied:

1. how should the definition of circuit availability be applied to the fixed satellite service;
2. what should be the objectives for circuit availability, for current and future systems, between points defined by the hypothetical reference circuit;
3. what circuit availability is now achieved in the fixed satellite service of current design;
4. what are the important factors affecting circuit availability and, in particular, what effects are introduced by the following factors:
 - 4.1 reliability of earth stations and satellites including the effects of protection arrangements,
 - 4.2 site diversity of earth stations,
 - 4.3 solar interference,
 - 4.4 attenuation due to hydrometeors,
 - 4.5 interruptions due to extreme weather conditions,
 - 4.6 interference from other satellite networks or arising within the same satellite networks,
 - 4.7 interference from terrestrial radio-relay systems?

Note. — See Recommendation 482-1 and Report 706.

STUDY PROGRAMME 24A/4 *

INTERRUPTIONS TO TRAFFIC ON CIRCUITS IN THE FIXED SATELLITE SERVICE

(1978)

The CCIR,

CONSIDERING

- (a) that continuity of traffic on established satellite links may be interrupted by equipment failure or by natural phenomena (i.e. solar interference, attenuation due to hydrometeors);
- (b) that the interruptions may be divided into self-restoring interruptions (i.e. protection switching, hydrometeors) and interruptions which include repair time;
- (c) that site diversity and protection switching converts longer interruptions into either very brief ones or prevents complete interruptions of the link;
- (d) that existing Recommendations 353-3, 354-2 and 522 permit a high noise level or a high bit error rate during very short periods for a very small percentage of the time; that circuit availability is affected by interruptions of typically more than about 10 s and that circuit quality is affected by momentary interruptions of traffic, typically less than 10 s;
- (e) that the CCITT is being asked for advice on the level of noise and its duration which it regards as equivalent to a total interruption, and is studying the duration and frequency of occurrence of short breaks in transmission and of sudden level variations on an international telephone circuit;
- (f) that interruptions to traffic may be manifested by sudden baseband level variations, by complete loss of the wanted signal or by high noise level; or in the case of digital transmission systems, by bursts of errors;
- (g) that the need for further study concerning bursts of errors is noted in Recommendation 552;
- (h) that the CCITT in its Recommendation G.221, § (c), has pointed out the malfunctioning which can arise due to noise in fault conditions, which may then be transferred to subsequent systems and that earth station equipment may contain devices which mute receivers under conditions of extreme noise;
- (j) that, in planning a satellite link, decisions must be taken on receive signal margins, provision of site diversity and protection switching, etc., which have a major impact on the link availability and the cost of its provision;
- (k) that different service applications may have different availability requirements (i.e. demand assigned telephony, data transmission, television);
- (l) that the duration of some interruptions may depend on the configuration of the satellite network; they may also depend on whether earth stations are always attended or unattended at the onset of an interruption, and on whether or not the earth station antennae are readily steerable to point from one satellite to another;
- (m) that terms and definitions that are required in connection with these studies should, as far as possible, be based on internationally accepted expressions,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. rate of incidence and the duration of self-restoring and other interruptions to be expected in modern satellite systems between points defined by the hypothetical reference circuit;
2. for satellite links with and without site diversity protection, the proportion (in frequency and in duration) of interruptions due to propagation effects;
3. preferred characteristics (i.e. switching time) for equipment protection arrangements;
4. for satellite links with protection arrangements and/or diversity site switching, the proportion (in frequency and in duration) of short breaks in transmission due to protection and diversity switching;
5. proportion of interruptions due to maintenance including human error;
6. preferred characteristics of devices that would prevent malfunctioning of other systems connected in tandem at baseband;
7. the terms and definitions now available in the documents of several international bodies interested in terminology which are not applicable for these studies and what additional terms and definitions, if any, are required.

Note. — In carrying out studies of interruptions as they concern availability, it may be useful to distinguish between satellite networks where the earth stations are always attended and the antennae are readily steerable and other satellite networks where these conditions do not apply.

* See also Question 27/4

QUESTION 25/4 *

**SPURIOUS EMISSIONS RADIATED FROM AND RECEIVED BY EARTH STATIONS
AND SPACE STATIONS OF THE FIXED SATELLITE SERVICE**

(1976)

The CCIR,

CONSIDERING

- (a) that the radiation of spurious emissions by space stations or earth stations of the fixed satellite service could cause interference to other services;
- (b) that the radiation of spurious emissions by other services could cause interference to the space stations and/or earth stations of the fixed satellite service;
- (c) that spurious emissions by space stations or earth stations of the fixed satellite service could cause interference to other stations of the fixed satellite service;
- (d) that suppression of spurious emissions to very low levels, in particular from space stations, may involve major technical problems;
- (e) that the various radio services differ greatly in the sensitivity of their stations to interference;
- (f) 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 limit should be placed upon the power of spurious emissions radiated by space stations and earth stations of the fixed satellite service in the various frequency bands in order to protect this service and other services;
2. what level of power flux-densities resulting from spurious emissions of stations of other services is acceptable at space and earth stations of the fixed satellite service?

Note. — See Reports 712 and 713.

 QUESTION 26/4 **

**FREQUENCY SHARING BETWEEN UP-PATHS AND DOWN-PATHS USED
FOR CONNECTIONS BETWEEN EARTH STATIONS AT SPECIFIED FIXED POINTS
AND SATELLITES OF VARIOUS SERVICES**

(1977)

The CCIR,

CONSIDERING

- (a) that at present the fixed satellite service includes on an equal primary basis the feeder connections between earth stations at specified fixed points and satellites used for any service (see Radio Regulations, No. 84AG);
- (b) that the frequency allocations for the fixed satellite service, in Article 5 of the Radio Regulations, provide approximately equal bandwidth for each direction of transmission but there is in general no other differentiation between the various applications to which these bands may be put;
- (c) that some feeder connection applications are unidirectional requirements, which may make inefficient use of the bi-directional frequency allocations to the fixed satellite service;
- (d) that the emission and equipment characteristics used for feeder connections to satellites of some services are likely to be very different from those typical of the fixed satellite service, and this inhomogeneity is likely to lead to inefficient use of the spectrum and the geostationary satellite orbit;
- (e) that it may be technically and operationally desirable for all satellites of a system to use particular frequency bands for feeder connections, regardless of orbital location or date of entry into service;

 * This Question is brought to the attention of Study Groups 1, 2, 7, 8, 9, 10 and 11.

** This Question is brought to the attention of Study Groups 2, 7, 8, 10 and 11.

(f) that studies on some of these topics are already in progress, for example under Study Programmes 2K-2/4 and 2M/4, and that reference is also made in Recommendation No. Sat – 5 from the WARC on Satellite Broadcasting at 12 GHz,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the technical characteristics of model systems of the various services, and consideration of the required orbital separation between satellites of different services which share frequency bands for feeder connections;
2. what technical and operational advantages can be gained by sub-allocations within the frequency bands of the fixed satellite service, for feeder connections of specific satellite services or groups of services;
3. which technical factors could determine whether any particular part of the frequency spectrum would be unsuitable for feeder connections to satellites of any particular service, for example:
 - 3.1 proximity to other frequency bands used by such satellites;
 - 3.2 the effect of propagation conditions on the performance of the service;
4. what other technical or operational factors should the WARC-1979 take into account in considering frequency allocations for feeder connections?

Note. – See Report 561-1.

QUESTION 27/4

SHORT BREAKS IN TRANSMISSION IN THE FIXED SATELLITE SERVICE FOR TELEPHONY AND TELEVISION

(1978)

The CCIR,

CONSIDERING

- (a) that the existing Recommendations provide no objectives for the duration and frequency of occurrence of short breaks in transmission, of short duration bursts of errors or of sudden baseband level variations within the Fixed Satellite Service;
- (b) that short breaks in transmission may be attributable to several causes including noise increase and attenuation due to hydrometeors, protection switching, diversity site switching and power supply transients;
- (c) that earth station equipment may contain devices which mute receivers under conditions of extreme noise or loss of carrier signal;
- (d) that short breaks in transmission and/or bursts or errors may cause loss of synchronization in digital transmission systems,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what should be the objectives for the duration and frequency of occurrence of short breaks in transmission, of short duration bursts of errors and of sudden baseband level variations, for current and future systems, between points defined by the hypothetical reference circuit;
 2. what statistical duration and frequency of occurrence of short breaks in transmission, of short duration bursts of errors and of sudden baseband level variations is now achieved in the Fixed Satellite Service of current design;
 3. what are the important factors affecting short breaks in transmission, short duration bursts of errors and sudden baseband level variations and in particular, what effects are introduced by the following factors:
 - 3.1 protection arrangements;
 - 3.2 diversity site switching;
 - 3.3 power supply transients;
 - 3.4 attenuation due to hydrometeors;
 - 3.5 short interruptions due to extreme wind and/or weather conditions;
 - 3.6 interference from other satellite networks or arising within the same satellite network;
 - 3.7 interference from terrestrial radio-relay systems?
-

DECISION 2-2

FREQUENCY SHARING BETWEEN RADIOCOMMUNICATION SATELLITES

Technical considerations affecting the efficient use
of the geostationary satellite orbit

(Study Programme 2J-2/4)

(1970 – 1974 – 1976 – 1978)

CCIR Study Group 4,

CONSIDERING

- (a) that studies on the technical factors affecting the efficient use of the geostationary satellite orbit need to be carried out urgently in view of the foreseeable congestion in certain parts of that orbit;
- (b) that the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, in Recommendation Spa2 – 15 requested that studies on a number of subjects related to this matter should be started or continued as a matter of urgency,

DECIDES

1. that Interim Working Party 4/1, established on the initiative of the Geneva Interim Meeting, 1968, should continue with the following terms of reference:
 - 1.1 to stimulate the collection when necessary and the critical analysis of relevant data needed to produce a synthesis of views on technical means of achieving the efficient use of the geostationary satellite orbit (see Study Programme 2J-2/4);
 - 1.2 to hold further meetings at such times as may be agreed;
 - 1.3 to review and consider such contributions as will have been received at the meetings of the Interim Working Party and to present reports on these contributions in a form which will best facilitate the work of Study Group 4 on this problem;
 - 1.4 to report on its work to the CCIR Special Preparatory Meeting, as well as the next meeting of Study Group 4, in case it should meet in the time between the Study Group 4 Final Meeting (October, 1977) and the SPM;
 2. that the Interim Working Party should be composed of representatives nominated (one from each Administration) by the Administrations of Germany (Federal Republic of), Australia, Canada, China (People's Republic of), United States of America, France, India, Italy, Japan, Poland (People's Republic of), United Kingdom and the U.S.S.R., together with the Chairman of Study Group 4 and an observer nominated by the IFRB;
 3. that the co-ordination of the work of the Interim Working Party, which should be conducted as far as is feasible by correspondence, and the chairmanship of the Interim Working Party be undertaken by a representative of the Administration of the United Kingdom;
 4. that the activities of the Interim Working Party should not involve any expenditure, other than normal, on the part of the ITU.
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OPINION 56

**LOCATION OF INTERFACE BETWEEN CCIR AND CCITT
RESPONSIBILITIES FOR TIME-DIVISION MULTIPLEX DIGITAL SYSTEMS
IN THE FIXED SATELLITE SERVICE**

(1978)

The CCIR,

CONSIDERING

that the CCITT Study Group XVIII (formerly Special Study Group D), in its document COM Sp.D.-No. 246, has suggested three possible CCIR/CCITT interfaces "A", "B" and "C" as indicated in Fig. 1,

IS UNANIMOUSLY OF THE OPINION

that the interface "A" is the most suitable. The reason for this is that the interworking that would exist between the Modem, the TDMA equipment and the DDIE would be complex. Therefore, the definition of the functional characteristics of all these equipments should come within the scope of a single organization and it is appropriate that CCIR should be that organization.

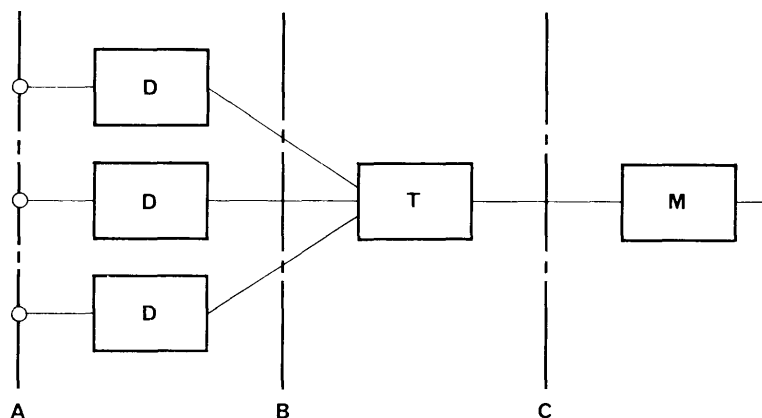


FIGURE 1 — *Alternative interface points A, B and C, between digital terrestrial network and digital satellite network proposed by CCITT in Doc. COM Sp.D-No. 246 (1973-1976)*

D: Direct digital interface equipment (DDIE)
T: Time division multiple access equipment (TDMA)
M: Modem

Note 1. — In non-TDMA systems, element T will not be present and elements D and M may be combined.

Note 2. — See Report 707 for further consideration of interface characteristics.

