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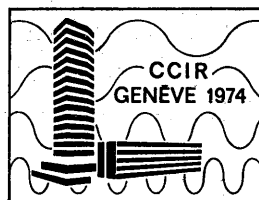
C.C.I.R.

XIIIth PLENARY ASSEMBLY

GENEVA, 1974

VOLUME IV

FIXED SERVICE USING COMMUNICATION SATELLITES
(STUDY GROUP 4)



Published by the
INTERNATIONAL TELECOMMUNICATION UNION
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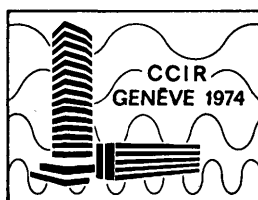
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**FIXED SERVICE
USING
COMMUNICATION
SATELLITES**

RECOMMENDATIONS AND REPORTS

4A Definitions

4B Frequencies, orbits and systems

**4C Baseband characteristics (hypothetical
reference circuit, noise, pre-emphasis,
energy-dispersal techniques, etc.)**

4D Methods of modulation and multiple access

4E Characteristics and maintenance of earth stations

**4F Sharing of frequencies between networks
of the fixed satellite service and
geostationary-satellite orbit utilization**

**4G Sharing of frequencies between the fixed
satellite service and other satellite services**

**QUESTIONS AND STUDY PROGRAMMES,
DECISIONS, RESOLUTIONS AND OPINIONS**

(Study Group 4)

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

Volumes I to XIII, XIIIth Plenary Assembly, contain all the valid texts of the C.C.I.R. and succeed those of the XIIth Plenary Assembly, New Delhi, 1970.

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 XIIIth Plenary Assembly adopted a new category of texts known as Decisions, by which Study Groups take action, generally of an organizational nature, relative to matters within their own terms of reference, particularly the formation of (Joint) Interim Working Parties (see Resolution 24-3, Volume XIII). Although the Plenary Assembly did adopt in the form of Resolutions a number of texts which fell into the category of Decisions after amendment of Resolution 24-2, these texts are published in the Volumes of the XIIIth Plenary Assembly as Decisions, for practical reasons. When one of these texts is so published, a reference to the Resolution on which the text is based, is given in parenthesis below the title.

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
45	VIII	310, 311	V	436	III
48, 49	X	313	VI	439	VIII
77	VIII	314	II	441	VIII
80	X	325-334	I	442, 443	I
100	I	335, 336	III	444	IX
106	III	337	I	445	I
139, 140	X	338, 339	III	446	IV
162	III	341	I	447-450	X
166	XII (CMV)	342-349	III	451	XII (CMTT)
182	I	352-354	IV	452, 453	V
205	X	355-359	IX	454-456	III
214-216	X	361	VIII	457-460	VII
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224	VIII	368-370	V	462, 463	IX
237	I	371-373	VI	464-466	IV
239	I	374-376	VII	467, 468	X
240	III	377-379	I	469-472	XI
246	III	380-393	IX	473-474	XII (CMTT)
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265, 266	XI	417-418	XI	480	III
268	IX	419	X, XI	481-484	IV
270	IX	421	XII (CMTT)	485, 486	VII
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283	IX	427-429	VIII	497	IX
289, 290	IX	430, 431	XII (CMV)	498, 499	X
302	IX	433	I	500, 501	XI
305, 306	IX	434, 435	VI	502-505	XII (CMTT)

1.3 Reports

Number	Volume	Number	Volume	Number	Volume
19	III	275-282	I	424-426	V
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79	X	294	XI	433-437	III
93	VIII	298-305	X	438, 439	VII
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109	III	311, 312	XI	441	XII (CMV)
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203	III	361	VIII	495-498	XII (CMTT)
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215	IX	374-382	IX	516	X
216	VIII	383-385	IV	518	VII
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226	II	390, 391	IV	535-548	II
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241	V	398-401	X	571-575	VI
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				650	XII (CMV)

(¹) Published separately.

1.4 Decisions

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2	IV	12-14	VII	18	XII (CMTT)
3-5	V	15	VIII	19, 20	XII (CMV)
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1.5 Resolutions

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15, 16	I	26, 27	XIII	59	X
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1.6 Opinions

Number	Volume	Number	Volume	Number	Volume
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11	I	32	I	47, 48	VII
13, 14	IX	34, 35	I	49	VIII
15, 16	X	36	VII	50	IX
22, 23	VI	38-40	XI	51, 52	X
24	VIII	41	XII (CMTT)	53, 54	XI
26-28	VII	42, 43	VIII	55	XII (CMTT)
		44	I		

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 8 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.

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

(Geneva, 1974)

- VOLUME I** Spectrum utilization and monitoring (Study Group 1).
- VOLUME II** Space research and radioastronomy (Study Group 2).
- VOLUME III** Fixed service at frequencies below about 30 MHz (Study Group 3).
- VOLUME IV** Fixed service using communication satellites (Study Group 4).
- VOLUME V** Propagation in non-ionized media (Study Group 5).
- VOLUME VI** Ionospheric propagation (Study Group 6).
- VOLUME VII** Standard frequency and time-signal services (Study Group 7).
- VOLUME VIII** Mobile services (Study Group 8).
- VOLUME IX** Fixed service using radio-relay systems (Study Group 9). Coordination and frequency sharing between systems in the fixed satellite service and terrestrial radio-relay systems (subjects common to Study Groups 4 and 9).
- VOLUME X** Broadcasting service (sound) including audio-recording and satellite applications (Study Group 10).
- VOLUME XI** Broadcasting service (television) including video-recording and satellite applications (Study Group 11).
- VOLUME XII** Transmission of sound broadcasting and television signals over long distances (CMTT). Vocabulary (CMV).
- VOLUME XIII** Information concerning the XIIIth Plenary Assembly.
Structure of the C.C.I.R.
Complete list of C.C.I.R. texts.

Note. — To facilitate reference, page numbering is identical in all three versions of each Volume, that is, in English, French and Spanish.

VOLUME IV *

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FIXED SERVICE USING COMMUNICATION SATELLITES

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* Although the working documents mentioned in this Volume bear the reference "Period 1970-1973" for documents published during 1971 and 1972 and "Period 1970-1974" for those published during 1973 and 1974, they are, of course, all documents of the period 1970-1974, between the Plenary Assembly of New Delhi and that of Geneva. For this reason, all references to these documents in this Volume take the form "Period 1970-1974".

** In this Volume, Recommendations and Reports dealing with the same subject are collected together. These texts are numbered in such a manner that they cannot be presented in numerical order and at the same time, in numerical sequence of pages. Consequently, this index, in numerical order of texts, does not follow the numerical sequence.

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RESOLUTIONS

There are no Resolutions concerning the work of this Study Group.

OPINIONS

There are no Opinions concerning the work of this Study Group.

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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).

Chairman: W. KLEIN (Switzerland)

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

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 4

Since the last Plenary Assembly of the C.C.I.R., New Delhi, 1970, telecommunications by satellite have expanded to all parts of the globe, new satellite systems with high capacities became operational and the number of participating earth stations and countries is growing rapidly. System reliability and economy, which were surprisingly good from the start, hardly ten years ago, are continuously improving. Operational flexibility and freedom of access on a global scale, never before attained by any communication system, guarantee an increasing interest in the fixed satellite service for communications over great distances in the near and far future. Competition with modern submarine cables on certain trunk-lines may, on the other hand, incite equipment builders to seek still better and more economical solutions.

1. General activity

The first period of activity of Study Group 4 since New Delhi was marked by the World Administrative Radio Conference for Space Telecommunications, 1971, and the preceding Special Joint Meeting in Geneva of C.C.I.R. Study Groups on space communications. Our efforts were then concentrated mainly on frequency-sharing and coordination problems and on how to make the best use of the available frequency spectrum, taking account of all relevant technical and operational factors and including frequencies well above 10 GHz which had been little used heretofore.

Two regular Study Group 4 meetings were held subsequently in Geneva (July, 1972 and February, 1974) during which account was taken of the relevant texts approved by the Special Joint Meeting and the World Administrative Radio Conference for Space Telecommunications, 1971, and some 200 new contributions were submitted by member countries and associated organizations. In the end, all but five existing texts were updated or completely redrafted, ten were deleted or transferred to other Study Groups and twenty-four new texts worked out.

2. State of progress

As is shown below, good progress was achieved in the most important fields of activity.

- Assessment of interference probabilities and determination of coordination distances, based on different geographical regions, path structures and on three distinct propagation modes (including hydrometeor-scatter). Two extensive revisions of the relevant Reports (Reports 382-1 and 448) have been undertaken, one on the occasion of the Special Joint Meeting, the other during the

Interim Meeting of Study Group 4 in 1972, and much effort was spent to make their application easier and more lucid. However, it was not possible to take full account of the latest and, to some extent, very important propagation data — which became known just during the Final Meeting.

- Assessment and synthesis of technical and operational factors influencing the efficient use of the geostationary-satellite orbit. A preliminary, though not yet entirely successful, attempt was made to define a quantitative measure of the efficiency of orbit use. Further studies are a matter of great importance.

- Assessment of technical and operational factors for the development and planning of systems in shared frequency bands above 10 GHz. More detailed data on hydrometeor propagation effects and their distribution in time and space are still required and are of prime importance for planning such systems. Deeper studies for determining an optimum antenna size or the best obtainable figure of merit, G/T , would be equally useful.

- Improved methods of modulation and multiple access, with particular regard to digital systems and techniques for reducing overall spectrum occupation and interference probability, for example by means of energy dispersal, special coding methods, coherent detection, speech interpolation. Some assumptions made require verification. Future progress, especially with TDMA-techniques, seems possible.

- Improved antenna characteristics with respect to unwanted radiation, for earth stations and satellites, for example by means of better side-lobe suppression, pit-shielding and shaped spot-beams. More information is required on these topics and, in particular, the near-field configuration of large antennae needs to be studied.

- New antenna concepts and constructions are being developed which may allow for better use of the available frequency spectrum by multi-frequency excitation of one antenna, by the use of cross-polarized fields or by the use of multiple spot-beams from a single satellite in identical frequency bands. These studies are still in their initial stages and considerable effort will be required if conclusive and generally applicable results are to be obtained.

- A start was made in standardizing earth-station maintenance and measuring techniques (performance and noise measurement in the baseband), but much remains open for future action. No proposals have been received so far by the C.C.I.R. in the field of satellite tracking, telecommand and telemeasuring methods, which of course do call for a minimum of international coordination.

3. New issues

A considerable number of existing texts have been fundamentally and extensively revised in the light of new knowledge and experience with regard to various system aspects and concepts, frequency sharing with other services and among similar and dissimilar satellite services, and with regard to the most economical use of the geostationary-satellite orbit, as well as the available frequency spectrum.

Apart from this, a series of new texts was produced on subjects which are either new or considered to be particularly important or urgent at this stage. They concern the following items:

3.1 *New frequency-sharing and associated operational problems arising from the decisions taken at the World Administrative Radio Conference for Space Telecommunications, 1971*

3.1.1 Sharing criteria and protection measures between the fixed satellite service and the radio-navigation services in the frequency band 14.0 to 14.4 GHz

Study Programme 2L/4
Report 560
Recommendation 496.

3.1.2 Use of the fixed satellite service frequency bands for the connection of satellites in the maritime mobile service

Study Programme 2M/4.

3.1.3 Use of the fixed satellite service Earth-to-space path for the connection of satellites in the broadcasting service

Study Programme 2K-1/4
Report 561.

3.2 *Efficient use of the geostationary-satellite orbit and the available frequency spectrum*

3.2.1 Station-keeping tolerances, their importance, technical feasibility and recommended limits

Report 556
Recommendation 484.

3.2.2 Use of frequency bands in the fixed satellite service for both the up-path and down-path studies on the feasibility and potential advantages and disadvantages

Report 557.

3.2.3 Interdependence of modulation characteristics, interference immunity and efficiency of use of the geostationary orbit

Report 559.

3.2.4 Use of frequency bands above 10 GHz, propagation problems due to hydrometeors and its effect on system design and planning

Report 552.

3.3 *Improved antenna characteristics, new antenna concepts*

The need for improved radiation characteristics for both earth-station and satellite antennae is stressed. Theoretical and experimental studies on the use of cross-polarized fields, multiple frequency bands and multiple beams in one single antenna are proposed and partly discussed. Such measures may become extremely important in the future, when satellites in certain segments of the geostationary-satellite orbit become crowded; the efficiency of use may then be very substantially increased.

3.3.1 Earth-station antennae

Study Programme 1A-1/4 (radiation diagrams)
Study Programme 1C/4 (general characteristics).

3.3.2 Satellite antennae

Study Programme 1B/4 (radiation characteristics)
Report 558 (radiation characteristics).

3.3.3 Use of linear or circular cross-polarization

Report 555.

- 3.4 *Operational and maintenance problems* with earth stations have received some attention in Study Group 4 for the first time; the C.C.I.T.T. has also urged the study of reliability and circuit availability and Study Group 4 has prepared a new Question on this subject.

Question 24/4 (circuit availability)
Report 553 (operation and maintenance)
Recommendation 481 (noise measurement)
Recommendation 482 (performance measurement).

- 3.5 *Low-capacity systems and transportable earth stations*

Following Recommendation No. Spa2-13 of the World Administrative Radio Conference for Space Telecommunications, 1971, and Resolution No. 18 of the Plenipotentiary Conference, Malaga-Torremolinos, 1974, two new Questions and one new Report have been set up:

Question 22/4 (transportable earth stations for relief actions)
Report 554 (preliminary discussion on Question 22/4)
Question 23/4 (low-capacity systems).

- 3.6 *Interference noise in a frequency-modulation television satellite link caused by other systems*

Recommendation 483.

4. Other matters and comments

- 4.1 *Decision 2 (Revision of Resolution 56) (Interim Working Party 4/1)*

Interim Working Party 4/1 held three meetings — Ottawa 1969, London 1970, Melbourne 1973 — and produced most useful material with regard to the efficient use of the geostationary-satellite orbit.

There was unanimous agreement that Interim Working Party 4/1 should continue its studies. The majority also felt that it might be beneficial for the future work to restrict in some way the range of subjects, so as to place more emphasis on a generalized system approach. Accordingly, the terms of reference have been slightly modified.

- 4.2 *Texts requiring revision*

Reports 382-2 and 448-1 dealing with determination of coordination distance and interference calculation in shared frequency bands, do not reflect the technical progress of 1974, but that of 1972, at which time they were entirely revised. The reason for this lies in the fact that new and important propagation data became available just during the Final Meeting and there was no time left for a profound evaluation and the subsequent refinement of the methods proposed in these Reports.

There was general agreement on the urgent need for early revision of these Reports. A higher occurrence probability of low transmission loss in certain conditions, such as mixed land-sea paths, was mentioned in particular.

A considerable amount of new propagation data has become available in the new and partly revised documentation of Study Group 5, whose Interim Working Party 5/2 will be convened in 1975, and it is to be expected that a revised version of the propagation sections of Reports 382-2 and 448-1 will be proposed to Study Group 4.

- 4.3 *Transportable earth stations* for emergencies and low-capacity satellite communication systems are of particular interest to the developing countries. The need for contributions to the new Questions 22/4 and 23/4 is therefore recalled and underlined here.
-

SECTION 4A: DEFINITIONS

RECOMMENDATIONS AND REPORTS

Recommendations

There are no Recommendations in this section.

Reports

REPORT 204-3 *

TERMS AND DEFINITIONS RELATING TO SPACE RADIOCOMMUNICATIONS

(1963 – 1966 – 1970 – 1974)

Terms and definitions concerning space systems, services and stations are included in the Radio Regulations (1972 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.

* Adopted unanimously.

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 it 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 coordinate 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.

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 coordinate 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 a 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.

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 of 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.

SECTION 4B: FREQUENCIES, ORBITS AND SYSTEMS

RECOMMENDATIONS AND REPORTS

Recommendations

There are no Recommendations in this section.

Reports

REPORT 205-3 *

**FACTORS AFFECTING THE SELECTION OF FREQUENCIES FOR
TELECOMMUNICATIONS WITH SPACE STATIONS**

(Questions 2-2/4, 34-1/10, 23-1/11, 2-1/2, 4/2, 5-1/2, 7-1/6
and Study Programmes 5C-2/5 and 18B-1/6)

(1959 – 1963 – 1966 – 1970 – 1974)

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.

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 Report 564 and Report 234-3) and of Study Group 6 (particularly Report 263-3) 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.

* Adopted unanimously.

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 theoretical one-way attenuation relative to free-space between 1 and 100 GHz for earth-normal and earth-tangential propagation paths for various relative humidities. A "clear" atmosphere (free from hydrometeors) is assumed. For more details see Figs. 3 and 4 of Report 234-3.

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.

All attenuation effects are more severe for signals arriving at low angles of elevation due to the greater path length traversing the atmosphere.

2.3 *Other propagation effects*

A number of other factors can be related with 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 263-3).

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 Report 234-3 and in Report 564.

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 234-3.

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 390-2).

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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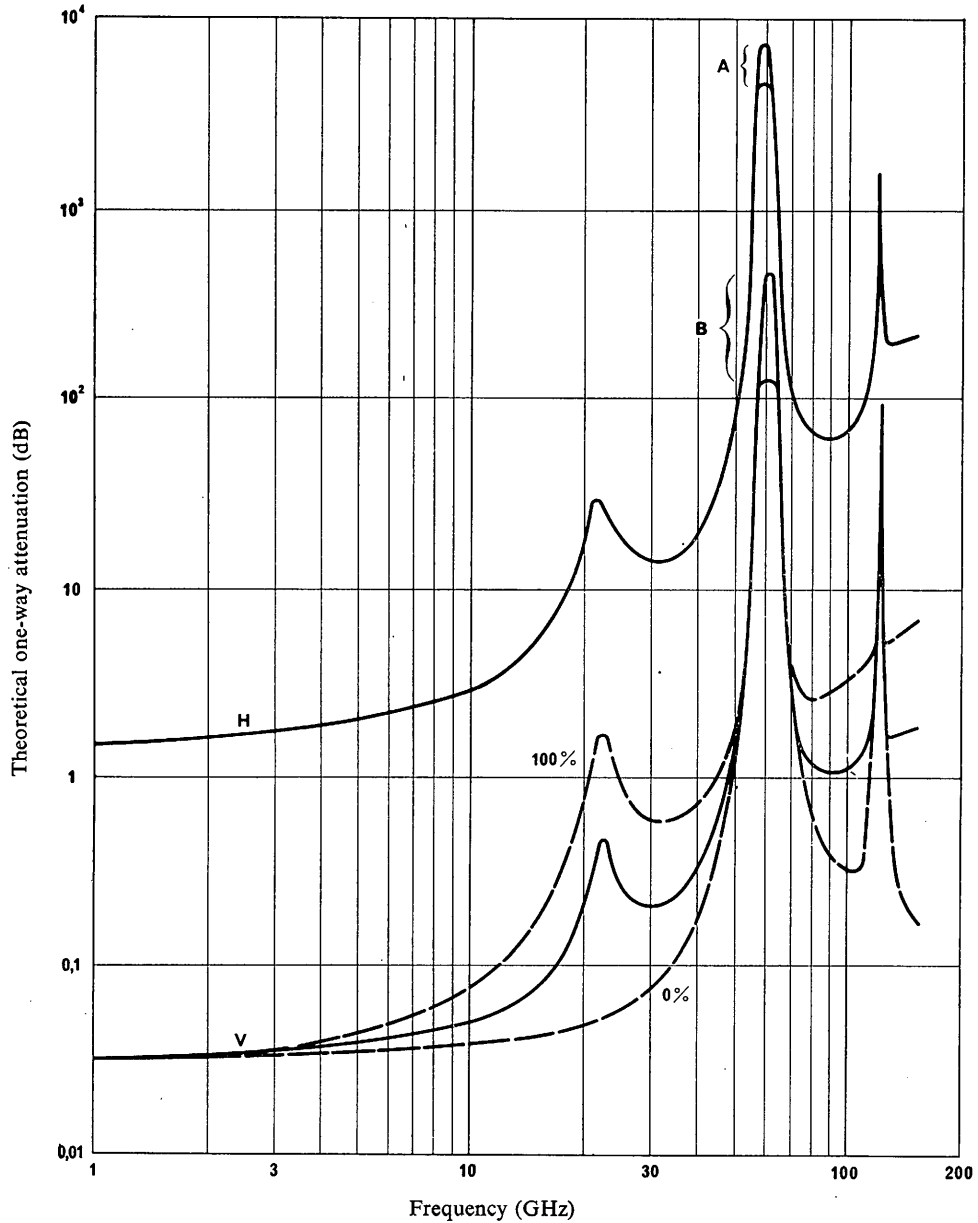


FIGURE 1

Theoretical one-way attenuation for vertical and horizontal 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 | H: Horizontal |
| B: Limits of uncertainty | V: Vertical |

REPORT 206-3 *

**TECHNICAL CHARACTERISTICS OF SYSTEMS IN THE
FIXED SATELLITE SERVICE**

General considerations relating to the choice of orbit parameters

(Question 2-2/4)

(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);

* Adopted unanimously.

- 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 383-2) 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-1/4 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.

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 390-2). 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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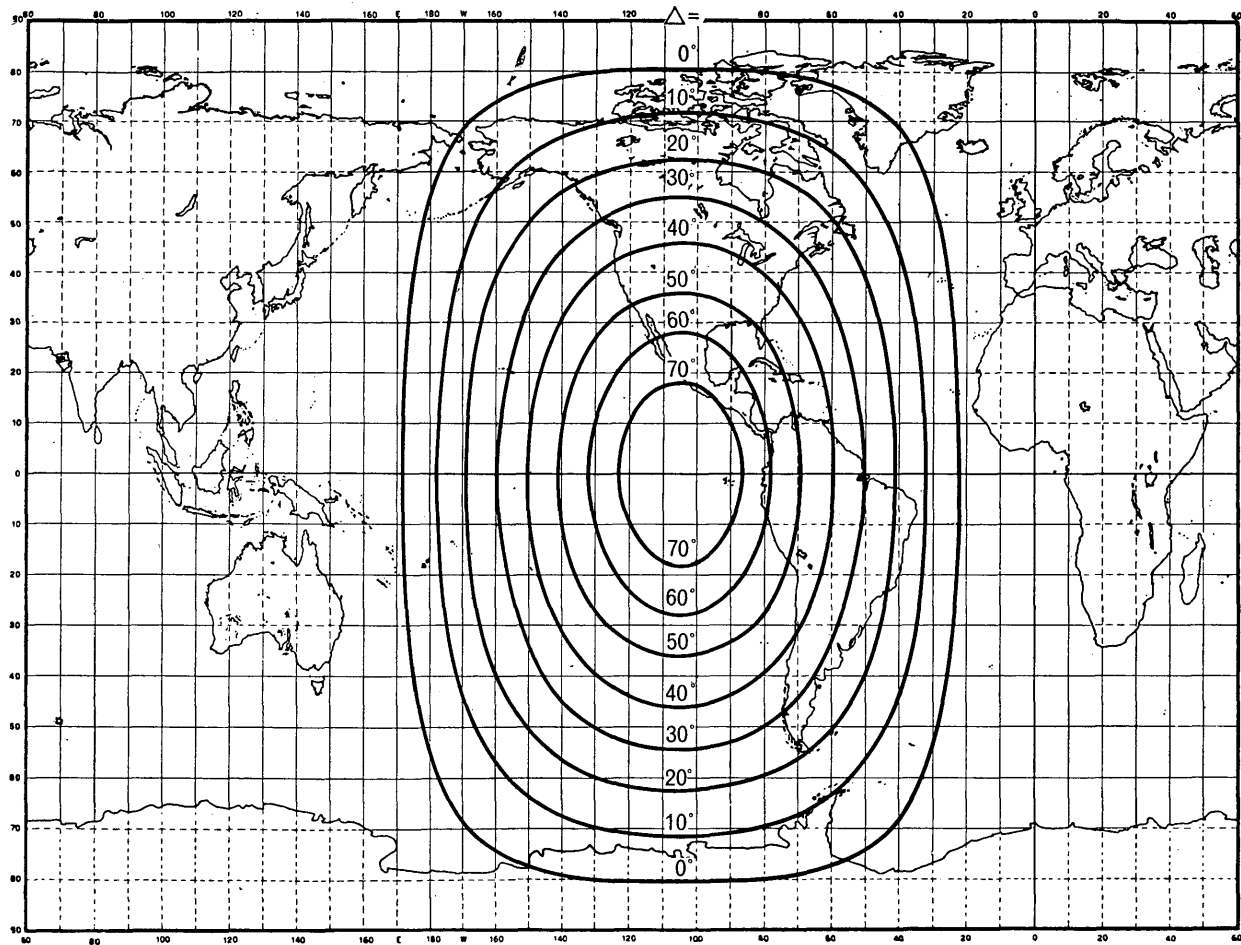


FIGURE 1

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

REPORT 207-3 *

ACTIVE COMMUNICATION-SATELLITE SYSTEMS

Characteristics of experimental and operational systems

(Question 2-2/4)

(1963 – 1966 – 1970 – 1974)

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 satellite systems initiated subsequently.

2. Early satellite projects

Active communication-satellite experiments prior to January 1965 were SCORE [IRE, 1960], COURIER [Ratcliffe, 1961], TELSTAR [B.S.T.J., 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 as part of an experimental 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 first of the INTELSAT IV series of space stations was put into service in March 1971 and, in connection with additional space stations of this type and supplemented by space stations of the INTELSAT III type, provided for high capacity traffic in each of the three Ocean regions. The next generation of space station to overlap with the INTELSAT IV service period is the INTELSAT IV-A series (initial service about 1975).

The up-link frequencies are at 6 GHz and the down-link frequencies are at 4 GHz.

* Adopted unanimously.

3.2 *The satellites*

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

TABLE I
Spacecraft data

	INTELSAT			
	I	II	III	IV
Mass (kg) in orbit	39	83	127	700
Size (cm): diameter	73	142	142	240
height	59	67	104	530
Number of repeaters	2	1	2	12
Bandwidth of repeater (MHz) .	25	125	225	40
Total bandwidth used (MHz) .	50	125	450	480
Total e.i.r.p. (dBW)	13	15.5	25.8	26/37 (1)
Polarization	Linear	Linear	Circular	Circular
First launch of series	6.4.65	11.1.67	18.12.68	26.3.71

(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.

3.3 *Earth stations*

The initially small number of earth stations has now increased considerably, with stations in operation on all continents. Many more earth stations are planned.

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 and ORBITA satellite systems**4.1 *System MOLNIYA-I* [Fortuchenko, 1965; Sviiazizdat, 1965; C.C.I.R., 1963-1966]4.1.1 *The satellite*

The first satellite MOLNIYA-I was launched in an elliptical orbit on 23 April 1965.

Spacecraft and initial orbit data

Altitude of apogee (km)	40 000 (above Northern hemisphere)
Altitude of perigee (km)	500 (above Southern hemisphere)
Inclination	65°
Approximate period	12 h
Transmitted power output	40 W
Satellite antenna gain (the antenna is directed automatically towards the Earth)	18 dB

4.1.2 *Earth stations*

There are stations in Moscow and Vladivostok separated by a distance of about 7000 km. These stations have the following technical characteristics:

Transmitter power output	5 kW
Noise temperature of the receiving system (with antenna noise)	230 K
Type of operation: television, multi-channel telephony, telegraphy and phototelegraphy services.	

4.1.3 *Experimental results*

4.1.3.1 A large number of experimental and commercial telephone calls were made from Moscow to Vladivostok and vice versa.

The quality of the communication service was good. Transmission delay gave rise to no significant degradation.

4.1.3.2 Black-and-white television transmission quality was adequate.

4.1.3.3 Colour television transmissions were made using the SECAM-III system from Moscow to Paris, and similarly from Paris to Moscow, through earth stations near Moscow and Pleumeur-Bodou (appropriate modifications were made to the equipment at Pleumeur-Bodou). The transmissions showed quite satisfactory results [C.C.I.R., 1963–1966].

4.2 “Orbita” distribution system [Talizin *et al.*, 1967]

4.2.1 *Description of the 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 the sound by means of the above-mentioned method, as well as newspaper pages, central broadcasting programmes either instead of the television signal or simultaneously with it.

4.2.2 *Satellites*

MOLNIYA-I satellites are used in the “Orbita” system; their parameters are given in § 4.1.

4.2.3 *Earth stations*

Earth stations have the following parameters:

Output power of the transmitter	5 to 10 kW
Diameter of transmitting antenna	25 or 12 m
Noise temperature of the receiver (with antenna noise)	100 K
Diameter of receiving antenna	12 m with an effective area S of 79 m ²

4.2.4 *Results*

The “Orbita” system has been in regular operation since November 1967. The number of receiving stations in 1969 exceeded 30 and new stations are under construction.

Qualitative indices of television images at the output of the receiving earth station meet C.C.I.R. standards, except that of the weighted r.m.s. noise, which, in relation to the peak-to-peak video signal, constitutes 45–48 dB.

4.3 *System MOLNIYA-II* [Kurakov and Petrov, 1972]

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 are in conformity with the appropriate C.C.I.R. Recommendations.

4.3.1 *The satellites*

The characteristics of the satellites in the MOLNIYA-II system are the same as those given in § 4.1.1.

4.3.2 *Earth stations*

In 1974 this system incorporates 45 earth stations. The earth stations have the same characteristics as those given in § 4.2.3, and are designed to operate with satellites in both the elliptical and the geostationary orbit.

5. **TELESAT satellite system [I.T.U., 1973]**

5.1 *Description of the system*

The Canadian domestic system was put into service in 1973 by TELESAT Canada to provide television, radio programme distribution and message communications throughout Canada. The system has in service at present two satellites and 40 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.

5.2 *The satellite*

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 $3^\circ \times 8.5^\circ$

5.3 *Earth stations*

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

6. **Applications technology satellite project**

6.1 *The satellites*

The initial applications technology satellite (ATS) programme includes five 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).

The fourth and fifth ATS 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. The last satellite, ATS-E, was launched 12 August 1969 and is now in geostationary orbit. The purpose of the ATS programme is to investigate new and advanced spacecraft stabilization technology, and to conduct experiments in several discipline areas including communications. The in-orbit mass of the satellites is in the range of 280 to 350 kg. The diameter of all five is approximately 145 cm; the length varies between 135 and 180 cm.

The sixth and seventh ATS satellites are now in the design and planning stages.

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 communications equipment and the telemetry and command equipment are nearly identical at the three stations. 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. The principal characteristics of the three prime stations are shown in Table II.

TABLE II
Supporting earth terminals

	Rosman	Goldstone	Cooby Creek
Type of antenna	Parabolic reflector	Parabolic reflector	Parabolic reflector
Diameter	26 m (85 ft)	12 m (40 ft)	12 m (40 ft)
Type of feed	Cassegrain or prime focus	Cassegrain	Cassegrain
Mount	X-Y	X-Y	Az-El

6.3 *Summary of experiments*

The ATS programme includes experiments in the areas of communications, mutation sensing, gravity-gradient and spin stabilization, attitude control at both high and low thrust levels, meteorology, navigation, and space environment measurements. Interim results of these experiments are given in C.C.I.R. Docs. IV/55 and IV/69 (United States of America) 1966–1969.

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REPORT 214-2 *

SYSTEMS IN THE FIXED SATELLITE SERVICE

The effects of Doppler frequency-shifts and switching discontinuities

(Question 7-1/4)

(1963 - 1966 - 1974)

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.

* Adopted unanimously. Should be read in conjunction with Report 383-2.

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:

$$\Delta F \approx \pm 3.0 \times 10^{-6} \times F \times s$$

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

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

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.

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
Minimum elevation of antenna: 5° 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.

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 C.C.I.T.T. 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 C.C.I.T.T. 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 acceptable small values.

The first of these methods has the advantage that it would effectively cancel 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 a satellite to the next one 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 C.C.I.T.T. 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 C.C.I.T.T. 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 C.C.I.T.T. 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 done 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 *. 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.

* DALGLEISH, D. I. and JEFFERIS, A. K. Some orbits for communication-satellite systems affording multiple access. *Proc. I.E.E.*, Vol. 112, 1, 21-30 (January, 1965).

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 relations which are explained in Report 383-2 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 C.C.I.T.T. No. 5 and TASI. Signalling techniques, such as C.C.I.T.T. 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 [T.A.T., 1955; 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 C.C.I.T.T. 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 C.C.I.T.T. 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 should 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 C.C.I.T.T. 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 C.C.I.T.T. 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 C.C.I.T.T. with regard to telephony, telegraphy, phototelegraphy and data transmission and the CMTT for television transmission, including the related sound channel.

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ANNEX I

1. C.C.I.T.T. Recommendations

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

C.C.I.T.T. 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 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 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 centring 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 substantially to 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, although 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-transmit 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 other type of link liable to introduce a relatively large number of telegraph errors.

REPORT 383-2 *

SYSTEMS IN THE FIXED SATELLITE SERVICE

The effects of transmission delay

(Question 7-1/4)

(1966 - 1970 - 1974)

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.

* Adopted unanimously. Should be read in conjunction with Report 214-2.

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:

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

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

$$t_{min} = 2h/c$$

and

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

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 C.C.I.T.T. Recommendation G.114):

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

or

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

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
Between earth stations	74	109	92	92	128	110	240	280	260
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 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.

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 Variation 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 214-2.

The variation in transmission delay is of particular importance in systems employing time division for multiple access (TDMA systems).

In such (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, Δ_τ , is

$$\Delta_\tau = \tau_B - \tau_A$$

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 Doc. IV/226 (Canada), 1963–1966.)

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 (2)
$V\Delta_\tau$ 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 $1/8000$ sec., 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.

In the TDMA system, all earth stations transmit on the same 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.

3. Telephony

3.1 *Transmission delay and echo*

Several series of subjective tests have been carried out by members of the C.C.I.T.T., 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 C.C.I.T.T. IVth Plenary Assembly, Mar del Plata, 1968.

The pertinent Section of C.C.I.T.T. Recommendation G.114 in Green Book, Vol. III-1, Geneva, 1972, 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 C.C.I.T.T. 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 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	3	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. In respect to terrestrial extensions of satellite circuits, the C.C.I.T.T. 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 C.C.I.T.T. Study Group XVI Contribution No. 37 (1964-1968), 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 C.C.I.T.T. 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 sometimes significant, such as when automatic error correction must be 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 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.

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 C.C.I.T.T. 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 C.C.I.T.T. 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 C.C.I.T.T. 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 C.C.I.T.T. 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 encountered on other transmission media. For television with an accompanying sound channel, which is the usual case, precautions will be required to see 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 C.C.I.T.T., 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 C.C.I.T.T. (see C.C.I.T.T. Green Book, Vol. III-1, Geneva, 1972).

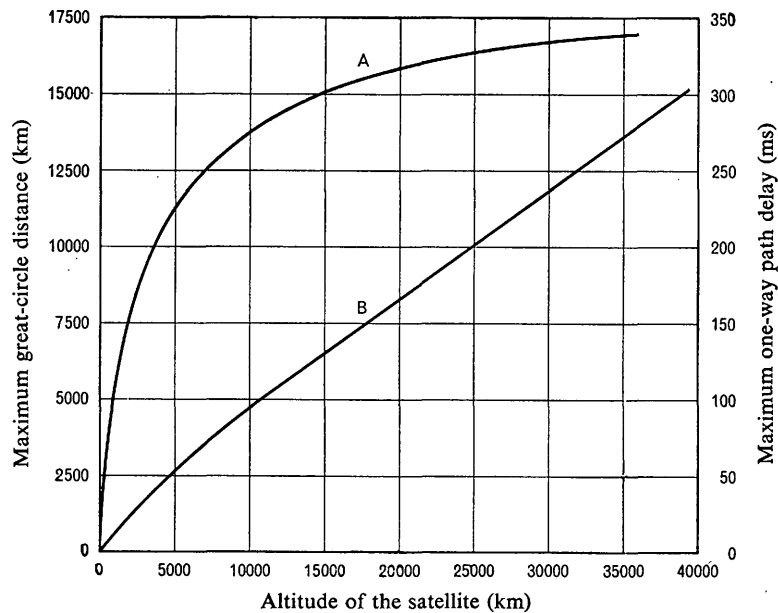


FIGURE 1

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

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

REPORT 451-1 *

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

(Question 2-2/4)

(1970 - 1974)

1. Introduction

The choice of frequencies for radio links between spacecraft is determined largely by limitations on the spacecraft antennae as determined by the spacecraft mission, and by cosmic noise. When using simple omnidirectional antennae, solar noise is an important limiting factor. Three configurations are considered. The simplest uses omnidirectional antennae on both spacecraft. The second has directional antennae on one of the spacecraft and the most advanced has directional antennae on both.

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 30 MHz to 300 GHz is considered in this Report.

For spacecraft-to-spacecraft communications, the controlling factors on system noise are cosmic and receiver noise. Cosmic noise decreases somewhat more rapidly than the square of the frequency as shown in Report 390-2 or Report 322-1. If the spacecraft are in the vicinity of the Moon, the Earth, or the other planets, the temperature and masking effects of these bodies must be included.

* Adopted unanimously.

In calculating received power-levels for these systems, use can be made of the free-space propagation formula.

2. Omnidirectional antennae on both spacecraft

For the particular case of omnidirectional antennae on both spacecraft, the frequency variation of signal-to-noise ratio for receiver noise temperatures of 300 K and 1500 K is shown in Fig. 1. It is seen that for this configuration, there is a broad optimum operating region extending from about 30 MHz to 150 MHz or more, the low-frequency limit being determined by cosmic noise. Much lower spacecraft receiver noise temperatures than those considered may eventually be achieved.

3. Directional antennae on one spacecraft

If directional antennae are used on the spacecraft, it is obvious that these antennae will require high angular stability to ensure that angular motions will be small compared with the antenna beamwidth. Also, depending on the difficulty of search, acquisition, and tracking of the signal being received, the beamwidth of the antenna may have to be larger than that determined only by spacecraft stability and maximum permissible antenna area. Thus, both the gain and antenna area may be limited. Under these conditions, a particular transition frequency f_t , above which the system gain is limited by the minimum acceptable beamwidth and below which it is limited by the maximum area of the antenna, may be defined by the following relation:

$$\lambda_t^2 = \frac{c^2}{f_t^2} = \frac{4\pi A_m}{G_m}$$

where A_m = maximum permissible antenna area;

G_m = maximum permissible antenna gain, relative to an isotropic antenna;

λ_t = free-space wavelength corresponding to the transition frequency.

The transition frequency, f_t , is the one frequency at which the maximum permissible values of both antenna area and antenna gain may be used.

Fig. 2 is a nomogram illustrating this relationship between maximum antenna area (A_m), maximum antenna gain (G_m), and the transition frequency. Paraboloidal antenna diameters corresponding to the physical antenna area and approximate half-power beamwidths for pencil-beam antennae as a function of antenna gain are also included. Based on the approximate relative gain = 30 000 divided by beamwidth squared [Westman, 1968] these beamwidths are applicable only below 20° and assume negligible power in the side lobes.

Curves illustrating available signal-to-noise ratios are shown in Fig. 3 for a directional antenna on one of the spacecraft and an omnidirectional antenna on the other. Above the transition frequency, the received signal decreases as the square of the frequency because of the beamwidth limitation. Below this frequency, the curves are controlled as before by the receiver noise temperature and the frequency variation of cosmic noise. It is seen from the diagram that as the transition frequency is increased, the optimum frequency region tends to broaden.

4. Directional antennae on both spacecraft

For similar directional antennae on both spacecraft, the received power will decrease on each side of the transition frequency (defined in § 3 above) as the square of the frequency if one disregards noise of cosmic origin. If the antennae on the spacecraft have different physical size or beamwidth limitations, the available signal-to-noise ratio (ignoring cosmic-noise limitations) will remain constant

between the transition frequencies for the antennae systems; i.e., the signal-to-noise ratio will increase with frequency until the transition frequency of one antenna is reached, remain constant until the transition frequency of the other antenna is reached, and decrease with frequency above this frequency. For systems presently envisaged, the optimum frequencies may lie anywhere above about 1 GHz depending markedly on maximum permissible antenna areas and maximum antenna gain (minimum permissible antenna beamwidth), as determined by the angular stability of the spacecraft as well as by possible search and acquisition requirements. Fig. 4 illustrates these relationships.

5. Summary

For communication between spacecraft having omnidirectional antennae on both spacecraft, there is a broad optimum frequency region centred around about 70 MHz for spacecraft receivers with relatively high effective noise temperature (e.g. 1500 K). As the receiver noise temperature decreases, the optimum frequency shifts to slightly higher frequencies and is centred around about 100 MHz for receivers with an effective noise temperature of 300 K.

For a directional antenna on one spacecraft, the most desirable region lies above about 300 MHz to 1 GHz depending upon whether the directive antenna is directed toward the higher cosmic-noise areas. There will be a broad maximum above this lower limit depending primarily upon the maximum antenna area and the maximum antenna gain (minimum acceptable beamwidth) of the directive antenna.

For directional antennae on both spacecraft, the optimum frequency can be expected to lie above 1 GHz and will be very dependent upon the maximum antenna areas and maximum antenna gains (minimum acceptable beamwidths).

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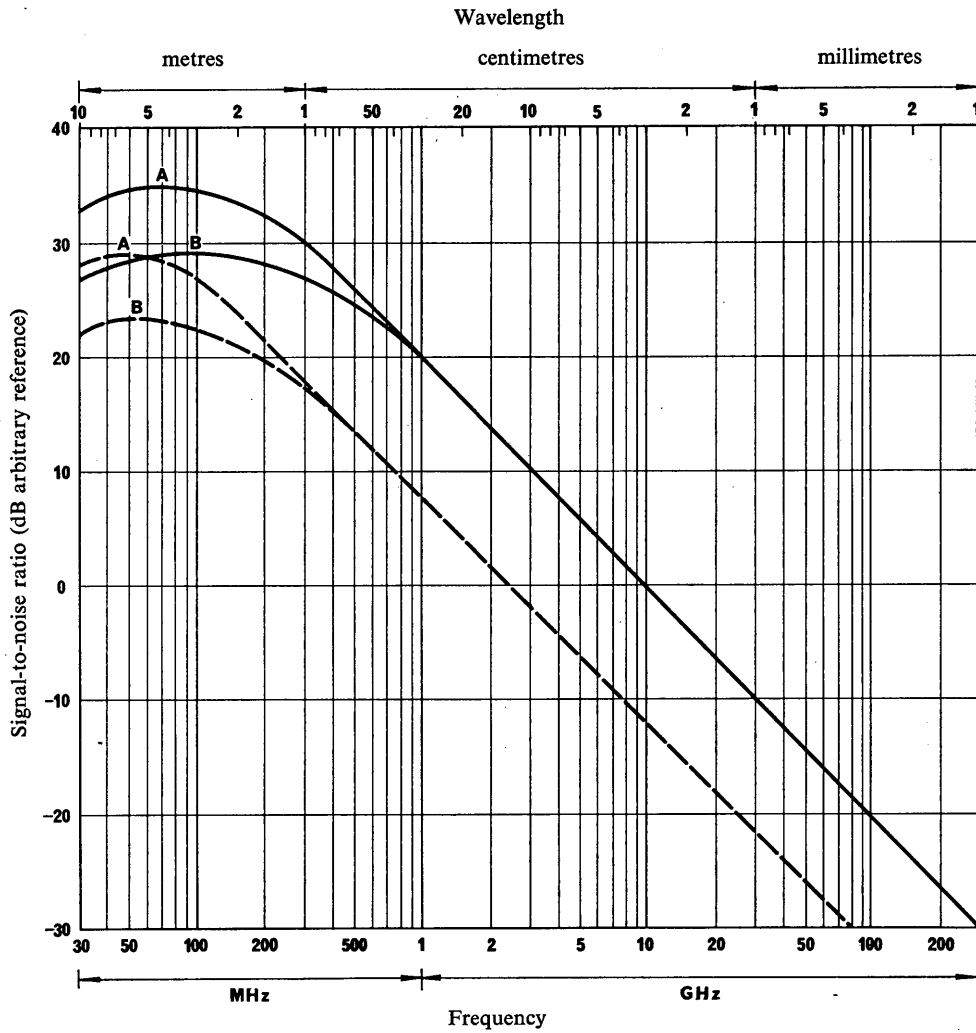


FIGURE 1

*System signal-to-noise ratio for communication between spacecraft,
both with omnidirectional antennae*

- Receiver noise temperature 300 K
- - - - Receiver noise temperature 1500 K
- A: Cosmic noise — quiet sun
- B: Disturbed sun

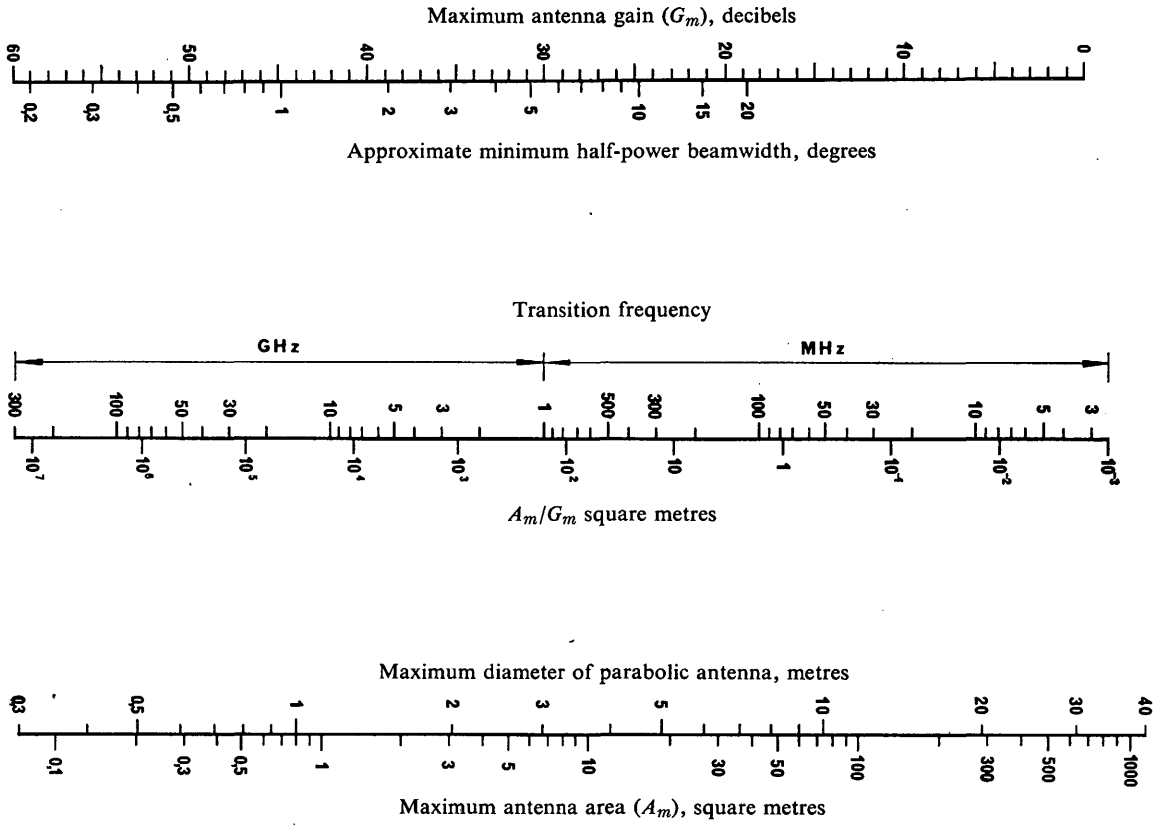


FIGURE 2

Nomogram to determine A_m/G_m and the corresponding transition frequency if maximum antenna area and maximum antenna gain (minimum beamwidth) are known

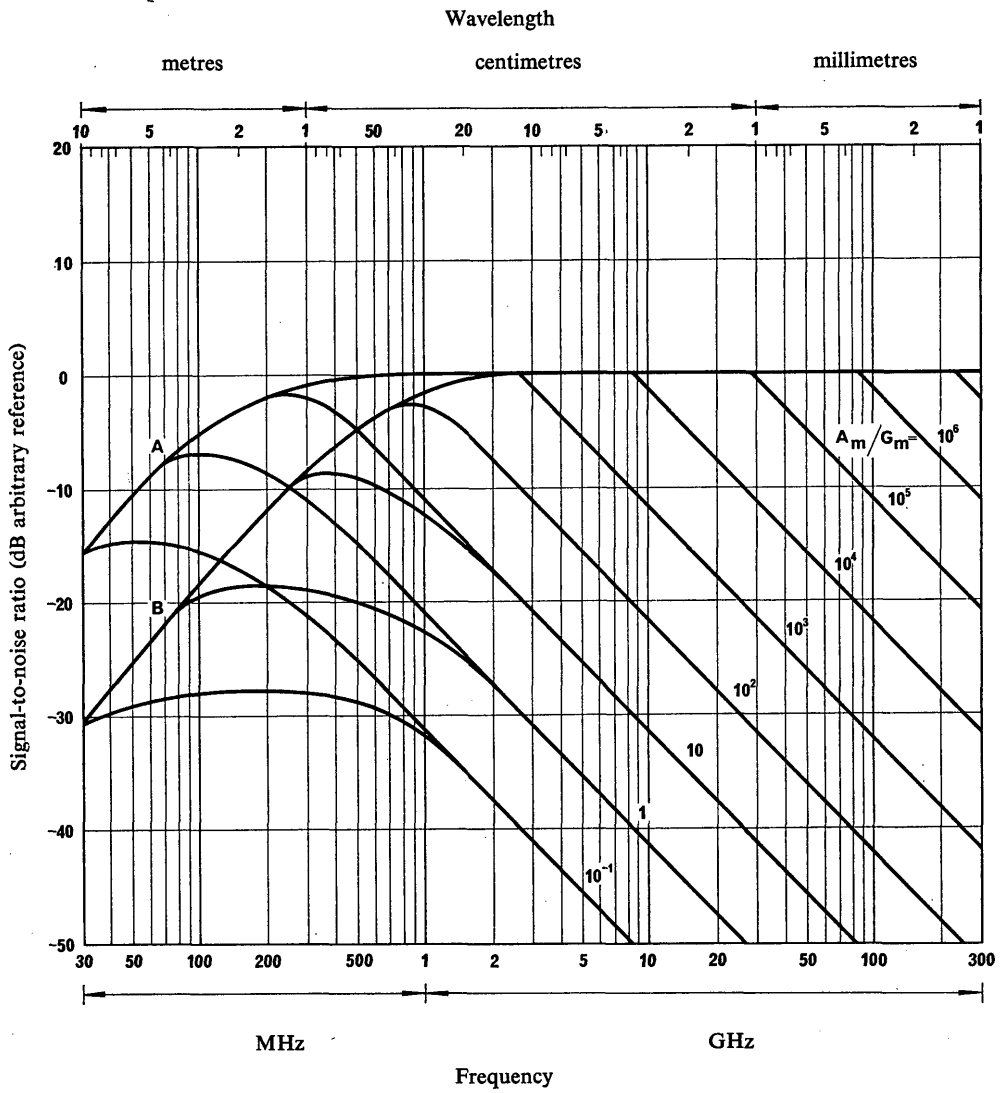


FIGURE 3

System signal-to-noise ratio for communication between spacecraft, one of which has a directional antenna and the other has an omnidirectional antenna

- A: Cosmic noise — non-directive antenna
- B: Galactic plane cosmic noise — directive antenna (receiver noise temperature 1500 K)

$$A_m/G_m = \frac{\text{Maximum antenna area (m}^2\text{)}}{\text{maximum antenna gain}}$$

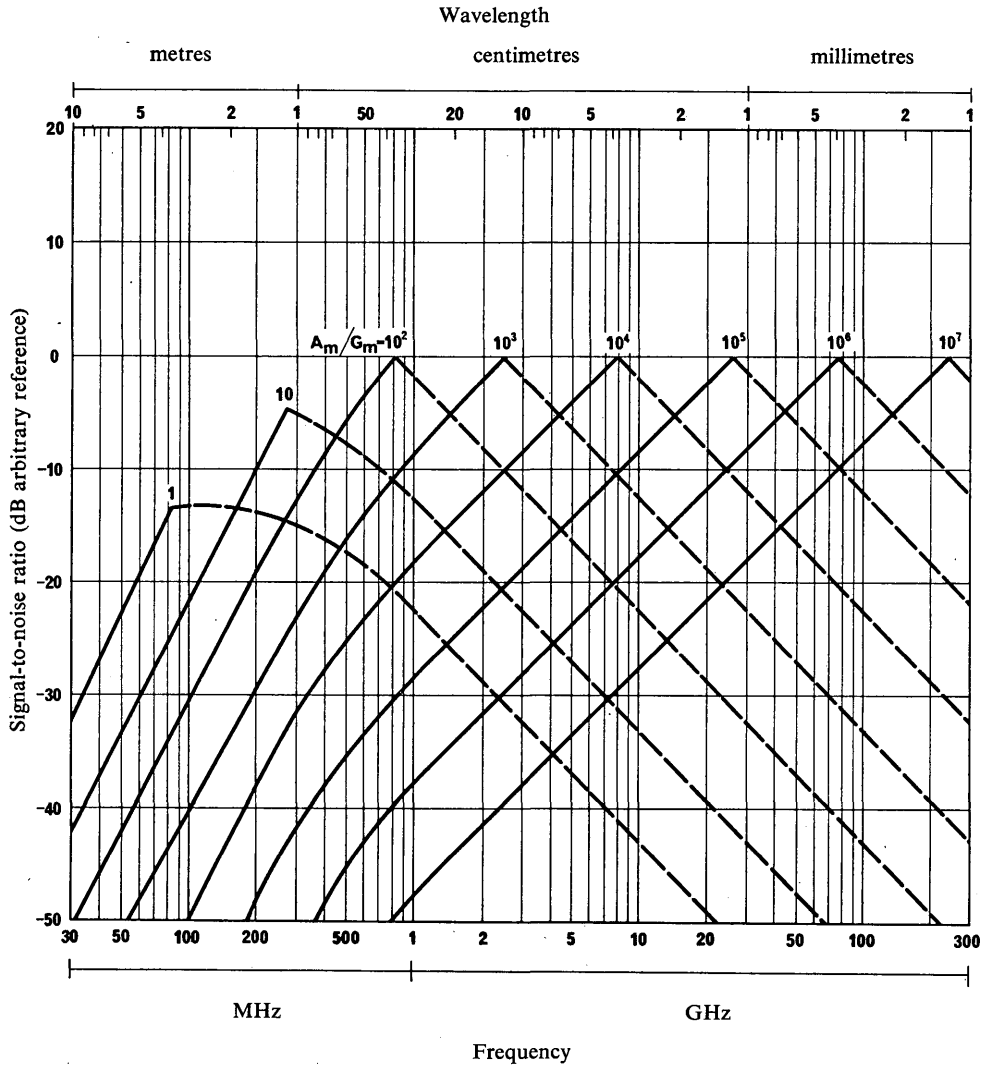


FIGURE 4

System signal-to-noise ratio for communication between spacecraft,
both with directional antenna

- Antenna (1)
- - - - - Antenna (2)

$$A_m/G_m = \frac{\text{maximum antenna area (m}^2\text{)}}{\text{maximum antenna gain}}$$

Receiver noise 1500 K

Galactic plane cosmic noise — directive antenna

REPORT 552 *

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

(Study Programme 2H-2/4)

(1974)

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 wider at frequencies above about 10 GHz, the use of these frequencies would facilitate the design of high capacity systems. In particular, 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.

Two 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.

For earth stations spaced a suitable distance apart (i.e. 10–30 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 together 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 can be employed of switching into use a lower frequency band at the earth station badly affected by precipitation.

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.

* Adopted unanimously.

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 about 10 GHz, the effects of precipitation are particularly important, and must be taken into account when the systems are designed. Attenuation due to precipitation varies with frequency, as does the free-space path loss; furthermore 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 on the down-path of a system may be very different.

In the Annex an example is presented of a design method for a PCM system in the fixed satellite service.

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.

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

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

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:

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

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

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

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 assuming that transponders are of the frequency converting type.

$(C/N)_t$ 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^{-z} , 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 to compensate for interference. Therefore, $(C/N)_t$ can be expressed as follows:

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

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), $(C/N)_t$ 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.

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 233-3, 563 and 564 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:

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

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

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

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 the 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.

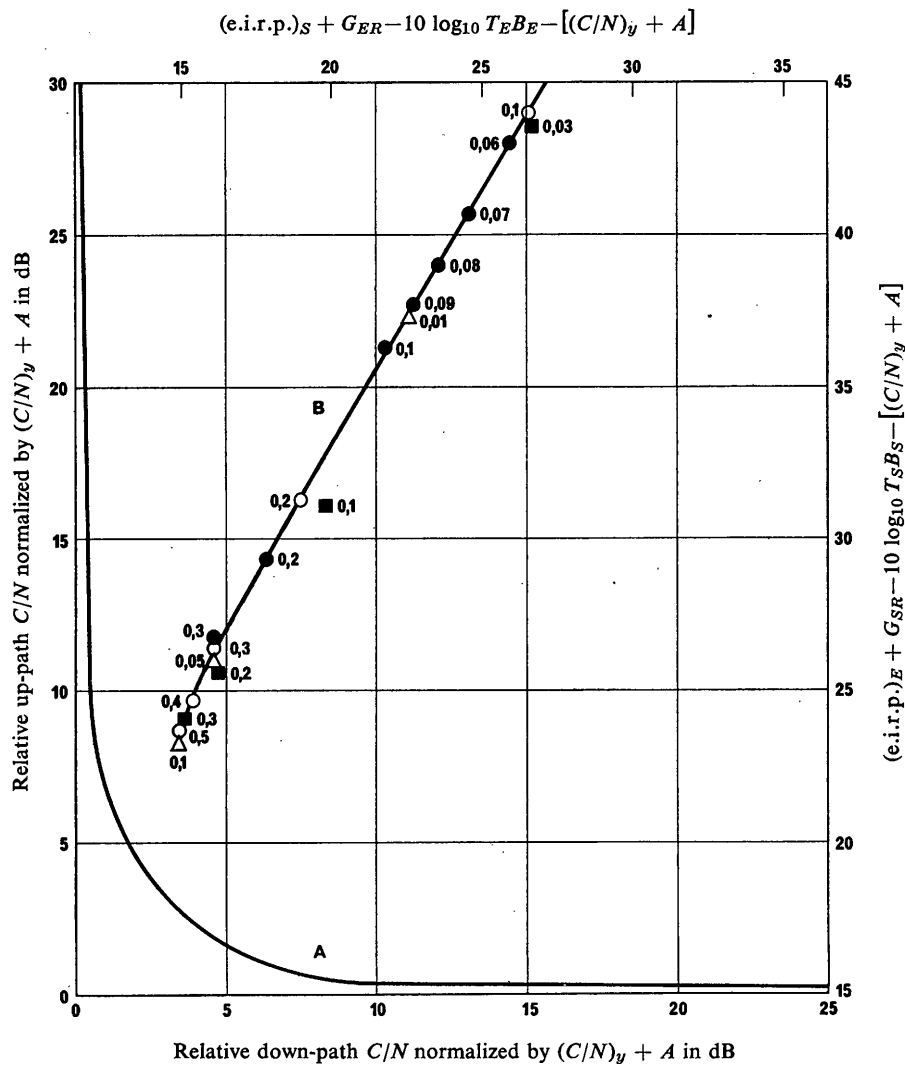


FIGURE 1

Relation between $(C/N)_u$ and $(C/N)_a$

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

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)

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SECTION 4C: BASEBAND CHARACTERISTICS (HYPOTHETICAL REFERENCE CIRCUIT,
NOISE, PRE-EMPHASIS, ENERGY-DISPERSAL TECHNIQUES, ETC.)

RECOMMENDATIONS AND REPORTS

Recommendations

RECOMMENDATION 352-2

**FIXED SATELLITE SERVICE SYSTEMS FOR TELEPHONY
AND/OR TELEVISION**

Hypothetical reference circuit

(Question 2-2/4)

(1963 – 1970 – 1974)

The C.C.I.R.,

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;

UNANIMOUSLY RECOMMENDS

1. that a hypothetical reference circuit for fixed satellite systems should consist of one Earth-satellite-Earth link (see Fig. 1);
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;
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.

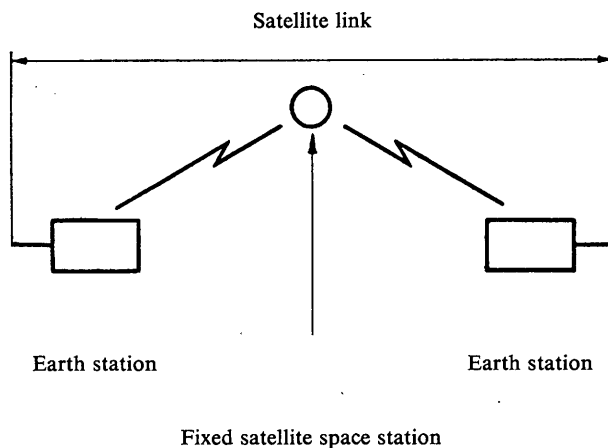


FIGURE 1
Hypothetical reference circuit

RECOMMENDATION 353-2
**SYSTEMS IN THE FIXED SATELLITE SERVICE
FOR FREQUENCY-DIVISION MULTIPLEX TELEPHONY**

Allowable noise power in the hypothetical reference circuit

(Question 2-2/4)

(1963 – 1966 – 1970)

The C.C.I.R.,

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 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 352-2 should not exceed the provisional values given below:
 - 1.1 10 000 pW psophometrically-weighted mean power in any hour;
 - 1.2 10 000 pW psophometrically-weighted one-minute mean power for more than 20% of any month;
 - 1.3 50 000 pW psophometrically-weighted one-minute mean power for more than 0.3% of any month;
 - 1.4 1 000 000 pW unweighted (with an integrating time of 5 ms), for more than 0.03% of any month;
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.

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. — 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 C.C.I.R., 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 4. — 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 $(-15 + 10 \log_{10} N)$ dBm for 240 channels or more, and $(-1 + 4 \log_{10} N)$ 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 C.C.I.T.T. Recommendation G.223 (Green Book, Vol. III-1, Geneva, 1972).

Note 5. — 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.

Note 6. — The noise power indicated in § 1 above should include interference noise (see Recommendation 356-3 and Recommendation 466-1) 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 C.C.I.T.T. Recommendation G.222, § (b) 6, are met.

Note 7. — The value given in § 1.4 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 390-2.

* 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.

RECOMMENDATION 354-2

SYSTEMS IN THE FIXED SATELLITE SERVICE CARRYING TELEVISION *

Video bandwidth and permissible noise level in the hypothetical reference circuit

(Question 2-2/4)

(1963 – 1970 – 1974)

The C.C.I.R.,

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 Recommendations 421-3 and 451-2);
- (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 352-2, 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 Recommendations 421-3 and 451-2);
2. that the signal-to-weighted noise ratios for continuous random noise at the end of the hypothetical reference circuit, defined in Recommendation 352-2, should provisionally be equal to the ratios recommended for the 2500 km terrestrial hypothetical reference circuit in Recommendations 421-3 and 451-2 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 5G/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 with regard to noise in the hypothetical reference circuit.

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

* These requirements are provisional. In Question 2-1/CMTT and Study Programme 2A-1/CMTT, the CMTT invites Administrations to study the characteristics of a hypothetical reference circuit for the transmission of television by satellite.

RECOMMENDATION 446-1

CARRIER ENERGY DISPERSAL IN SYSTEMS IN THE FIXED SATELLITE SERVICE

(Study Programme 2D-1/4)

(1966 – 1974)

The C.C.I.R.,

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 the use of such techniques can result in a substantial reduction in the level of interference between systems in the fixed satellite service operating in the same frequency bands;
- (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 employing angle modulation by analogue signals should use carrier energy dispersal techniques as far as is practicable, with a view to spreading energy at all times and in a manner consistent with the satisfactory operation of the systems (see Report 384-2, § 2);
- 2. that systems in the fixed satellite service employing digital modulation should use carrier energy dispersal techniques when this becomes technically feasible and is practical (see Report 384-2, § 3).

RECOMMENDATION 464

SYSTEMS IN THE FIXED SATELLITE SERVICE FOR MULTIPLEX TELEPHONY

Pre-emphasis characteristic for frequency-modulation systems

(Study Programme 2D-1/4)

(1970)

The C.C.I.R.,

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 $\pm (0.1 + 0.05 f/f_{max})$ 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. 2(a) and 2(b), respectively. An example to work between matched resistive input and output impedances is shown in Figs. 3(a) and 3(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.

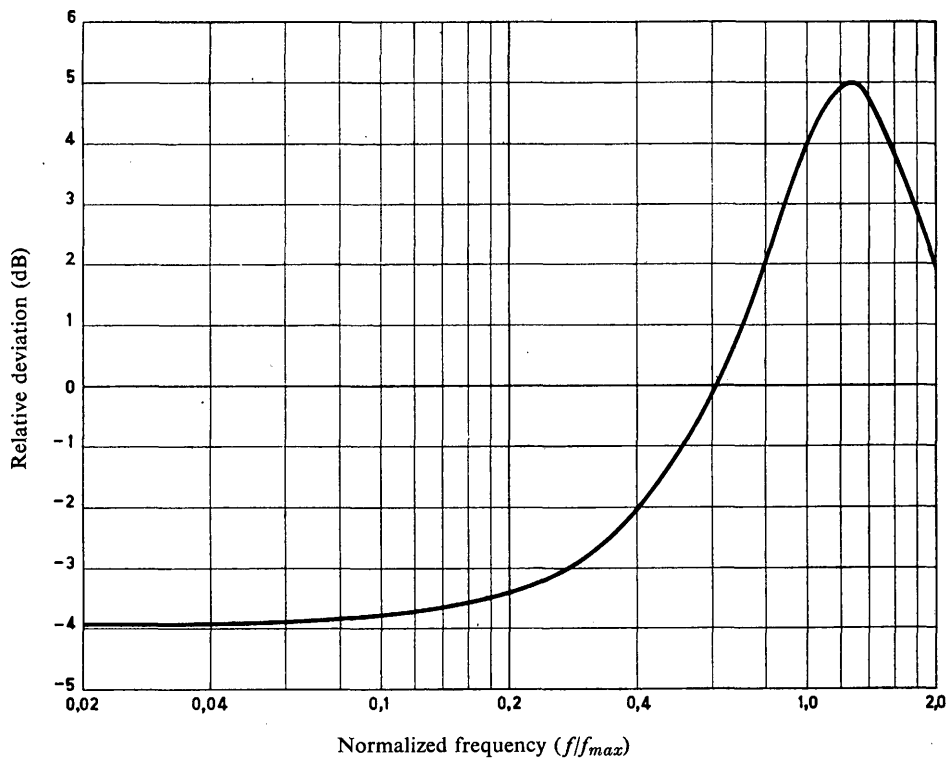
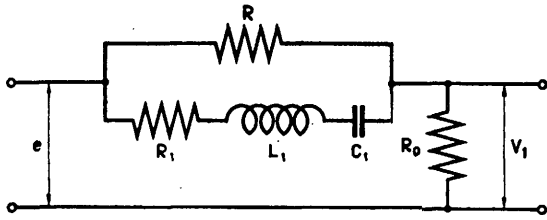


FIGURE 1
Pre-emphasis characteristic for telephony



$$R = 1.81 R_0$$

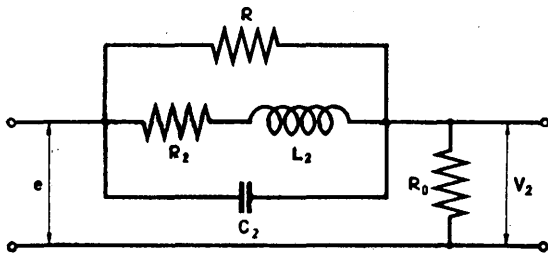
$$R_1 < 0.01 R_0 \text{ at } f_r$$

$$\sqrt{\frac{L_1}{C_1}} = 0.79 R_0$$

$$f_r = 1.25 f_{max} = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1}}$$

Where f_{max} is the highest baseband frequency

(a) Pre-emphasis network



$$R = 1.81 R_0$$

$$R_2 < 0.02 R_0 \text{ at } f_r$$

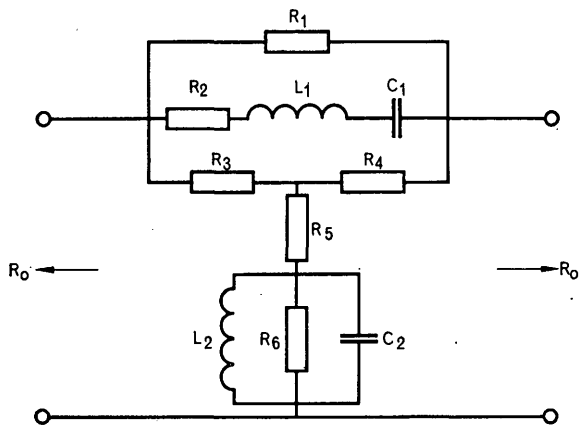
$$\sqrt{\frac{L_2}{C_2}} = 1.47 R_0$$

$$f_r = 1.25 f_{max} = \frac{1}{2\pi} \sqrt{\frac{1}{L_2 C_2}}$$

(b) De-emphasis network

FIGURE 2

Pre-emphasis and de-emphasis networks to work between a constant-voltage source and an open-circuited load



(a) Pre-emphasis network

$$R_1 = 1.81 R_0$$

$$R_2 < 0.01 R_0$$

$$R_3 = R_4 = R_0$$

$$R_5 = \frac{R_0}{1.81}$$

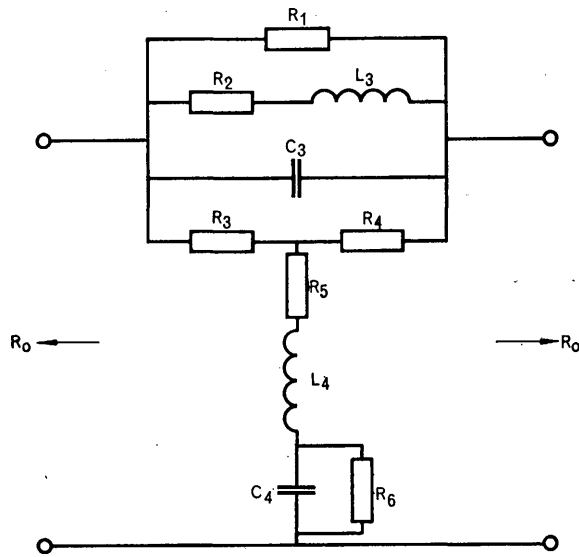
$$R_6 > 100 R_0$$

$$f_r = 1.25 f_{max} = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1}}$$

$$= \frac{1}{2\pi} \sqrt{\frac{1}{L_2 C_2}}$$

$$\sqrt{\frac{L_1}{C_1}} = 0.79 R_0$$

$$\sqrt{\frac{L_2}{C_2}} = \frac{R_0}{0.79}$$



(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

RECOMMENDATION 481

SYSTEMS IN THE FIXED SATELLITE SERVICE FOR TELEPHONY
USING FREQUENCY-DIVISION MULTIPLEX

Measurement of noise in actual traffic

(Question 20-1/4)

(1974)

The C.C.I.R.,

CONSIDERING

- (a) that measurements by means of a generator producing white noise (Recommendation 482) are only possible when the radio-frequency channel is not carrying traffic;
- (b) that systems carrying multi-channel telephony cannot be withdrawn from service at will for measurement;
- (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 concerned 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)
24	12- 108	116
36	12- 156	172
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
1872	12-8120	8932

RECOMMENDATION 482

**SYSTEMS USING FREQUENCY-DIVISION MULTIPLEX
IN THE FIXED SATELLITE SERVICE FOR TELEPHONY**

Measurement of performance by means of a signal of a uniform spectrum

(Question 24/4)

(1974)

The C.C.I.R.,

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 C.C.I.T.T. 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 (C.C.I.T.T. Recommendation G.223, Green 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 C.C.I.T.T. Recommendation G.223, Green 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 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 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);
- 3.1 that the discrimination of a low-pass filter should be at least 20 dB at a frequency more than 10% above nominal cut-off and at least 25 dB at frequencies more than 20% above nominal cut-off. The discrimination of a high-pass filter should be at least 25 dB at frequencies 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; these characteristics are intended to apply over a temperature range from 10°C 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 § 4, the ratio of the noise power indicated by the receiving equipment when the band-stop filter is bypassed, 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 level of the conventional load in dBm0 is given by: $-1 + 4 \log_{10} N$, for $N < 240$ channels
 $-15 + 10 \log_{10} N$, for $N \geq 240$ channels.

- 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 should be taken into account.

Note. — An overall accuracy of ± 2 dB or better is assumed for systems in operation in the fixed satellite service. Attention is also drawn to C.C.I.T.T. Recommendation G.228, Green Book, Vol. III-1, which discusses the method of measurements.

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				
24	12- 108	12 \pm 0.5	108 \pm 1.0	16	98		
36	12- 156	12 \pm 0.5	156 \pm 1.0	16	140		
60	12- 252	12 \pm 0.5	252 \pm 2.0	16	240		
72	12- 300	12 \pm 0.5	300 \pm 2.0	16	270		
96	12- 408	12 \pm 0.5	408 \pm 3.0	16	240	394	
132	12- 552	12 \pm 0.5	552 \pm 4.0	16	240	534	
192	12- 804	12 \pm 0.5	804 \pm 6.0	16	394	770	
252	12-1052	12 \pm 0.5	1052 \pm 8.0	16	534	1002	
312	12-1300	12 \pm 0.5	1296 \pm 8.0	16	534	1248	
432	12-1796	12 \pm 0.5	1796 \pm 12	16	534	1002	1730
612	12-2540	12 \pm 0.5	2600 \pm 20	16	770	1730	2438
792	12-3284	12 \pm 0.5	3284 \pm 25	16	1002	2438	3150
972	12-4028	12 \pm 0.5	4100 \pm 30	16	1002	2438	3886
1092	12-4892	12 \pm 0.5	4892 \pm 40	70	1002	2438	4650
1872	12-8120	12 \pm 0.5	8160 \pm 75	70	1002	3150	5340 7600

⁽¹⁾ Each measuring channel filter shall be designed to cover at least the largest baseband frequency with which it is to be used, as indicated in the column entitled "Limits of band . . .". (See also RECOMMENDS 6.1.)

TABLE II

Centre frequency f_c (kHz)	Bandwidth (kHz) in relation to f_c over which the discrimination should be at least the value shown: ⁽¹⁾			Bandwidth (kHz) in relation to f_c outside of which the discrimination should not exceed the value shown:	
	70 dB	55 dB	30 dB	3 dB	0.5 dB
16	± 1.5	± 2.1	± 2.7	± 5	± 7
70	± 1.5	± 2.2	± 3.5	± 12	± 18
98	± 1.5	± 1.8	± 2.1	± 4	± 9
140	± 1.5	± 1.8	± 2.2	± 5	± 14
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 (²) (³)	± 1.5	± 15.0	± 30.0	± 110	± 350
		± 1.8	± 3.5	± 12	± 100
4650	± 1.5	± 2.0	± 3.8	± 13	± 120
5340	± 1.5	± 2.2	± 4.0	± 14	± 140
7600	± 1.5	± 2.4	± 4.6	± 16	± 200

⁽¹⁾ (a) The discrimination values quoted for inductor-capacitor-type filters are referred to the attenuation of the band-stop filters at the lowest baseband frequency.

(b) To make allowance for the use of transformers, the discrimination values quoted for crystal-type filters are referred to the minimum attenuation of the band-stop filter within the baseband frequency range.

⁽²⁾ 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).

⁽³⁾ 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 5340 kHz the receiver selectivity should be related to the characteristics of crystal-type band-stop filters.

4C: Reports

REPORT 208-3 *

**SYSTEMS IN THE FIXED SATELLITE SERVICE FOR FREQUENCY-DIVISION
MULTIPLEX TELEPHONY AND TELEVISION**

**Form of the hypothetical reference circuit and allowable noise standard ;
video bandwidth and sound channel for television**

(Question 2-2/4)

(1963 - 1966 - 1970 - 1974)

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 352-2. 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 421-3, 451-2 and 354-2, and Report 486-1.

Developments in the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, introduced new factors which should be considered in 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 352-2 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 C.C.I.T.T./C.C.I.R. Special Study Group C 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 353-2 and 356-3 were derived from those applicable to terrestrial circuits. However, it is concluded in Annex I that for a system using the 4 and 6 GHz shared frequency bands the percentage of time for which

* Adopted unanimously.

50 000 pWp of thermal noise is exceeded may be considerably less than the 0.3% allowed by Recommendation 353-2. This suggests that further study of the short-term noise criteria for satellite systems would be desirable in the light of the actual transmission behaviour of such systems but bearing in mind the relevant principles established by the Joint C.C.I.T.T./C.C.I.R. Special Study Group C 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 353-2 was prepared giving objectives in the light of the advice of Joint C.C.I.T.T./C.C.I.R. Special Study Group C. The maximum value of 10 000 pW (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.

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 Recommendations 421-3 and 451-2).

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.

5. Indirect television distribution systems

Indirect television distribution systems must meet certain special requirements, and the performance may need to be different from that of intercontinental links. Furthermore, the characteristics of the earth stations, of which there may be a relatively large number in the same system, may also be very different. In most cases, it will be desirable to maintain a final quality (at the viewer's receiver) equivalent to that obtained with other modes of distribution. It may be desirable to define the form and characteristics of new hypothetical reference circuits for indirect television distribution, but experience with such systems is insufficient to do this at present.

Annex II to this Report contains some results of studies conducted for a specific example of this kind of system.

ANNEX I

OVERALL NOISE CHARACTERISTICS OF EARTH STATION RECEIVING SYSTEMS

1. Introduction

Recommendation 353-2 provides for one minute mean noise power of 50 000 pWp not to be exceeded for 0.3% of any month. Operating experience gained with geostationary satellite circuits has shown carrier fading and noise increase to be primarily due to a rainy environment.

Rain absorption in the up- and down-links may be assumed to be statistically independent of each other; while noise temperature increase must be assumed to be correlated with down-link absorption.

2. Discussion

Fig. 1 shows rain absorption at 4 and 6 GHz along a 5° elevated ray path as a function of surface rainfall rate. The curves were derived from Fig. 2 of C.C.I.R. Report 234-1, Oslo, 1966, under the assumption of an 18 km long equivalent rain bearing distance.

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.

If T_p is made artificially larger by omitting, in equation (2), a from the next-to-last right-hand term, and w from the last right-hand term, one obtains:

$$T'_p = T_0 + \left(\frac{a-1}{a}\right) 290 \text{ K} > T_p \quad (3)$$

assuming, conservatively, that the rain has a noise temperature of 290 K. This equation permits the conversion of the 4 GHz absorption values to receiving system noise temperature.

Fig. 2 shows T'_p/T_0 versus surface rainfall rate for $T_0 = 50 \text{ K}$. Since it has to be assumed that down-link absorption and noise temperature increase are correlated, the corresponding resultant increases in channel noise are combined. If the nominal (20% of the time) signal/noise ratio is called s_0/n_0 and if it is assumed that the nominal thermal noise in the down-link accounts for no more than 80% of the total noise, the signal/noise ratio for a rainfall environment which produces an attenuation " a " can be computed from:

$$s/n = \frac{s_0}{n_0 (0.2 + 0.8 a T'_p/T_0)} \quad (4)$$

so that the total dB increase in channel noise (for a system operating well above threshold) is:

$$\Delta n = 10 \log_{10} (0.2 + 0.8 a T'_p/T_0) \quad (5)$$

Equation (5) is valid since up- and down-link fading are not expected to be correlated for small percentages of time.

Fig. 2 shows Δn as a function of surface rainfall rate.

A distribution of surface rainfall rate is shown in Fig. 3 and is the cumulative distribution of one-minute rainfall-rate extrapolated to mm/hr for New Orleans, Louisiana [Handbook, 1965]. This distribution is used in the following calculations.

Fig. 4 shows the circuit noise objective as per Recommendation 353-2 (log-normal interpolation between the 20% and the 0.3% values). Also shown are two cumulative distributions of total channel noise power for (a) up-link fading only, and (b) down-link fading only, using the 6 GHz curve from Fig. 1 and the Δn curve from Fig. 2 in conjunction with the distribution of Fig. 3. The noise increase for small percentages of the time is quite substantial both for the up- and the down-link. Measurements to date have yielded considerably lower circuit degradations.

From the curves of Fig. 4, it can be seen that the up-link noise will exceed the 50 000 pWp level for only 0.06% of the time, and down-link noise for only 0.033% of the time. The total percentage of time, for a system operating well above threshold, is then 0.093%. Assuming that the normal operating C/N is 6 dB above threshold, the corresponding percentage of time is 0.113%. If e.i.r.p. adjustment could be used in the up-link during heavy rainfall, the down-link noise alone would be responsible for the channel noise increase.

3. Conclusions

When thermal noise alone is considered, it is apparent that the percentage of time, for which 50 000 pWp is exceeded, may be considerably less than the 0.3% allowed by Recommendation 353-2.

REFERENCE

Handbook of Geophysics and Space Environments [1965] Air Force Cambridge Research Laboratories. (1965 edition.)

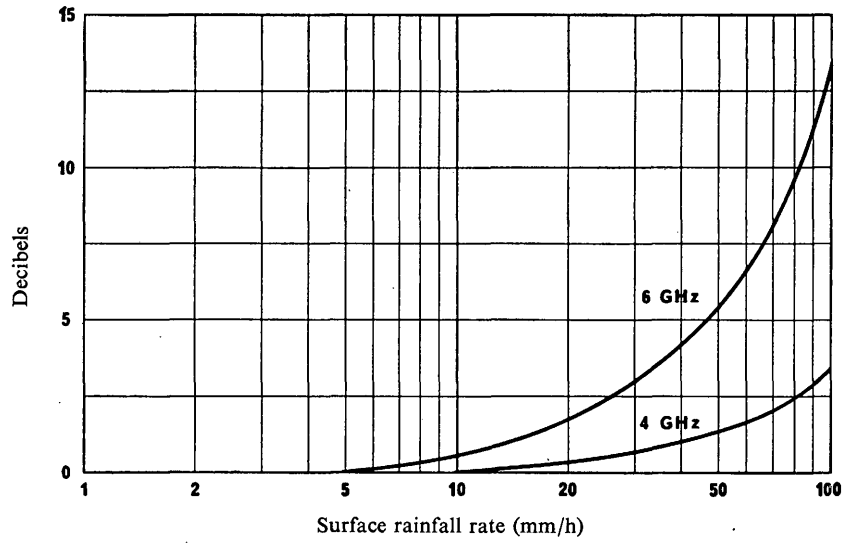


FIGURE 1

Attenuation due to absorption along a 5° elevated ray path versus surface rainfall rate

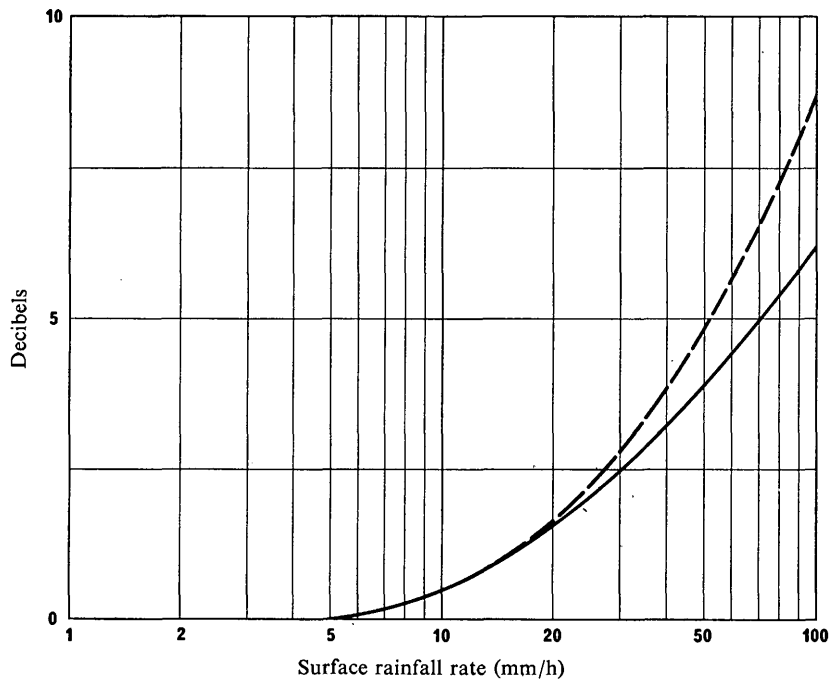


FIGURE 2

*Noise increase due to rain on the down-link at 4 GHz
(nominal earth-station noise temperature $T_0 = 50$ K)*

- Relative total down-link noise increase Δn
- Relative noise temperature increase $10 \log_{10} (T_p'/T_0)$

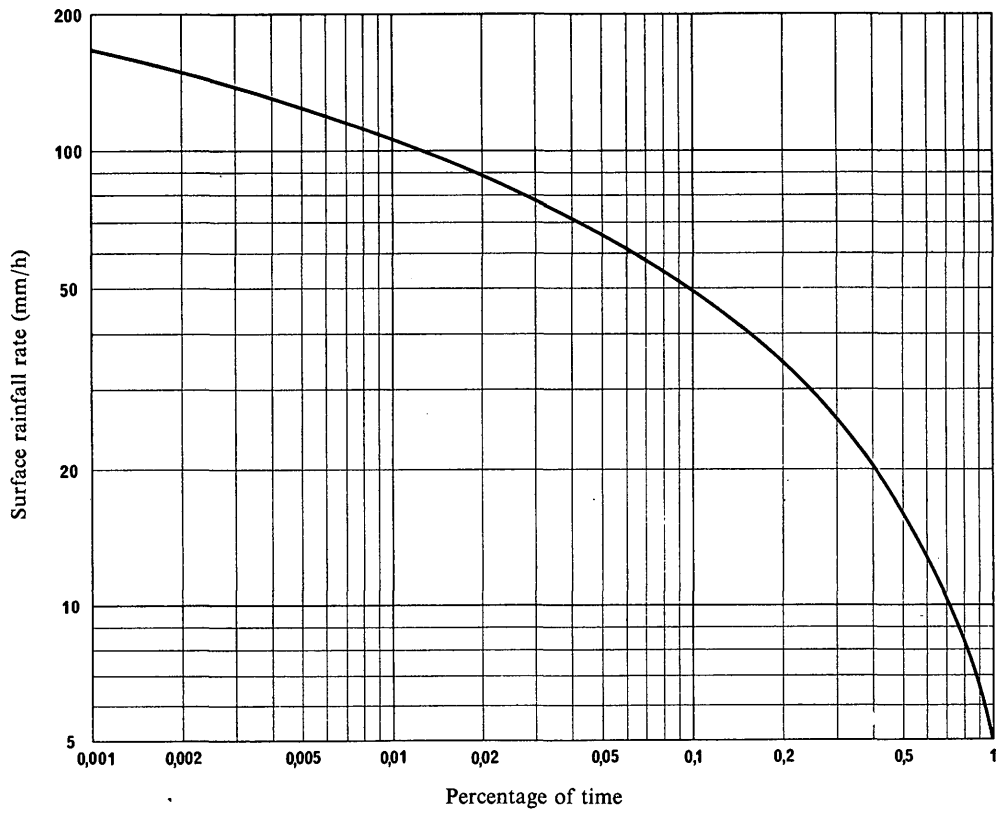


FIGURE 3

Cumulative distribution of one-minute rainfall rate extrapolated to mm/h at New Orleans

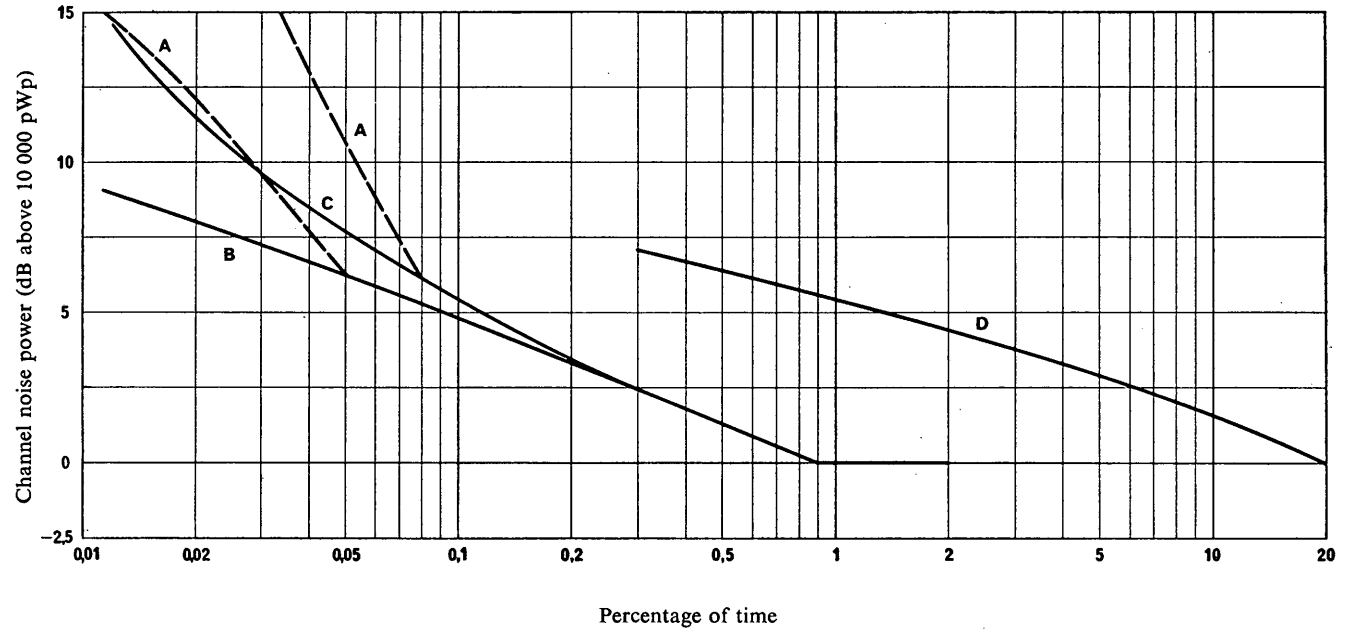


FIGURE 4

Cumulative distributions of total channel noise and of various channel noise components

- A: Threshold for 6 dB margin
- B: Down-link only
- C: Up-link only
- D: Channel overall objective

ANNEX II

QUALITY CHARACTERISTICS OF A PARTICULAR
INDIRECT TELEVISION DISTRIBUTION SYSTEM

Studies of a system for the indirect distribution in Europe and Africa of a television picture accompanied by high-quality sound and by twenty commentaries have been made by the European Broadcasting Union, the European Conference on Satellite Telecommunications and the European Space Research Organisation. The purpose of these studies was to obtain for the picture presented to the televiewer a subjective quality index of about 2.5 on the six-grade impairment scale (Note 2 of Report 405-2), adjacent to the limits of the service area of the emitters. The proposed video bandwidth was about 6 MHz, to allow for the transmission of 625-line video signals under systems D, K and L.

As a result of these studies it has been possible to specify the characteristics of the satellite link for this particular system and a summary of this specification is as follows:

- *Luminance*: signal-to-weighted noise ratio for systems D, K and L, of 55 dB, according to Recommendation 421-3.
- *Chrominance*: signal-to-weighted noise ratio between 3.5 and 5.5 MHz, equal to 46 dB, according to Recommendation 451-2. A value of 43 dB is permissible, however, if studies on pre-emphasis show any difficulty in meeting luminance and chrominance requirements simultaneously.

With regard to the sound components accompanying the television picture, the studies lead to the assumption that the following characteristics may be regarded as satisfactory:

- *International sound channel*: audio-frequency bandwidth of 12 kHz and signal-to-unweighted noise ratio of 57 dB.
- *Commentary channel*: audio-frequency band between 300 and 3400 Hz and signal-to-unweighted noise ratio of 29 dB with a signal at the maximum level in the channel concerned (use of an amplitude compandor).

It should be noted that the reason for using an amplitude compandor for commentary channels is not to increase the radio-frequency bandwidth of a satellite distribution system unduly when the number of commentaries to be transmitted simultaneously is about twenty. It should also be borne in mind that the commentaries accompanying the same television picture may have a certain correlation, in the sense that the maximum level is sometimes attained simultaneously on all the channels.

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REPORT 212-3 *

**SYSTEMS IN THE FIXED SATELLITE SERVICE FOR FREQUENCY-DIVISION
MULTIPLEX TELEPHONY AND TELEVISION**

Use of pre-emphasis in frequency-modulation systems

(Question 2-2/4)

(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 353-2. 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.

* Adopted unanimously.

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 451-2, 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 [C.C.I.R., 1966-1969a] 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 [C.C.I.R., 1966-1969b] 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 [C.C.I.R., 1970-1974a]. 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 421-2, 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 451-2.

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 $20 \log_{10} y$ 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:

$$y = 8 \quad (\text{instead of } y = 5 \text{ as in Recommendation 405-1});$$

$$\tau_p = 227 \text{ ns} \quad (\text{instead of } \tau_p = 508 \text{ ns as in Recommendation 405-1}).$$

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 421-3 and Report 486-1 concerning the hypothetical reference circuit.

3.3 625-line PAL system I

A study has been carried out [C.C.I.R., 1970-1974b] 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 451-2.

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 C.C.I.R. 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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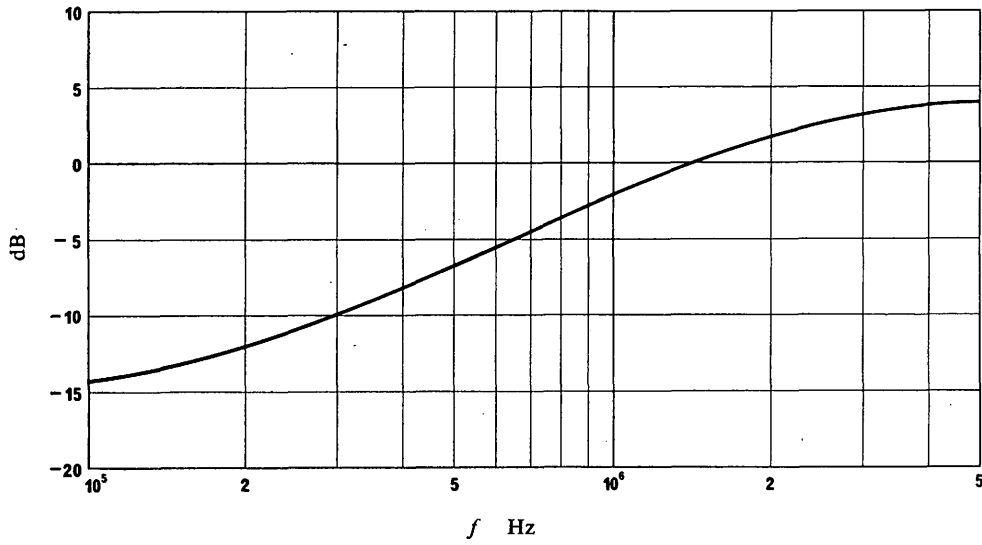


FIGURE 1
Experimental pre-emphasis characteristics for the PAL system

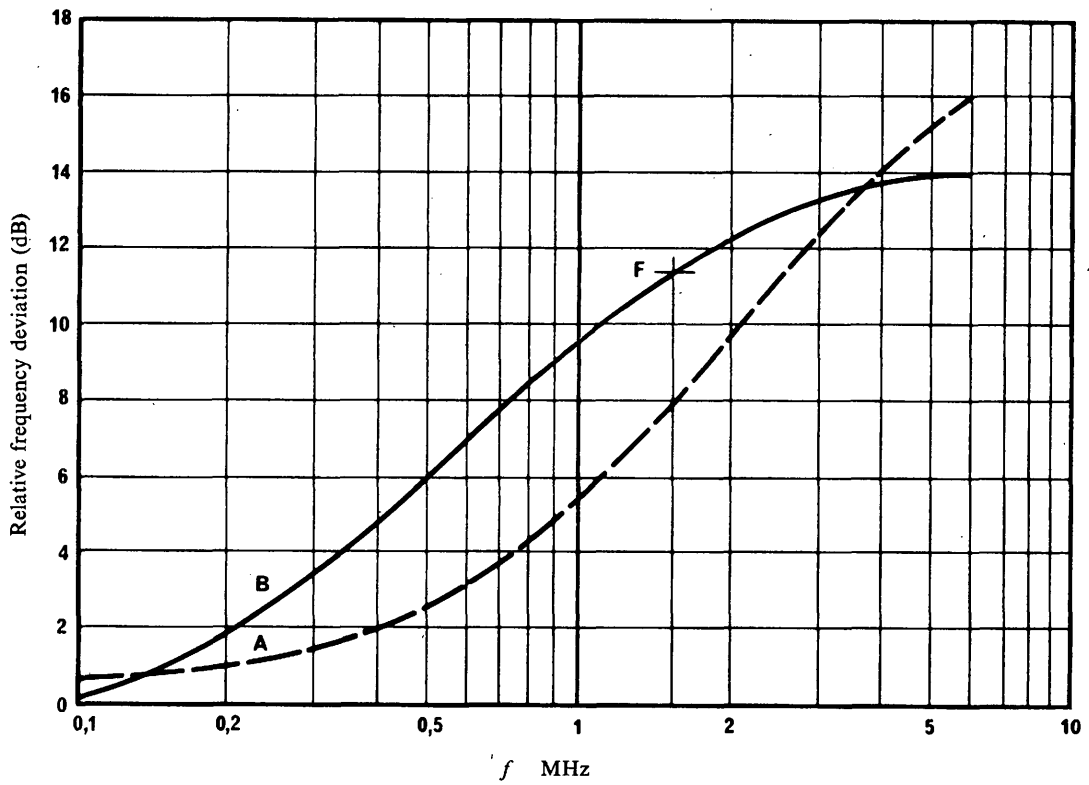


FIGURE 2
A: Calculated pre-emphasis curve proposed for the SECAM system
B: Pre-emphasis curve recommended in Recommendation 405-1
F: Reference frequency

REPORT 384-2 *

**FREQUENCY SHARING BETWEEN RADIOCOMMUNICATION-SATELLITE SYSTEMS
AND TERRESTRIAL RADIO-RELAY SYSTEMS****Energy dispersal in radiocommunication-satellite systems**

(Study Programme 2D-1/4)

(1966 – 1970 – 1974)

1. Introduction

It is clear from studies of frequency sharing between radiocommunication-satellite systems and terrestrial radio-relay systems 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:

- frequency-sharing between radiocommunication-satellite systems themselves; 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 2C-1/4 and 2D-1/4. 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 and suggestions for further experimental work are made.

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 classes; 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 those two methods are discussed in Annex I and are 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 considered are:

- a sinusoidal signal (Curve A of Fig. 2),
- a sinusoidal signal plus 30% third harmonic added in suitable phase (Curve B of Fig. 2),

* Adopted unanimously.

- a band of low-frequency noise (Curve C of Fig. 2),
- a low-frequency triangular waveform (Curve D of Fig. 2).

It is evident from Fig. 2, that the low-frequency triangular waveform (Curve D) is the most effective of these waveforms and that, 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.

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 one for general application. Uncertainty about the character of baseband spectra under practical conditions, is one of the main problems which militate against an adequate assessment of Method 2 at this stage.

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. The conventional load, representing mean busy-hour conditions, was originally evolved for the purpose of calculating intermodulation noise and may not be a particularly accurate representation for the purpose of dispersal studies; this is particularly so for small capacity systems, i.e. those of 60 channels or less. For this reason, 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 full 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:

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

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:

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

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.

Finally, it should be noted that the use of the proposed method 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. Summary

It appears from this work 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.

It should be noted that 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 would provide energy dispersal as great as that provided under full-load conditions. 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. If substantial addition to the radio-frequency bandwidth occupied is to be avoided in telephony systems, even this amount of energy dispersal may well present difficulties, especially for low-capacity transmissions.

Further experimental work is needed to determine the practicability of these methods. In particular, this work should be directed towards assessing:

- whether the amounts of dispersal predicted can in fact be achieved;
- what distortion is likely to result from intermodulation between the signal and dispersal waveforms due to the non-linearities of a practical system;
- the relationship between baseband distortion and radio-frequency bandwidth.

It is also desirable that a study should be made of the spectra of telephone baseband signals, of the kind likely to be routed via communication-satellite systems under various conditions of loading and of the resulting radio-frequency spectra. In the light of this information, it should be possible to make a better assessment of the potentiality of Method 2 of Fig. 1 for telephony systems.

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 (dF) 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:

$$10 \log_{10} \left(\frac{\text{maximum energy per 4 kHz}}{\text{total energy}} \right)$$

$$= 10 \log_{10} \frac{0.004}{\sqrt{2\pi} dF} = -(28 + 10 \log_{10} dF) \text{ dB}$$

(dF is expressed in MHz).

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 211-1 (Oslo, 1966).

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 what 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 all numbers of channels.

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 *Dispersion by a band of low-frequency noise*

A form of carrier energy-dispersion that is not critical in its application and shares with triangular dispersion the property of yielding a maximum energy spectral-density, inversely proportional to the amplitude of the wave form, 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 dispersion signal is not fixed the required amount of dispersion can be attained by the methods given in [C.C.I.R., 1970–1974].

2.2 *Method 1(b)*

An obvious variant of Method 1(a), would incorporate automatic means for adjusting the degree of artificial energy-dispersion, 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 dispersion, 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 dispersion 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 that has been proposed for applying the variable degree of dispersion 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 dispersion 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. **Dispersion 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 dispersion. 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-dispersion 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-dispersion 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, 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.

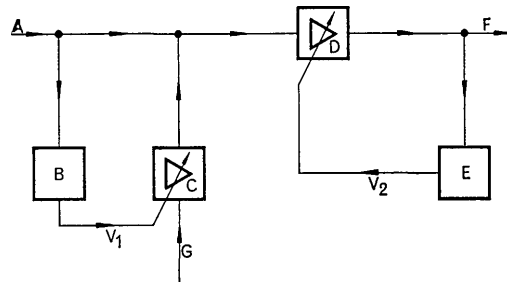
3.4 *Method 2(c)*

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 obtaining 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

C.C.I.R. [1970-1974] Doc. 4/273, U.S.S.R.



- 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

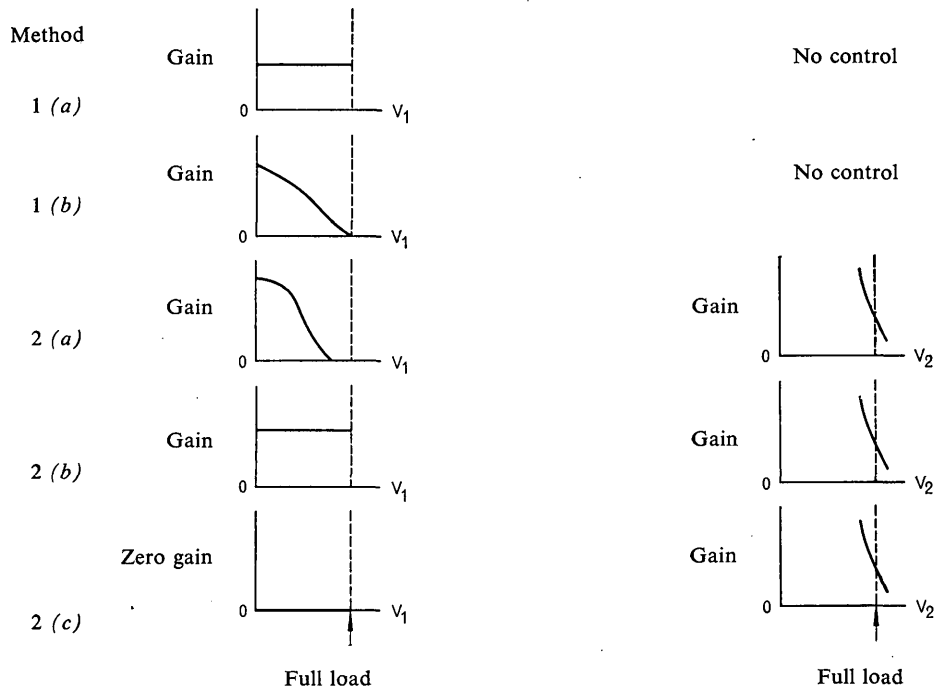


FIGURE 1

Simplified block diagram

(Possible filters, buffer-amplifiers and gain-regulating pilots omitted)

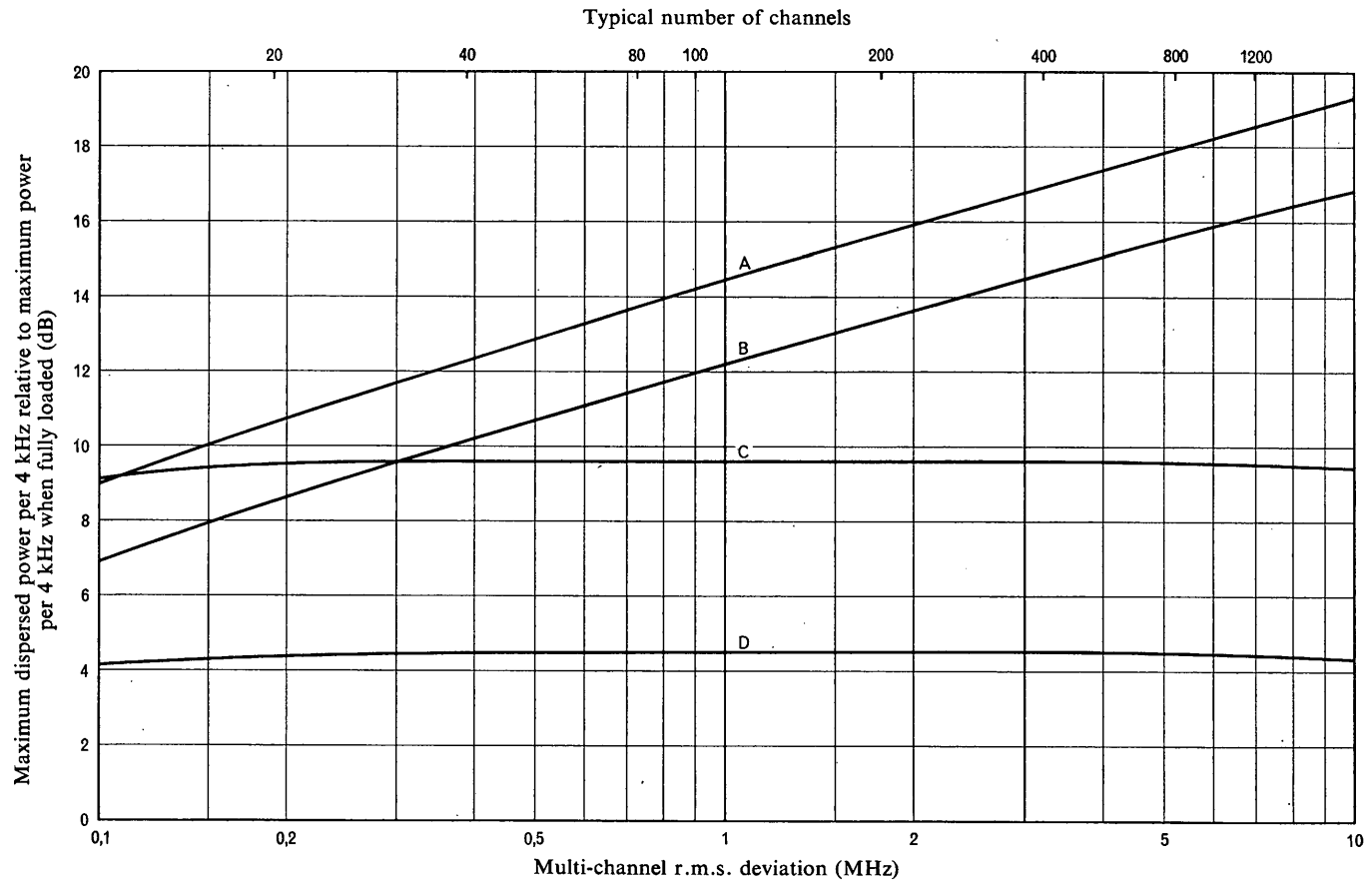


FIGURE 2

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.

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 270-1) showed that the subjective quality

index of the picture was equal to 3 in the six-grade quality scale (Note 2 in Report 405-2) 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 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.

REFERENCES

- DOBA, S. and RIEKE, J. W. [1950] Clampers in video transmission. *AIEE Transactions*, **69**, 477.
- SAVAGE, D. C. [1962] Three types of television signal stabilising amplifier. Report of International Television Conference, I.E.E., 251, London.

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 C.C.I.R.

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

n = integer

f_c = RF carrier frequency

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 shaping 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:

$$D = 10 \log_{10} \frac{\text{total power}}{\text{maximum power per 4 kHz}} \quad (3)$$

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 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. 3(a). 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. 3(b) 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.

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 Figs. 4(a) 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.

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 scrambling 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:

$$D = 10 \log_{10} N + 10 \log_{10} B - K, \quad \text{when } N < M \quad (4)$$

$$D = 10 \log_{10} M + 10 \log_{10} B - K, \quad \text{when } N > M \quad (5)$$

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 one 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 Mbit/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.

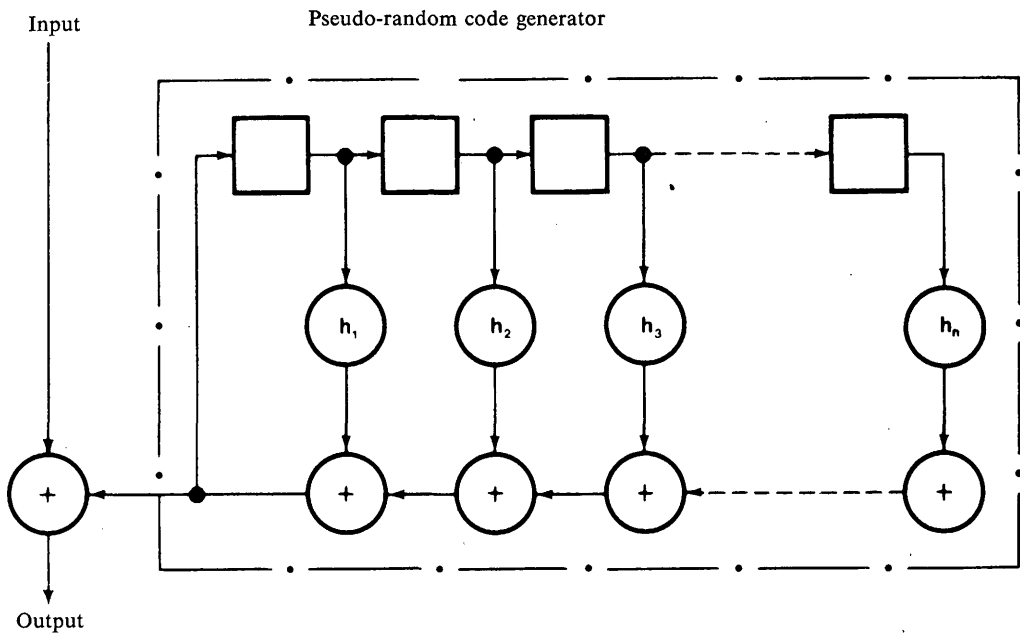
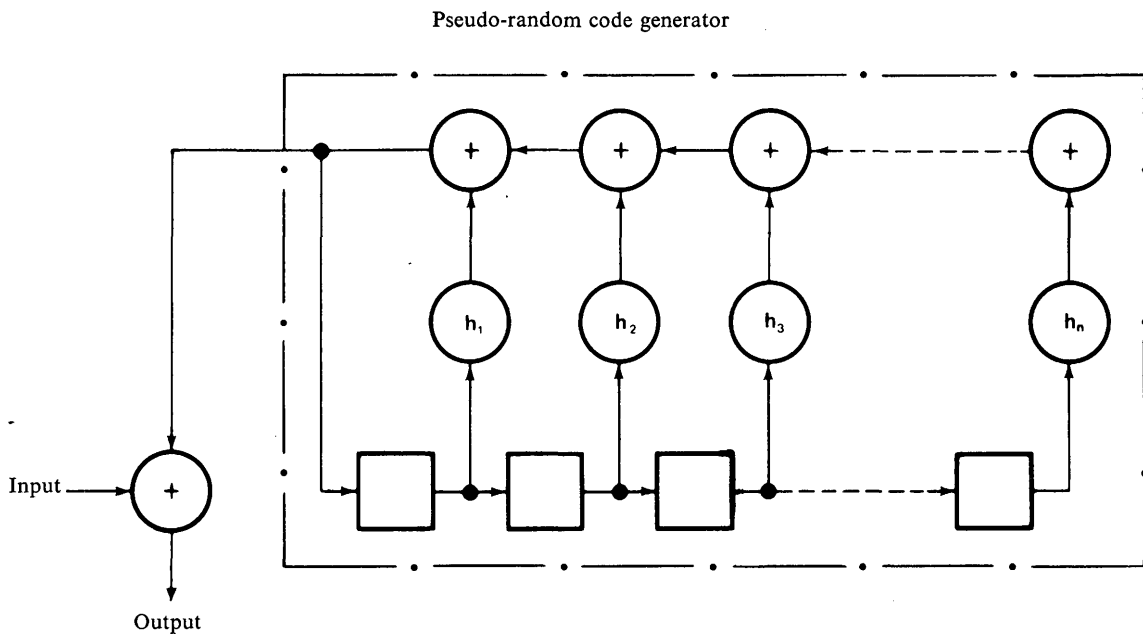
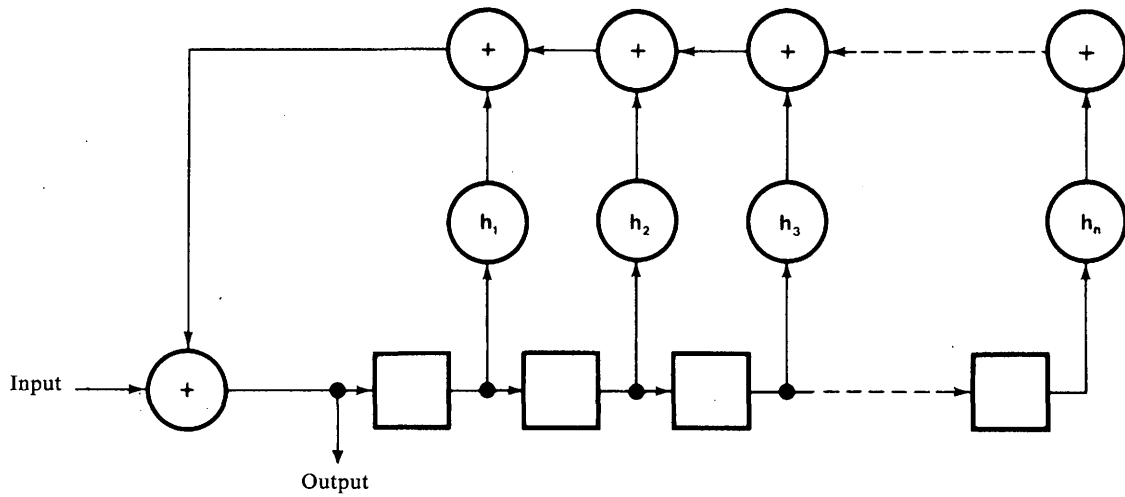


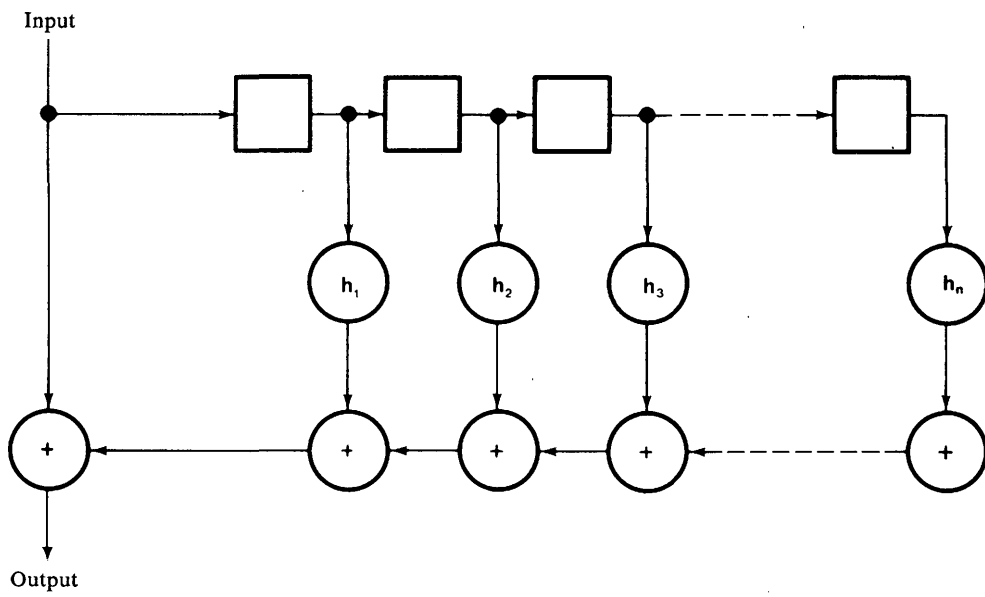
FIGURE 3

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.



(a) Scrambler



(b) Descrambler

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.

REPORT 553 *

FIXED SATELLITE SERVICE

Operation and maintenance of earth stations

(Question 20-1/4)

(1974)

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.

2. Compatibility of equipment

In order to allow the measurements to be performed with the required accuracy and permit correct interpretation 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 C.C.I.R. and C.C.I.T.T. Recommendations (for example Recommendation 482). 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 sets forth the reasons for the specification of filters in Recommendation 482.

3. Equipment utilization

Procurement and storage of test instruments at earth stations could 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.

* Adopted unanimously.

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.

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].

REFERENCE

INTELSAT [1971] Satellite system operations guide. Vol. II.

ANNEX

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, centre frequencies are derived from Annex I to C.C.I.T.T./C.C.I.R. Joint Special Study Group C Question 8/C, C.C.I.R. Recommendation 399-2 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.

The bandwidth characteristics of possible new filters can be obtained by interpolation of the values indicated in Fig. 1 of this Annex, which shows typical values for the relative bandwidth of band-stop filters in relation to centre frequency. As an example, referring to Table II of Recommendation 482 at the 55 dB attenuation point for the 394 kHz filter, the minimum bandwidth is given as ± 3.0 kHz. This is expressed in Fig. 1 by:

$$\frac{3.0}{394} = 0.76\% \text{ at the } 394 \text{ kHz frequency.}$$

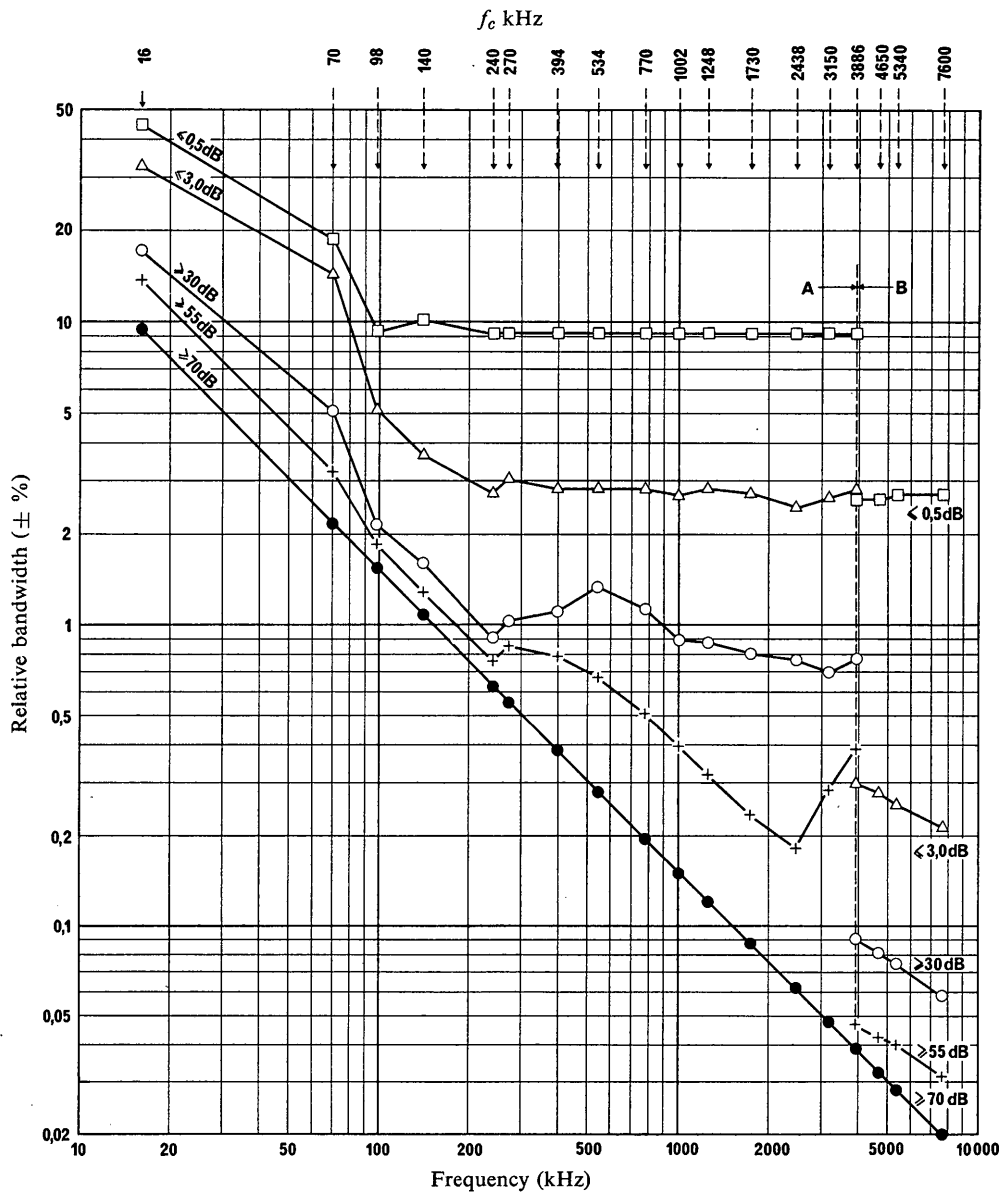


FIGURE 1

Relative bandwidth $\Delta f/f_c$ of the band-stop filters in relation to the centre frequency f_c for the specified attenuations as contained in Table II of Recommendation 482

A: Coil-capacitor-type filter B: Crystal-type filter

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SECTION 4D: METHODS OF MODULATION AND MULTIPLE ACCESS

RECOMMENDATIONS AND REPORTS

Recommendations

There are no Recommendations in this section.

Reports

REPORT 211-3 *

ACTIVE COMMUNICATION-SATELLITE SYSTEMS

A comparative study of possible methods of modulation and multiple access
(for multi-channel telephony)

(Question 2-2/4, Study Programme 2D-1/4)

(1963 – 1966 – 1970 – 1974)

1. Introduction

Several factors enter into the choice of a method of modulation or access technique for active communication-satellite systems. The most important aspects to be considered in this comparison are:

- the radio-frequency transmitter power available in the satellite;
- the radio-frequency transmitter power needed at the earth station to give acceptable signal-to-noise values for the earth-to-satellite link;
- bandwidth requirements in relation to the traffic capacity to be accommodated, i.e. the comparative economy in the use of the radio-frequency spectrum;
- the system flexibility, particularly in regard to the manner by which provision can be made for multi-station access to the system as discussed in Report 213-3;
- liability to cause interference to, or to receive interference from, systems sharing the same frequency bands;
- practicability in the light of current, and probable future technology.

The present study is concerned with multi-channel telephony systems. Two distinctly separate methods of modulation at this stage warrant detailed consideration. They are:

- *analogue*: frequency-division multiplexing (FDM) of individual telephone channels. This baseband can be transmitted by frequency-modulation of the carrier (FDM-FM) or by single-sideband modulation of the carrier (FDM-SSB);
- *digital*: conversion of an FDM baseband of telephone channels to digital format by pulse-code modulation (FDM-PCM) or time-division multiplexing of telephone channels which have been individually converted to a PCM format (TDM-PCM). Either PCM format can be used to modulate (key) the radio-frequency carrier. One well-established technique is phase-shift keying (PSK).

Both methods have variants which are not considered in greater detail here, and each method can be considered for frequency-division multiple access (FDMA) to the satellite repeater. PCM-PSK

* Adopted unanimously.

is applicable for time-division multiple access (TDMA) to the satellite repeater because of the particular time structure of its signals.

2. Assumptions made and limitations involved in the comparison

2.1 General assumptions

- 2.1.1 Calculations refer to multi-channel telephony, and are based on typical present operating systems and future state of the art projections.
- 2.1.2 The noise allowance for any telephone channel in the hypothetical reference circuit for FDM-FM systems is given in Recommendation 353-2. Interference from terrestrial systems is taken into consideration. At this stage for digital systems, no allowance is made for outside interference.
- 2.1.3 A very suitable characteristic indicative of the quality of a receiving system (earth or satellite system) is the figure of merit G/T , that is the ratio of the receiving antenna gain to the system noise temperature in kelvins, expressed in dB. A large earth station, having an antenna diameter of about 25 m and a system noise temperature of about 50 K, operating at 4 GHz has a G/T figure of about 41 dB. Similarly a geostationary satellite, having an antenna with full earth coverage and a system noise temperature of 1200 K will have a value of G/T of about -14 dB. In smaller earth stations the G/T figure decreases: for example, an earth station with an antenna diameter of 9 m and a system noise temperature of 150 K would have a G/T figure of about 27 dB.
- 2.1.4 The examples are based on the assumption that the satellites are in the geostationary orbit and that their operating frequencies are 6 GHz for the up-link and 4 GHz for the down-link. In geostationary orbit the up- and down-link losses to the edge of the earth (41 300 km) are assumed to be 200.6 and 196.8 dB respectively.
- 2.1.5 The effects of transmission delay and its variation (e.g., Doppler shift and pulse width variation) on various methods of modulation, are discussed in Reports 214-2 and 383-2.

2.2 Basis of comparison and limitations involved in the study

- 2.2.1 Two different situations are considered which are encountered in practice:
- “power limitation” as necessitated by restrictions on space station power,
 - “bandwidth limitation” as necessitated by restrictions on the use of radio-frequency spectrum.

Within these categories, interference is expected to be an increasingly important factor when multi-beam satellites, employing frequency re-use a number of times, enter into operational service.

Initial satellites introduced into commercial service such as INTELSAT II and III were power-limited and used repeater bandwidths up to 225 MHz wide. The availability of greater spacecraft power, however, as in the INTELSAT IV satellite, if used in similar multiple access circumstances, would have caused the in-band intermodulation products to be a limiting factor, so that channelized repeaters were introduced. In this case the basic repeater bandwidth is kept at 40 MHz and when utilized with the high-gain “spot beam” antenna, the repeater is in some cases severely bandwidth limited.

The noise in a telephone channel originates from various sources, which include:

- thermal noise arising on the Earth-to-satellite and satellite-to-Earth paths;
- interference noise from terrestrial systems and possibly other satellite systems;

- intermodulation noise;
- clicks when operation is near the threshold point.

Additionally for digital transmission:

- PCM quantization noise;
- idle channel noise when PCM signals are transmitted.

This Report does not suggest optimum noise allocations. Typical values presently in use are described, but each system will probably present a different set of operating values.

2.2.2 The detailed calculations do not take into account the use of syllabic companders.

3. General analysis

In this section a number of factors common to all system designs are discussed. The basic formulae used to determine system performance are presented, and practical performance of demodulators etc. are shown.

3.1 Frequency modulation

3.1.1 System performance

Signal-to-noise ratios

One form of the basic relationship between the carrier-to-noise ratio and the signal-to-noise ratio in a conventional frequency-modulation system is:

$$S/N = (C/N)(F_{ch}/f_m)^2 \times (B_{RF}/b) \times p \times W$$

where S/N is the ratio of test-tone power (i.e., 1 mW at a point of zero relative level) to the psophometrically-weighted noise power in the highest telephone channel;

C/N is the carrier-to-noise ratio in the bandwidth B_{RF} ;

B_{RF} is the radio-frequency bandwidth (Hz);

b is the bandwidth of the telephone channel (3100 Hz);

F_{ch} is the r.m.s. test-tone deviation per channel (Hz);

f_m is the mid-frequency of the highest baseband channel (Hz);

p is the pre-emphasis improvement factor;

and W is the psophometric weighting factor.

In this Report, p and W are assumed to have the values of 4 dB and 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:

$$B_{RF} = 2(\Delta F + f_m)$$

(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:

$$\Delta F = F_{ch} \times g \times L$$

where ΔF = peak deviation in Hz;

F_{ch} = per channel r.m.s. test-tone deviation in Hz;

g = peak-to-r.m.s. factor: for 13 dB = $\text{anti-log} \frac{13}{20}$
= 4.47

for 10 dB = $\text{anti-log} \frac{10}{20}$
= 3.16.

L = $\text{anti-log} \frac{-15 + 10 \log n}{20}$ for $n \geq 240$ channels

= $\text{anti-log} \frac{-1 + 4 \log n}{20}$ for $n < 240$ channels.

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.

Carrier-to-noise ratios

The carrier-to-noise ratio available in a given satellite link depends on a number of factors, such as whether the repeater is being operated in a single access or multiple access mode, and in the case of multiple access, the actual number of accessing carriers. Transmission of several radio-frequency carriers through a common space station repeater produces intermodulation noise, whereas when only a single carrier is transmitted this factor is non-existent. The allowable 9000 pW psophometrically-weighted noise power at a point of zero relative level (pW0p) in a telephone channel (see § 2.1.2) may be allotted in several ways, depending on the mode of transmission, i.e. single access or multiple access, and whether an earth coverage beam or a spot beam is utilized since this has an impact on earth station power requirements. Typical examples are shown in Table I.

Examination of this Table shows that various carrier-to-noise ratios are utilized and that the individual noise contributions of the various space link components are different, depending on the mode of operation. This difference is a consequence of various system trade-off analyses that reflect earth station power limitations when transmitting multiple carriers, as well as spacecraft gain and power limitations. In all cases, a 6 dB fade in the down-path still results in the carrier-to-noise ratio remaining above 10 dB, and it also demonstrates that as more satellite power has become available, the down-path has become less dominant while the up-path and intermodulation noise contributions have come to equal approximately 40% of the total space link noise budget.

3.1.2 *FM demodulators*

Frequency modulation systems have characteristic thresholds of operation, and originally, an operating margin (m) of 6 dB above threshold in the satellite-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} defined in § 3.1.1 can be extended by such techniques as frequency feedback or phase-locked demodulators so that threshold occurs approximately 4 dB lower than in conventional demodulators.

When these demodulators are used in systems that must comply with Recommendation 353-2, it is convenient and precise to identify the threshold as the point at which the worst channel reaches 50 000 pW0p.

The use of threshold extension demodulators in frequency modulation systems does not modify the basic relationship between signal-to-noise and carrier-to-noise; it merely permits the use of lower carrier-to-noise ratios than would otherwise be possible.

TABLE I
Carrier-to-noise ratios

Parameter	Budget	17° Earth coverage beam		4.5° Spot coverage beam	
		Single access	Multiple access	Single access	Multiple access
(a) Total earth station equipment noise including group delay noise	1000 pW0p				
(b) Earth station HPA intermodulation noise	500 pW0p				
(c) Space segment noise including up-path thermal, down-path thermal, and satellite repeater intermodulation noise	7500 pW0p	$\left\{ \begin{array}{l} C/N_{up} = 24.7 \text{ dB} \\ (1500 \text{ pW0p}) \\ C/N_{im} = \text{---} \\ C/N_{dn} = 18.8 \text{ dB} \\ (6000 \text{ pW0p}) \\ C/N_T = 17.8 \text{ dB} \\ (7500 \text{ pW0p}) \end{array} \right.$	$\left\{ \begin{array}{l} C/N_{up} = 22.5 \text{ dB} \\ (900 \text{ pW0p}) \\ C/N_{im} = 17.2 \text{ dB} \\ (3100 \text{ pW0p}) \\ C/N_{dn} = 16.6 \text{ dB} \\ (3500 \text{ pW0p}) \\ C/N_T = 13.3 \text{ dB} \\ (7500 \text{ pW0p}) \end{array} \right.$	$\left\{ \begin{array}{l} C/N_{up} = 31.9 \text{ dB} \\ (4300 \text{ pW0p}) \\ C/N_{im} = \text{---} \\ C/N_{dn} = 33.2 \text{ dB} \\ (3200 \text{ pW0p}) \\ C/N_T = 29.5 \text{ dB} \\ (7500 \text{ pW0p}) \end{array} \right.$	$\left\{ \begin{array}{l} C/N_{up} = 29.2 \text{ dB} \\ (2000 \text{ pW0p}) \\ C/N_{im} = 28.3 \text{ dB} \\ (2500 \text{ pW0p}) \\ C/N_{dn} = 27.5 \text{ dB} \\ (3000 \text{ pW0p}) \\ C/N_T = 23.5 \text{ dB} \\ (7500 \text{ pW0p}) \end{array} \right.$
	9000 pW0p				

C/N_{up} = carrier-to-noise power ratio in the up-link.

C/N_{im} = the ratio of carrier power to the intermodulation noise in the common repeater.

C/N_{dn} = carrier-to-noise power ratio in the down-link.

C/N_T = carrier-to-total-noise power ratio.

Typical results of a number of measurements made on threshold extension demodulators for different carrier types and sizes are shown in Fig. 1. The curves shown represent the change of signal-to-noise ratio as a function of the input C/T value. Appropriate pre-detection C/N values are indicated, as well as the 50 000 pW0p threshold point. Pre-emphasis used was in accordance with Recommendation 464.

As more power has become available in succeeding satellite series, deviations have been reduced in order to reduce the bandwidth occupancy. This requires that the C/T values be increased in order to obtain the required top channel performance and, consequently, results in higher carrier-to-noise ratios being employed. Fig. 2 shows typical deviations utilized.

Fig. 3 shows values of $(C/T)_T$ at 50 000 pW0p as a function of channel capacity for the measurements made. Also shown are observed values for a conventional demodulator. From this curve it is seen that the best available "threshold extension" varies from approximately 5 dB at 24 channels to about 2.5 dB at 600 channels. Referring to Fig. 1, it can be seen that for a typical INTELSAT IV spot beam carrier, the degradation of signal-to-noise performance to the 50 000 pW0p threshold is linear with the input power variation at the demodulator input.

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 of 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. This filter, however, also causes 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.

Figs. 4a and 4b show the results of laboratory measurements that were made to test for this interference, where interference was specified by the number of impulse counts per 15 minutes at a set threshold as a function of both the desired carrier and the interfering carrier's deviation. Fig. 4a shows the effect due to the adjacent carriers interference both with and without the earth station transmit filters, while Fig. 4b shows the effects due to truncation by the system filters.

The behaviour of different types of demodulator under the varying of operation and interference needs further study.

3.1.3 Channel capacity

The curves labelled FDM/FM in Figs. 5 and 6 show 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). In the first case, a single access is presented and maximum capacity is obtained since the satellite repeater can operate at its saturated power output. In the second case, multiple access is shown, and the loss of capacity as the number of accesses increases is clearly demonstrated.

This comparison in the multiple access case is shown in the following example A.

3.1.3.1 Example A (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

$$B_{RF0} = 32/N \text{ MHz, where } N \text{ is the number of carriers.}$$

3.2 *Single-sideband transmission (FDM-SSB)*

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 the other two methods, e.g. it requires higher transmitter power than wide deviation frequency modulation, it is more sensitive to non-linearity; it requires highly accurate frequency synchronization, which is particularly difficult to achieve with non-geostationary satellites; it is both more susceptible to interference than wide deviation frequency modulation, and will produce more interference when its signals fall within one base-bandwidth of the carrier of other systems.

Similar noise allocations can be considered for single-sideband as for frequency-modulation (see § 3.1), 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. In this case, peak-to-r.m.s. voltage ratios of 10 and 13 dB can be used in a manner similar to § 3.1.

Present-day amplifiers would give results according to the curve E in Fig. 5 for peak-to-r.m.s. ratios of 10 dB. Perhaps in the future, special amplifiers employing additional circuits to carry the peak load could operate closer to the mean power curve D.

Curve A in Fig. 6 shows the number of channels as a function of (e.i.r.p. + G/T) for the multiple-access case. This curve is based on the following example B.

3.2.1 *Example B (SSB-FDM/FM)*

- modulation conversion is performed at the space station,
- up-path thermal noise is ignored, since this does not affect the threshold,
- no repeater back-off is provided in the space station, since only one radio carrier is being transmitted.

3.3 *Pulse-code modulation (PCM)*

3.3.1 *Analogue to digital coding*

The performance characteristics of PCM systems for telephony are still under study in C.C.I.T.T. Study Group XII and Special Study Group D.

Transmission of a large number of telephone channels is possible, either by encoding individual telephone channels and multiplexing them in time-division (TDM-PCM), or by encoding a frequency-division multiplex baseband (FDM-PCM). It can be shown that the

radio-frequency bandwidth and transmitter powers required both differ by a small amount in favour of TDM-PCM for a given capacity. Therefore, these cases will not be treated separately.

According to C.C.I.T.T. Recommendation G.711 (Green Book, Geneva, 1972, Volume III-2) in the case of TDM-PCM, eight bits per sample should be used for international circuits and the sampling frequency should be 8 kHz per speech channel. Adding about 5% for frame alignment, the bit rate for n speech channels is then:

$$1.05 \times 64 \times 10^3 \times n = 67\,200\,n \text{ bit/s}$$

3.3.2 Phase-shift keying

A few simple examples are considered here assuming the system is only subjected to thermal noise and using an extra margin in the signal-to-noise ratio to take into account other effects.

The number of phase positions considered in the examples is 2, 4, 8 and 16 (see Report 378-2). 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.

The bit energy to noise density ratio E/N_0 corresponding to this error-rate is given in Table II for coherent (CPSK) and differential (DPSK) detection of PSK signals.

TABLE II

Number of states	E/N_0 ($P_{be} = 1 \times 10^{-4}$)	
	CPSK	DPSK
2	8.4	9.3
4	8.4	10.7
8	11.8	14.8
16	16.1	19.1

E is the energy per bit in W.s and N_0 is the noise power in a bandwidth of 1 Hz [Lundquist *et al.*, 1974]. The above Table accounts for a Gaussian noise signal disturbing the information signal.

In comparison to CPSK, DPSK has about a 3 dB penalty for a system with 8 or more phases and there is only 0.9 dB penalty for binary systems. However, the interference performance of CPSK and DPSK can be significantly different, for example for $E/N_0 = 20$ dB, $C/I = 10$ dB, and $M = 4$, the CPSK error-rate is about 10^{-9} , but in order to satisfy the same error-rate objective, the interference in the DPSK system must be reduced by 10 dB ($C/I = 20$ dB) (see Report 388-2).

In CPSK, however, there is the problem of resolving at the receiving end which of the n possible states of the recovered reference carrier is the reference state. The most suitable way to resolve this problem is to differentially encode the data bit stream before modulation. This implies an additional power requirement which for example, in the case of 4 phase differentially encoded CPSK, amounts to 0.4 dB.

The transmission degradations of PSK are not completely understood. Several authors have reported on results for different systems [Lundquist *et al.*, 1974; Lundquist, 1974; Muratani *et al.*, 1972].

3.3.3 *Signal coding and processing*

One advantage inherent in PCM is that it lends itself to all the encoding techniques available to data transmission systems.

For a power-limited system, the use of error-correcting codes permits lower satellite power or lower G/T of the earth stations. For example, a rate of 0.5, constraint length $K = 7$, convolutional encoder, soft-decision decoder requires 5 dB less energy-per-bit than an uncoded coherent PSK modem to achieve a bit error probability of 10^{-5} [Jacobs, 1972].

Additionally PCM allows full advantage to be taken of the application of digital speech interpolation technique as is shown in the Annex.

3.3.4 *Channel capacity*

The curves B and C in Figs. 5 and 7 show the number of channels as a function of (e.i.r.p. + G/T) for a PCM-PSK system operating 6.3 dB above the point equivalent to 50 000 pWp in the analogue system (10^{-4}). The steps in these curves are a consequence of the limitation of the satellite bandwidth to 40 MHz. It is clearly shown that the loss of capacity as the number of accesses increases is very little for TDM-PCM-CPSK-TDMA and TDM-PCM-DPSK-TDMA systems.

These comparisons in the multiple-access case are made by the following examples.

3.3.4.1 *Example C (PCM-PSK-FDMA)*

The assumption of noise allocation, multi-carrier back-off and guard bands are the same as those in § 3.1.3.

3.3.4.2 *Example D (PCM-PSK-TDMA)*

- there are up to 10 earth stations assigned to this 40 MHz channel 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 coordination.

4. Comparison of modulation and access techniques

Comparison of the various methods of modulation and access techniques can be conveniently broken out as follows:

4.1 *Single access mode*

Three alternative modulation techniques for satellite communication under a single access mode of operation:

Comparing the curves of Fig. 5, it can be observed that, while the required values of satellite power for FM and PSK are of the same order, those for single-sideband differ greatly. Where spectrum economy is of great importance, the use of single-sideband may need to be considered.

It is apparent from Fig. 5 that both 2-level coherent phase-shift keying and frequency-modulation require about the same transmitter power. Both differential phase-shift keying and coherent phase-shift keying are seen to be more attractive than FDM-FM when 4, 8 or 16 levels are considered under the conditions of bandwidth limiting we have taken here. It should be kept in mind that a different assumption for the peak-to-r.m.s. ratio of the multi-channel signal will lead to different traffic capacities for the FDM-FM case. Frequency-modulation is a better-established technique than PCM-PSK and therefore its performance as given here may be closer to practice than the PCM-PSK performance. Some points should be noted in favour of pulse-code modulation:

- the signal-to-noise ratio for PCM-PSK under normal operating conditions is better than for frequency modulation, as far as idle channel noise is concerned;
- under normal operating conditions, PCM-PSK has a very high degree of immunity against interference;
- TDM-PCM systems are more readily adaptable to the transmission of digital information.

4.2 *Multiple access mode*

The use of FDM-FM-FDMA, PCM-PSK-FDMA, and PCM-PSK-TDMA would all technically permit the inclusion of large and small antenna earth stations in a system; but the FDMA techniques are the most likely to aggravate space station-inter-modulation problems.

It should be noted that in PCM-PSK-TDMA, it is alternatively possible to use correspondingly longer pulses for transmission to less sensitive stations.

In SSB-FDMA/FM, all earth stations must demodulate the entire down-path transmission, and the system channel capacity is therefore limited by the least sensitive station.

A high degree of coordination among earth stations is required for these multiple-access methods.

Except for the PCM-PSK-TDMA case, earth-station transmitter power must be controlled to ensure that all carriers have the same power level at the space station, regardless of the variations in transmission loss. It is also necessary to ensure that frequencies transmitted by the earth stations are received at the space stations in the correct relationship and this requirement is particularly stringent for SSB-FDMA/FM. Stringent requirements of synchronization apply to PCM-PSK-TDMA, but this is a matter of low power level digital circuitry.

Another method of multiple access, which is equally suitable for different methods of modulation, involves the use of a separate repeater for each carrier. This has not been discussed separately here, since it is a straightforward extension of the single-access cases discussed earlier and the assumption of a bandwidth limitation of 40 MHz per repeater permits the use of about a dozen such repeaters in a 500 MHz frequency band.

5. **Interference between communication-satellite systems and other radio services**

5.1 *Frequency modulation*

Frequency modulation produces a spectrum with an energy distribution which is a function of the modulating signal. With lightly loaded or unmodulated frequency-modulation multi-channel telephony systems, a considerable part of the total energy is concentrated in relatively narrow frequency bands, so that a greater interference potential exists than for a normally loaded frequency-modulation system. This situation may be avoided by carrier energy-dispersal.

5.2 Pulse-code modulation

Under conditions of light loading, a pulse-code modulation system produces a multiple line spectrum with components spaced at $1/yt$ where y is the number of bits per sample and t the bit duration. The effect of loading is to decrease the amplitudes of the line components and to fill in the spaces between the lines. With $y = 7$, the maximum line amplitude is about 0.3 of the unmodulated carrier power. In the absence of special precautions, the interference potential of lightly loaded pulse-code modulation systems could be significantly greater than that of frequency-modulation systems of similar capacity and performance. However, the interference potential of pulse-code modulation systems under light-loading conditions can readily be reduced by one of several techniques, for example, the use of modified coding which avoids repetitive patterns. Two methods of modified coding for energy-dispersal of pulse modulation systems are shown in Annex III to Report 384-2.

Attention is drawn to Report 388-2 which discusses interference to pulse-code modulation systems.

5.3 Single-sideband modulation

Single-sideband modulation concentrates the transmitted energy into a bandwidth equal to the width of the baseband, and the power of any telephone channel is confined to a bandwidth equal to that of the channel. As a result, there is a risk of a high level of interference from the single-sideband modulation down-link transmission to terrestrial radio-relay systems which use frequency modulation, when a single-sideband modulation signal falls within the first set of sidebands of the terrestrial system. Since there is no demodulation improvement associated with single-sideband modulation it is more vulnerable to interference than wide deviation frequency modulation or pulse-code modulation.

6. Summary

This Report has considered the advantages and disadvantages of several modulation methods suitable for systems in the fixed satellite service. An available bandwidth of 40 MHz for the space-station repeater has been considered throughout. The various modulation techniques are compared on the basis of the communication capacity of the system (measured in telephone channels) vs. the available ratio of carrier power, at the input of the earth-station receiver, to the receiving system noise temperature. The degradation of the communication capacity inherent to the multiple-access mode of operation is discussed and it is found to be severe when frequency modulation and a great number of carriers is considered. It has been necessary to make a number of assumptions, some of which require verification.

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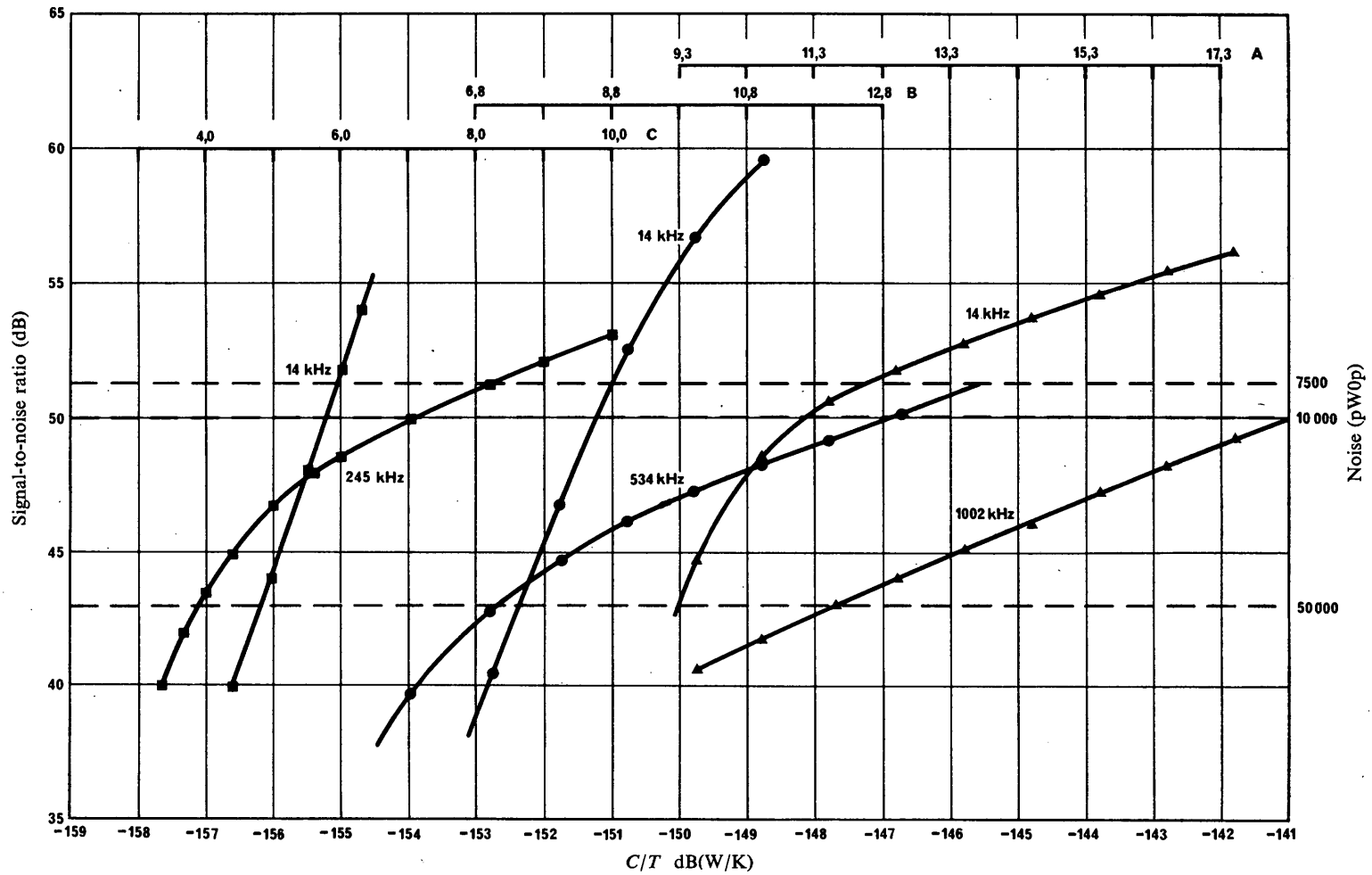


FIGURE 1
FM demodulator noise performance
(Threshold extension type)

- INTELSAT III, 60 channel carrier
- INTELSAT IV, 132 channel global carrier
- ▲ INTELSAT IV, 252 channel spot beam carrier

A = C/N (252 channels) B = C/N (132 channels) C = C/N (60 channels)

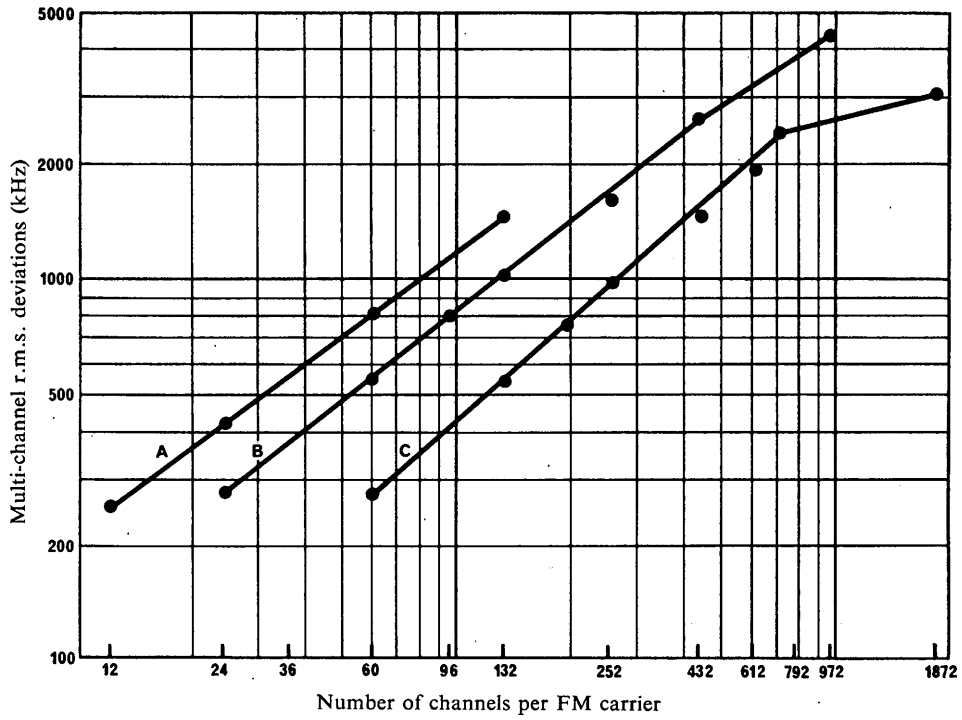


FIGURE 2

Typical INTELSAT r.m.s. multi-channel deviations

- A: INTELSAT II and III
- B: INTELSAT IV global beam
- C: INTELSAT IV spot beam

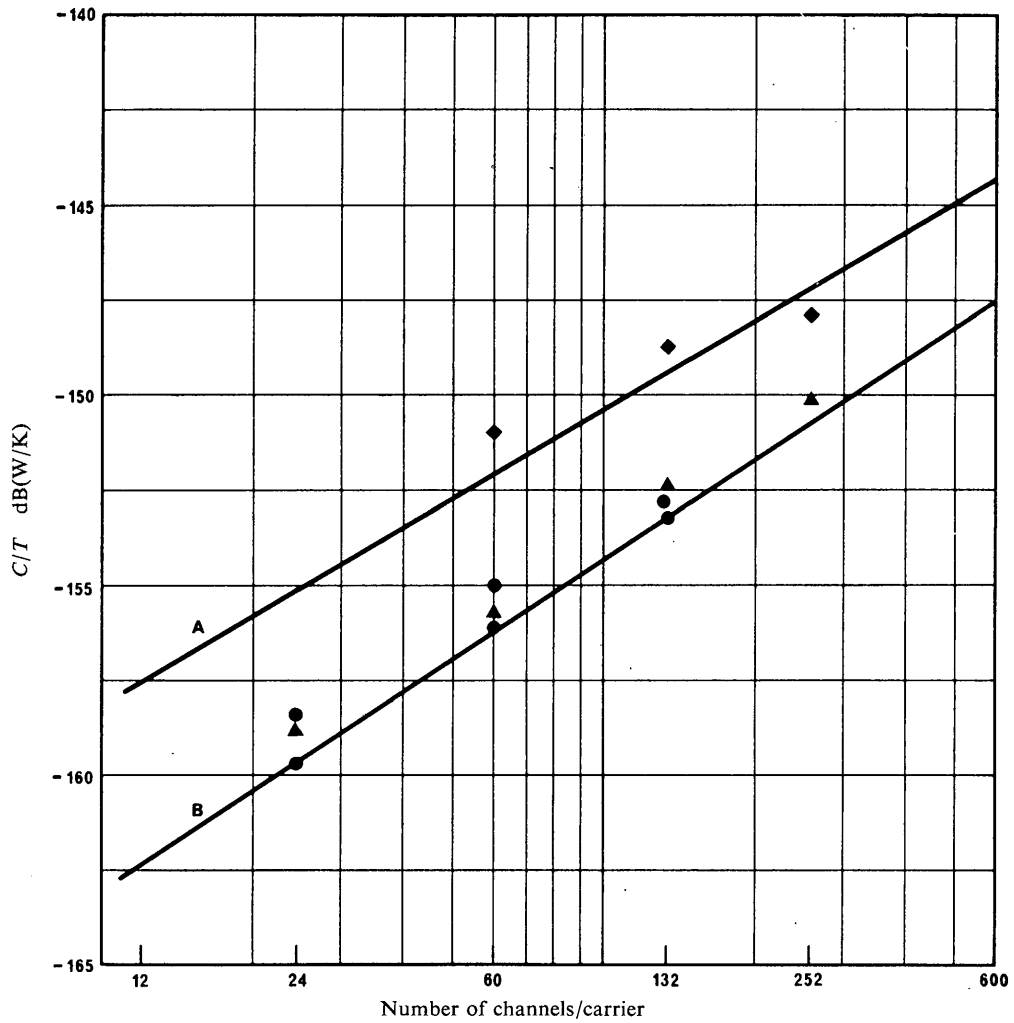


FIGURE 3

C/T at 50 000 pW0p in FM demodulators
 (*C/T when noise in worst channel = 50 000 pW0p*)

- Typical INTELSAT III deviations and carrier-to-noise ratios
- ▲ Typical INTELSAT IV global beam deviations and carrier-to-noise ratios
- ◆ Typical INTELSAT IV spot beam deviations and carrier-to-noise ratios
- A: Conventional demodulator
- B: Threshold extension demodulator (line represents slope given by:
 $(C/T)_{TH} = -171.7 + 8.7 \log_{10} n$)

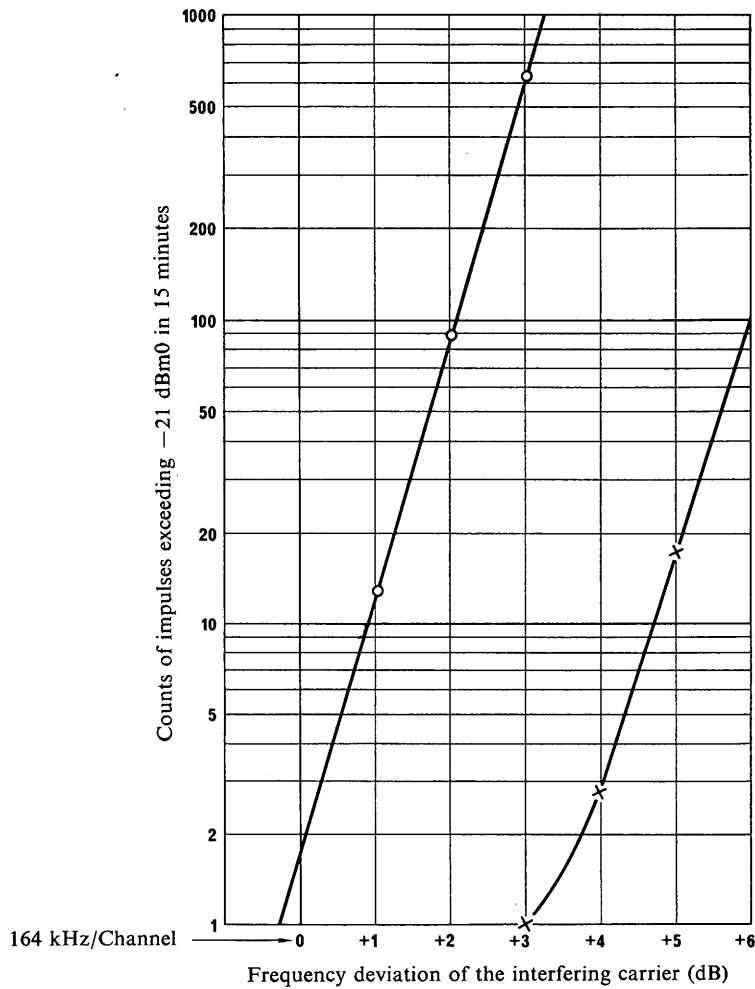


FIGURE 4a

Impulsive noise due to adjacent carrier interference
(D/I: 0 dB)

Desired: 24 Channels, deviation 164 kHz/Channel, $C/T = -153$ dB(W/K)
Interfering: 24 Channels

- D: with R BPF
- ×— D: with T BPF and R BPF
- I: without T BPF
- I: with T BPF

T BPF: transmit bandpass filter
R BPF: receive bandpass filter

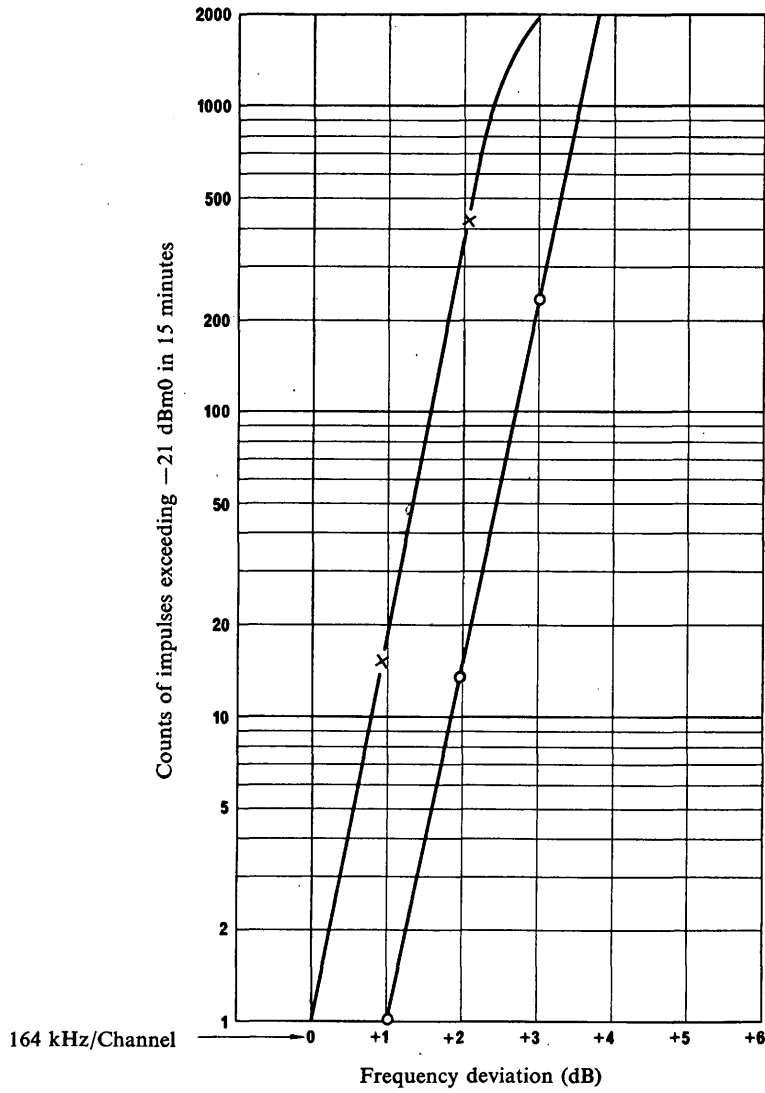


FIGURE 4b

Impulsive noise due to bandpass filters (24 channels)
C/T: -153 dB(W/K)

- with R BPF only
- X— with T BPF and R BPF

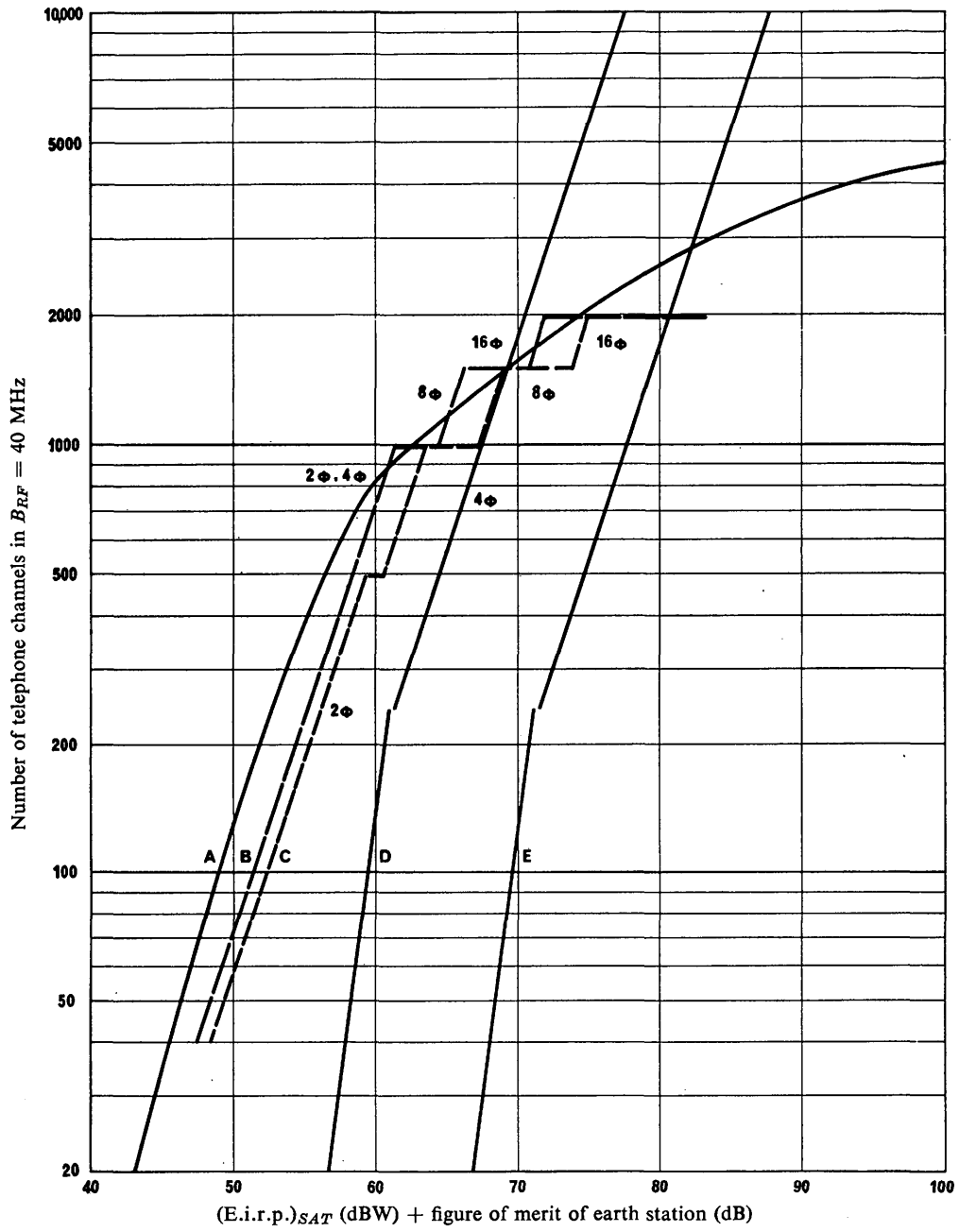


FIGURE 5
Single access

Curves A: FDM-FM
B: TDM-PCM-CPSK
C: TDM-PCM-DPSK

Curves D: FDM-SSB-average
E: FDM-SSB-peak

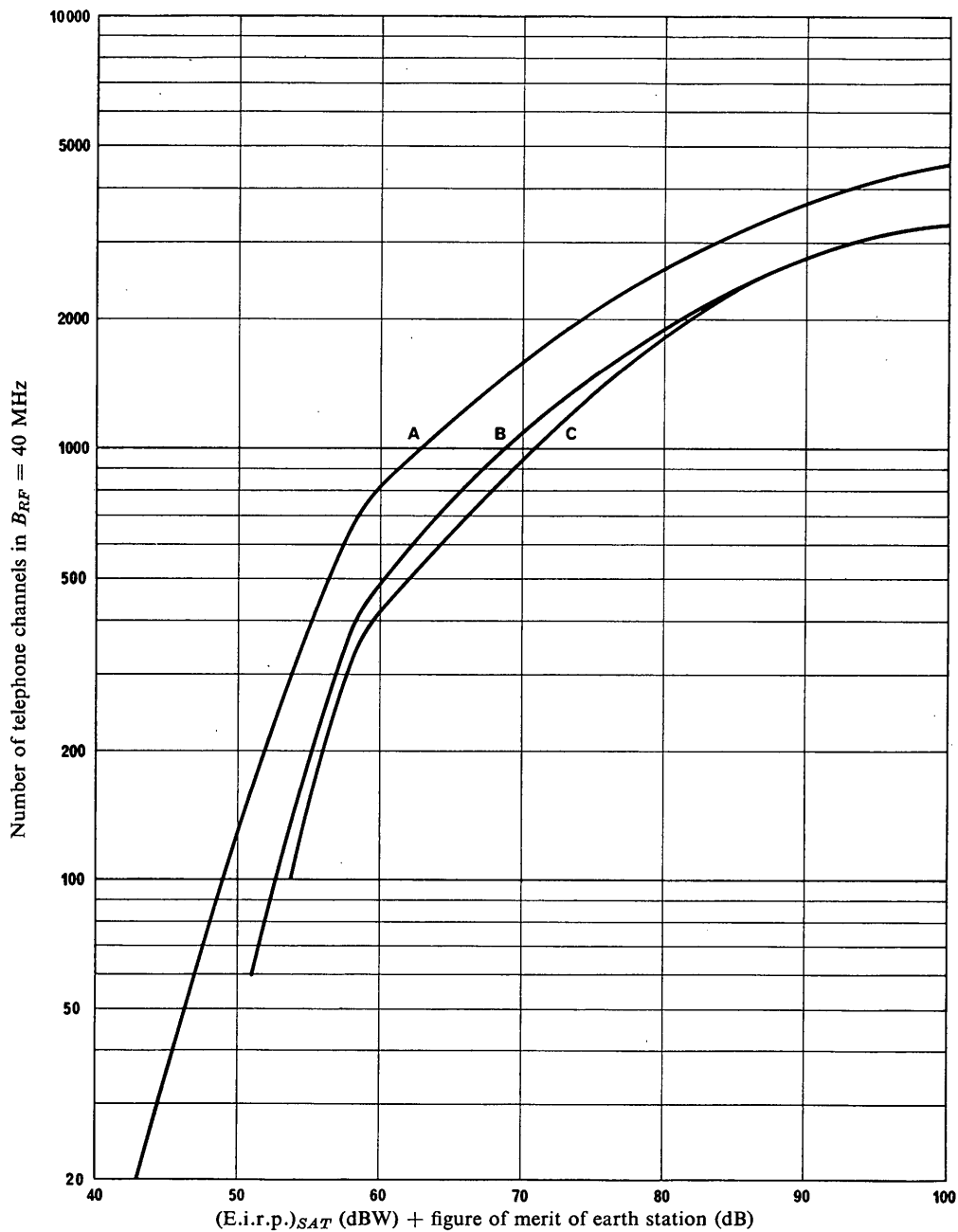


FIGURE 6

Multiple access, examples A and B

Curves A: SSB-FDMA/FM
B: FDM-FM-FDMA 5 carriers

Curve C: FDM-FM-FDMA 10 carriers

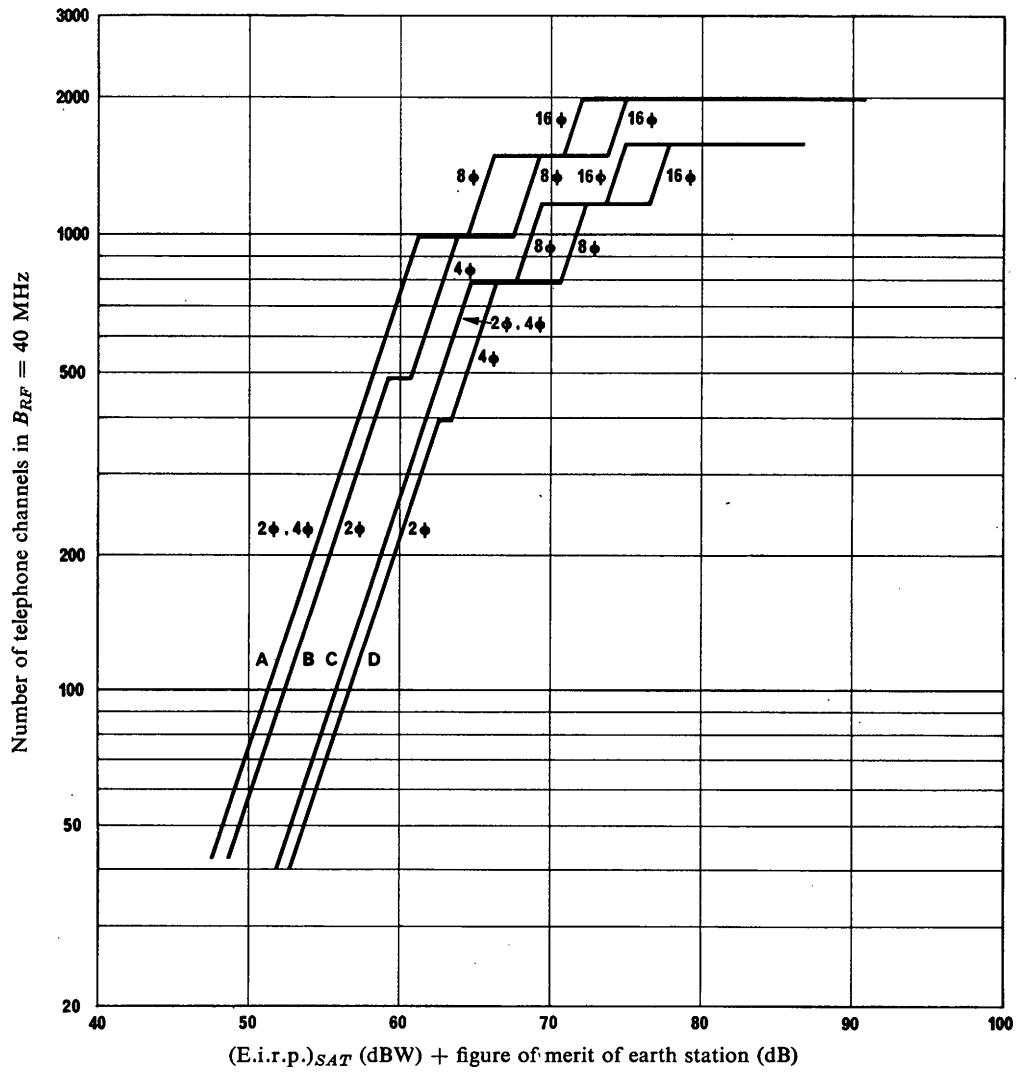


FIGURE 7

Multiple access, examples C and D

- Curves A: TDM-PCM-CPSK-TDMA
- B: TDM-PCM-DPSK-TDMA
- C: TDM-PCM-CPSK-FDMA
- D: TDM-PCM-DPSK-FDMA

ANNEX

SPEECH INTERPOLATION TECHNIQUE IN TDMA SYSTEMS

Speech interpolation (SI) techniques are based on the fact that, in a normal two-way conversation, each talker 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 the mean activity factor (A), as derived by tests carried out by several Administrations (C.C.I.T.T. Recommendation G.223) for a telephone channel in one direction of transmission is of the order of 25%.

Accordingly, if the talker's connection can be disconnected from the transmission channel in such a manner that the same transmission channel can be assigned to different talkers 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; Amano and Ota, 1969]. The theoretical speech interpolation gain (G) is defined by the ratio between the number of talkers (input trunks, N_i) and the number of transmission channels (N_c) required to serve them.

In the case of analogue systems such as FDM/FM, the increase of 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 TDMA, 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 TDMA system with speech interpolation is greater than that obtained for an FDM/FM system using this technique [Lyghounis and Costa, 1971].

There are two ways of incorporating a digital speech interpolation (DSI) facility in a TDMA 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 to as "multi-destination" DSI.

In TDMA systems, the theoretical capacity gain obtained by the use of DSI, where the speech interpolation process is done at PCM/TDM level, 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 systematic 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, Monti and Bagnoli, 1972; Quaglione, Ruspantini and Lembo, 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 the available transmission channels. The degradations introduced, depend, in this case, upon the speech interpolation strategy employed and are directly related to the desired DSI gain and, therefore, to the system capacity.

The most significant DSI strategies are:

- a concentrated freeze-out strategy;
- a strategy whereby the number of bits per transmission channel is reduced to 7 (bit reduction strategy).

With the first strategy when the system goes into overload, clipping is introduced, whose average value is defined as freeze-out (Φ). Practical tests on users' reaction to the presence of speech degradation introduced by DSI, show that a "freeze-out" grade varying between 0.5% and 1% is practically unnoticeable by an average listener. Nevertheless, the theoretical gain, G , is related to the

“freeze-out” introduced by DSI so that, to calculate N_c relative to a specified N_t , it is necessary to take into account a given “freeze-out” percentage [Bullington and Fraser, 1959] as shown in the following approximate relationship:

$$N_c = N_t A + Y \sqrt{N_t A}$$

where:

A : mean voice activity factor,

Y : parameter related to the “freeze-out” grade.

In Fig. 8 the dotted line shows G as a function of N_c , when the mean activity $A = 35\%$ and for a freeze-out fraction $\Phi \leq 1\%$, corresponding to $Y = 1$ [Bullington and Fraser, 1959]. From this curve it appears that the DSI advantage increases as the number of communication channels increases.

The DSI advantage considered here does not take into account the assignment signalling bits required for the organization and operation of the DSI. However, these DSI signalling bits do not introduce a significant reduction in the theoretical gain of DSI, provided that a suitable format is chosen for this signalling message [Lyghounis, 1968].

With the bit reduction strategy, the request for additional transmission channels is met by using the eighth bit of the various channels. 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 of a possible residual freeze-out, which is qualitatively similar to that which occurs with the concentrated freeze-out strategy.

Subjective tests performed in Italy on equipments employing both strategies under the same operating conditions, i.e. with same N_t , A and G , revealed that the voice quality obtained by means of the bit reduction strategy is better than that achieved with the concentrated freeze-out strategy [Poretti, Monti, and Bagnoli, 1972]. Moreover, a higher DSI gain and therefore a greater total system capacity is achieved through the bit reduction strategy as compared with the concentrated freeze-out for the same voice quality, other conditions being equal [Poretti, Monti, Bagnoli and Bernasconi, 1974].

The continuous curve of Fig. 8 shows the equivalent value of the DSI gain as a function of N_c with $A = 35\%$, in the case of the bit reduction strategy. To draw this curve the number of 7 bit channels which can be obtained from the number of available 8 bit channels and the resulting increased G have been taken into account.

Fig. 9 shows, as an example, the comparison of channel capacities using TDMA multi-frame and DSI for the two strategies assuming equivalent subjective quality of service.

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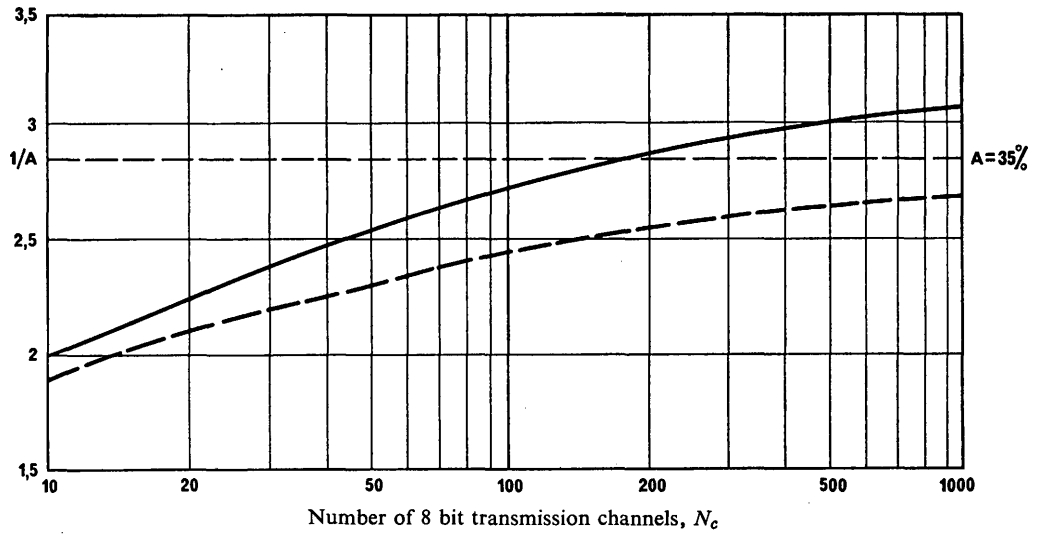


FIGURE 8
DSI gain (G) for different numbers of transmission channels (N_c)

- Bit reduction strategy: curve of equivalent gain: $\Phi \leq 0.5\%$
- - - Concentrated freeze-out strategy: $\Phi \leq 1\%$

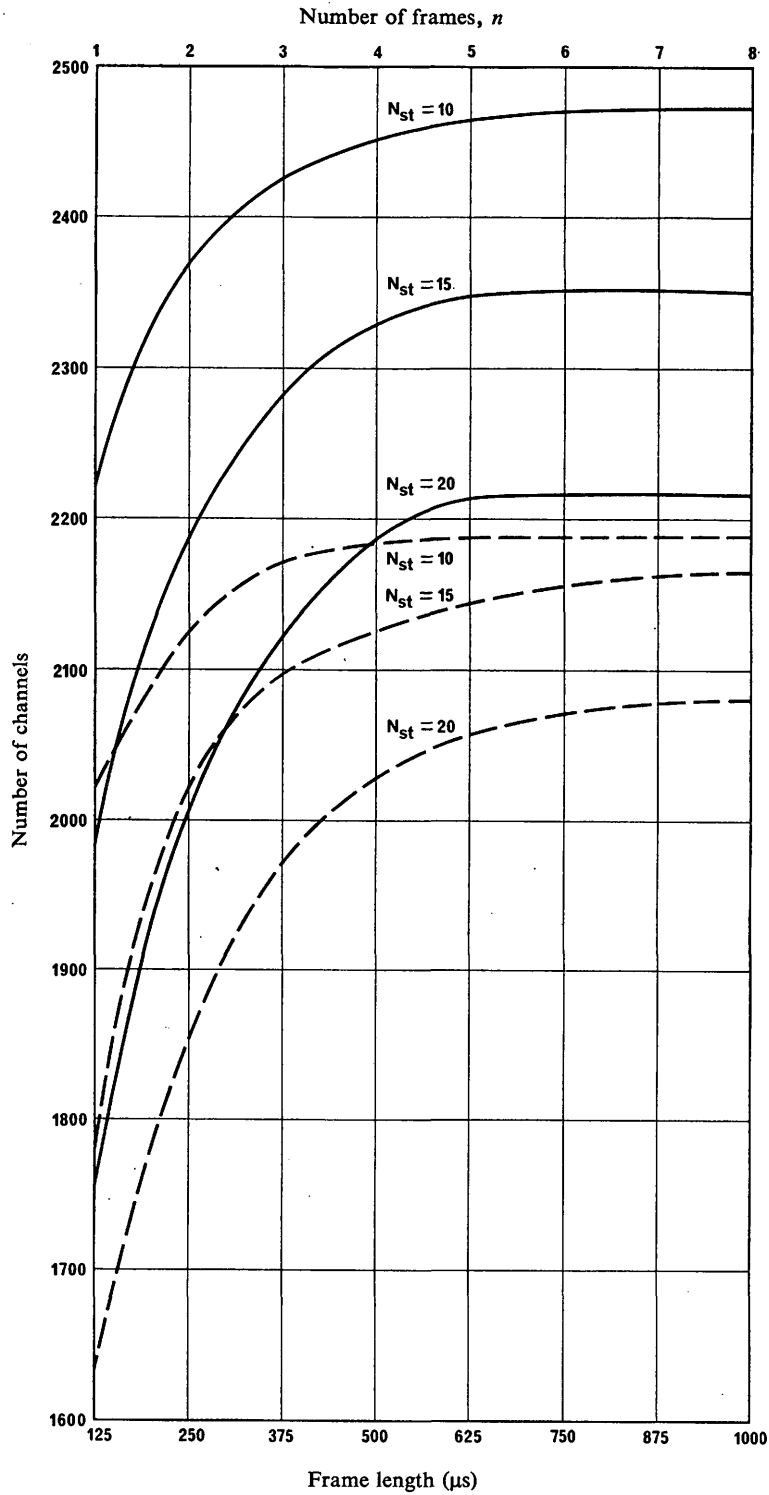


FIGURE 9

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: average time of operating at 7 bit $\leq 6\%$
residual $\Phi \leq 0.5\%$

REPORT 213-3 *

**FACTORS AFFECTING MULTIPLE ACCESS IN SYSTEMS IN THE
FIXED SATELLITE SERVICE**

Methods of modulation, multiplexing, orbital parameters and earth-station sensitivity

(Study Programme 2E-1/4)

(1963 – 1966 – 1970 – 1974)

1. Introduction — nature of the problem

The satellite in a system in the fixed satellite service is a nodal point in the circuits to the earth stations involved. The problem of multiple access in satellite communications is to achieve, with the satellite, as high a degree of flexibility of interconnection between the earth stations as may be desired. In this respect, the satellite repeater differs from the repeater in a terrestrial radio-relay system. In the terrestrial radio-relay system, the repeaters have not been called upon to provide multiple access of the type and scope which is envisaged with the satellite repeater.

In the satellite repeater, multi-channel transmissions from a number of earth stations will be brought together (thus “multiplexed” in a general sense) for amplification and retransmission to these same earth stations.

In the extreme, one can envisage an enormous and complex satellite having remodulating facilities for each of its earth stations, and having switching equipment to interconnect and reconnect all of these circuits as needed. The objective in the development of multiple-access satellite communication is to approach the communication utility of such an ideal “exchange in orbit”, while at the same time keeping the satellite small and reliable, hence relatively simple, consistent with the state of development. At present, any circuit switching or its equivalent should be accomplished and controlled from the Earth. There still, however, may be a degree of signal processing performed in the satellite.

2. Factors determining the accessibility of a system in the fixed satellite service to a number of earth stations

A system in the fixed satellite service should function within the technical and operational framework of the international world network as defined by the C.C.I.T.T. Since an orbiting satellite’s field of view at any given time generally encompasses a large number of countries, the introduction into service of earth stations by these countries and their consequent desire for interconnectivity may require some adjustments in these world network concepts.

The accessibility or “freedom of access” available to earth stations to enter a system in the fixed satellite service is governed by the following factors, which are discussed in the subsequent sections of this Report:

- the methods of multiple access;
- the orbital parameters of the system;
- the antenna coverage of the space station;
- the methods of modulation;
- the methods of multiplexing;
- the possible diversity of earth-station characteristics, such as transmitting power, antenna gain and receiving system noise temperature. (Earth-station sensitivity is determined by the ratio of antenna gain to the noise temperature of the receiving system.)

* Adopted unanimously.

Indirectly, the permissible complexity in the satellite, in earth stations, and in terrestrial control networks, will also affect the accessibility.

3. Multiple access and the effects of systems of modulation and methods of multiplexing

3.1 *Information processing in the satellite, general remarks*

The following four possibilities have received particular consideration:

- a satellite involving a minimum of signal processing, consisting of frequency translation of all signals together from the receiving to the transmitting frequency bands, through a single repeater;
- a satellite involving frequency translation, accompanied by a change of modulation, as for example from a single-sideband transmission to a phase-modulated transmission;
- a satellite employing more than one repeater simultaneously, with one or more carriers per repeater;
- a satellite in which the earth-station signals are demodulated to baseband, then suitably transposed and recombined before modulating the transmitted carrier or carriers.

3.2 *Design considerations for satellite repeaters*

Considerations in the design of present-day satellites affect the choice of modulation systems. One of these is that satellite repeaters have been limited in output power, due to limitations on mass and on primary power, and due to the power demands of sub-systems other than the repeater.

Active communication satellites, thus far, have used output powers of the order of 5 to 10 W per transmitter, although, in some cases as in the U.S.S.R. *MOLNIYA-I* satellite, the output power is about 40 W. High gain narrow beam antennae have been utilized, such as the 4.5° spot beams of the *INTELSAT IV* satellites as well as earth coverage beams.

Satellite repeaters used thus far, as well as those contemplated for use in the near future, all employ travelling-wave tubes in the final power amplifier. For high efficiency these tubes are operated as close to saturation as possible, although due to the increased earth station and satellite powers now available, when operating simultaneously with multiple carriers considerable back-off from the saturation point is required in order to maintain the non-linear distortion of these tubes at an acceptable 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-keyed) is most likely to be the method of modulation employed. However, the PSK signal operating in a bandwidth limited system will exhibit amplitude modulation and will therefore undergo non-linear distortion in the satellite travelling-wave tube. The bandwidth of the distorted signal is usually greater than the signal bandwidth. Therefore, a TDMA system employing PSK modulation may suffer some degradation from non-linear effects in the satellite, and may impose interference on the adjacent radio-frequency channels. Depending on the bandwidth of the filter following the travelling-wave tube, this interference can become the limiting factor in the performance of an FM/FDMA system operating in a channel adjacent to a PSK/TDMA system.

3.3 *Specific methods of modulation and multiplexing*

3.3.1 *General considerations*

This Report deals with methods by which all the radio-frequency signals in the desired multiple-access configuration can share the available transmitter power in a satellite repeater.

Each method is classified according to the technique used to associate the received radio-frequency signal with the particular remote earth source.

Any conventional form of amplitude modulation or angle modulation may be used with any baseband signals. If the baseband signal is in pulse code format, phase-shift keying is usually preferred. If the technique of multiple access at radio frequencies dictates intermittent use of the radio-frequency carrier, a pulse format is necessary.

The baseband signal may be in any conventional form such as frequency-division multiplex of message channels, or it may be put into a pulse format. The pulse format may be a time-division multiplex of pulse samples of each message channel, or pulse samples of a frequency-division multiplex of message channels. The pulse samples may use an analogue representation such as pulse amplitude, pulse width or pulse-position modulation or may use a digital representation such as pulse-code modulation (PCM). A digital pulse format is attractive because it is generally less susceptible to interference and intermodulation.

3.3.2 *Four methods of multiple access at radio frequencies*

Four methods are summarized below. A more detailed explanation is presented in Annex I.

- 3.3.2.1 Frequency-division multiplexing at radio frequencies without change of modulation in the repeater. Each up-path radio-frequency carrier occupies a particular frequency allocation. All radio-frequency carriers are amplified simultaneously and translated to a new set of frequencies in the down-path. The earth receiving station filters out the desired radio-frequency carrier or carriers prior to demodulation. (It may be necessary in addition to select channels addressed to that station.) INTELSAT satellite series II, III, and IV have employed this method of multiple access.
- 3.3.2.2 Frequency-division multiplexing at radio frequencies with change of modulation in the repeater. The particular method discussed employs single-sideband suppressed carrier amplitude modulation for the up-path, with all stations employing the same radio-frequency carrier, and each station employing a unique portion of a frequency-division multiplexed baseband. In the satellite repeater, the composite signal from the several earth stations modulates the down-path radio-frequency carrier with angle modulation. The receiving earth station identifies its message channels after it demodulates the down-path radio-frequency carrier.
- 3.3.2.3 Time-division multiplexing at radio frequencies requires that all participating earth stations transmit periodically in an established sequence such that the communication repeater in the satellite is only amplifying the signals of one earth station at any instant. Thus the satellite travelling-wave tube can be operated near saturation and the power loss due to back-off can be reduced. This loss is constant and independent of the number of accesses.

A particular earth-station receiver identifies the desired transmission by observing the information in the periodically distributed time-slots associated with the corresponding transmitting earth station. All earth stations transmit at nominally the same frequency.

3.3.2.4 *Common-spectrum techniques*

Common-spectrum systems are those in which signals from all of the participating earth stations make common use of the time-frequency domain and receiver

processing is employed to detect a wanted signal, in the presence of others. By design, two or more signals at the same frequency can exist simultaneously in such systems. Three typical approaches to providing multiple-access capability are:

- spread spectrum;
- frequency-time matrix;
- frequency-hopping.

3.4 *Methods of control*

It is possible that channels will be available for use by any of the participating earth stations using one of the following three methods of gaining access.

— *Controlled access*

An earth station desiring access to the system must request and obtain access to the system via a network management facility.

— *Self-ordered access*

An earth station desiring access to the system would be able (by appropriate means) to ascertain which radio-frequency channels or time-slots are available, and consequently to be able to enter an available channel. (The "channel" can be a radio-frequency channel, or a channel or group of channels in a frequency-division multiplex or time-division multiplex baseband. In the latter case, an addressing procedure is necessary.)

— *Un-ordered access*

In common spectrum or random-access discrete address systems, access would normally be gained to a radio-frequency channel without first determining the availability of a channel.

Maximum utilization efficiency in this method is obtained if all participating stations adopt operational procedures which ensure that each station transmits at the lowest message information rate consistent with instantaneous traffic demand.

4. **The effects of orbital parameters and satellite antenna coverages on multi-station access**

For satellites at a given altitude, there will be an area in space within which a satellite will be visible to two or more earth stations. The radial projection of this area on the Earth is the area of mutual visibility. Alternatively, the sub-satellite point on Earth is surrounded by a circle on the Earth enclosing the area from which the satellite is visible above a certain minimum angle of elevation. The diameter of this circle is a function of the altitude; this circle is the visible zone for that one satellite. In case the satellite antenna coverage is narrower than the visible zone, the accessibility of a satellite is restricted by the coverage of the satellite antenna.

4.1 *Geostationary satellites*

A geostationary satellite has a constant visible zone so that all earth stations can have continuous direct connectivity with each other using one antenna system per earth station. Although a large propagation delay is associated with this altitude, such a satellite needs minimal compensation for variations in frequency or propagation delay due to changing ranges.

A geostationary satellite can be designed to have narrow beam satellite antennae. Adoption of narrow beam satellite antennae yields advantages in improving the receiver sensitivity of the satellite, increasing its effective isotropic radiation power, and in some cases, making it possible to re-use the given portion of the frequency band.

With fixed earth-station antennae, a truly geostationary satellite would be desirable. However, the satellite need not be perfectly geostationary, because the antenna beam of a fixed reflector can be moved somewhat by moving the antenna feed, or by other appropriate means.

A geostationary satellite must carry controllable thrust, adequate for station-keeping throughout its life.

4.2 *Non-geostationary satellites*

— *Unphased satellites*

Assuming equal repeater capabilities, satellites for use in unphased satellite systems can be light and simple, because they need not carry controllable thrust equipment.

Systems of unphased satellites have a low probability that a particular satellite will be in the area of mutual visibility and, therefore, need a much higher number of satellites for the same coverage (see Fig. 1).

— *Phased satellites*

Systems of phased satellites (particularly those following recurrent earth tracks) can give the required coverage with a relatively low number of satellites. In general, the greater the altitude of such systems, the greater will be the coverage areas, but the greater also will be the propagation delay. Phased satellite systems, with their defined coverage areas and defined "active" arcs, need less complex systems of earth-station antennae than do systems of unphased satellites.

— *General considerations*

The continuity of the service of a non-geostationary satellite system, with respect to the chosen group of earth stations, is defined as the probability of finding at least one satellite in the corresponding area of mutual visibility. As the area over which the earth stations are dispersed increases, the mutual visibility area decreases, necessitating an increase in the number of satellites required to maintain a given probability of finding one satellite in the mutual visibility area. Reducing the area covered by a given group of earth stations increases the area of mutual visibility, but gives rise to other problems. If the coverage zones chosen are small, connection over long distances will require multi-hop routing. This can result in large propagation delays and complex operating procedures.

Hand-over is required except with geostationary or synchronous near-stationary satellites. Because large steerable earth station antennae cannot be moved quickly from a "setting" satellite to a "rising" one, uninterrupted hand-over requires the use of two such antennae, each with its own transmitter, receiver and tracking system.

The choice of a non-geostationary satellite raises the problem of the switching discontinuity at hand-over, due to differences between the lengths of the radio paths. Systems of non-geostationary satellites must be capable of compensating for larger Doppler shifts and a greater range of time delay. These considerations are discussed further in Reports 214-2 and 383-2.

4.3 *Preferred orbital systems*

There are conflicting factors governing the choice of orbital parameters, but on balance it would appear that the types of system may be placed in the following order of preference so far as multi-station access is concerned:

- geostationary satellite systems;
- systems using closed earth tracks;
- unphased satellite systems.

Reports 206-3 and 207-3 provide further information on these systems.

5. The effect of different earth-station sensitivities

In principle, it would seem desirable that earth stations handling little traffic be smaller and simpler — and therefore cheaper — than those handling large amounts of traffic. This would imply the use of smaller antennae and perhaps less powerful transmitters and less sensitive (noisier) receivers. Such stations would therefore require more satellite power and/or radio-frequency bandwidth per telephone channel. A small station is most efficient when all of the baseband channels addressed to it are on separate carriers.

Similarly, in digital systems, for the same satellite power, in a time-division multiple-access system, the bit-rate could be decreased in appropriate time-slots to accommodate less sensitive earth stations.

The conclusion seems to be that small station access to the system is possible in many systems, but always leads to technically less efficient use of the satellite system as a whole.

6. Conclusion

As indicated in this Report, many facets of the design of multiple-access systems are being studied, and there are numerous satellite orbits, modulation and multiplexing methods, methods of gaining access, etc., between which to choose (each with its advantages and limitations). A trade-off between these factors will influence the final selection of techniques to be employed.

The attached Bibliography contains references providing more detail on the factors discussed in this Report.

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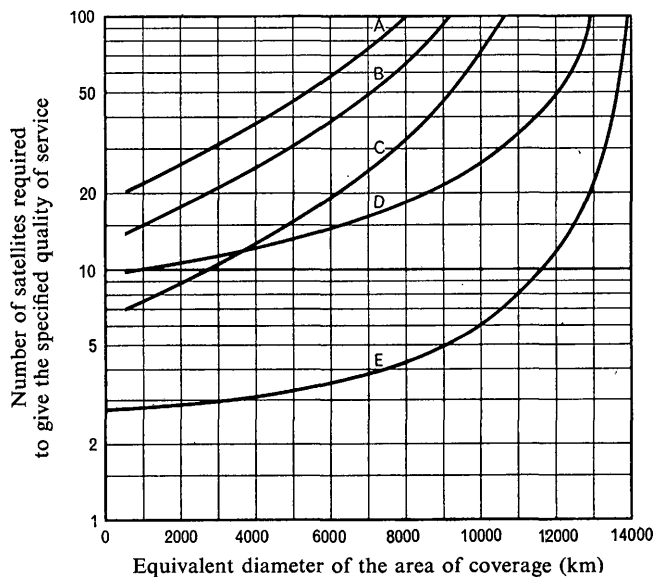


FIGURE 1

Areas of coverage for unphased and equi-spaced equatorial satellite systems
(Minimum elevation: 5°; Altitude: 14 000 km)

- Curves A: Unphased satellite, $q = 99.9\%$
- B: Unphased satellite, $q = 99\%$
- C: Unphased satellite, $q = 90\%$
- D: Unphased equatorial satellite, $q = 99\%$
- E: Equi-spaced equatorial satellite, $q = 100\%$

ANNEX I

THE EFFECTS ON MULTIPLE ACCESS OF SYSTEMS USING
MULTIPLEXING AT RADIO FREQUENCIES**1. Introduction**

The purpose of this Annex is to present a review of some of the techniques applicable to multiple access by a number of earth stations to a system in the fixed satellite service.

In these discussions, the term multiplexing will be used to describe the method of combining, in the communication-satellite repeater, the radio-frequency signals received from the individual earth stations, as distinct from multiplexing as a means of forming a baseband from several voice-frequency channels. As will be evident from the discussion, the technique employed to combine individual message channels at a particular earth station is not necessarily the same as the technique employed to combine (multiplex), in the satellite repeater, the signals received from individual earth stations.

Three classes of techniques for multiple access will be discussed: frequency division, time division and common spectrum. All of these techniques can be employed with essentially the same type of radio-frequency amplifier in the satellite repeater, although the design of the repeater unit will be influenced by the technique employed.

One important aspect of multi-station access techniques is the extent to which a particular technique permits interconnection of earth stations of different receiving sensitivities (ratio of antenna gain to system noise temperature). This is referred to as the station mix adaptability of each technique.

2. Particular techniques**2.1 Frequency-division multiple access****2.1.1 Multiple radio-frequency carriers with no change of modulation**

It is assumed that each up-path radio-frequency carrier occupies a particular frequency allocation. All radio-frequency carriers are amplified simultaneously and translated to a new set of frequencies in the down-path without change of type or degree of modulation. The earth receiving station filters out the desired radio-frequency carrier or carriers prior to demodulation. (It may be necessary in addition to select channels addressed to that station.)

The use of a travelling-wave tube or other saturating power amplifier causes several types of transmission impairments which must be considered in designing a multiple-access system using frequency-division multiplexing. Depending on the type of modulation employed, e.g. FDM/FM or PCM/PSK etc., the satellite repeater's amplitude and phase non-linearities should be optimized to minimize intermodulation, intelligible cross-talk or other interfering effects by taking into account the number and size of carriers expected to access 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. This method of operation always results in less capacity being available when compared to the single-access mode, due to the power back-off.

To ensure that all carriers arrive at the repeater with appropriate power ratios, it is necessary, in multiple-carrier operation, to control the power transmitted to the repeater from each earth station. The actual transmitted power is a function of the number of voice channels modulating the carrier.

This multiple-access technique is applicable to medium altitude or geostationary satellites. However, with medium altitude satellites the baseband frequencies may have to be corrected

for Doppler shift (see Report 214-2). When operating with earth stations having different sensitivities, the amount of satellite power required is determined by the least sensitive station.

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 operating with FDM/FM carriers normally will 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, which include 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

2.1.2 Multiple radio-frequency carriers with modulation conversion

One technique which has been experimented with employs a single-sideband suppressed-carrier amplitude-modulated signal in the up-link. All stations employ the same virtual carrier-frequency, with each station employing a unique portion of a frequency-division multiplexed baseband. At the space station repeater, these up-link signals combine to form a continuous baseband. The repeater converts this signal to a single broadband, phase-modulated signal for transmission to all earth stations. This modulation conversion takes place at intermediate frequency without demodulation to baseband.

The single-sideband, phase-modulation (SSB/PM) system can provide either heavy-density trunks or as little as one channel at a time from each to any other earth station.

Orbits of geostationary or non-geostationary satellites may be used. However, the use of a geostationary satellite minimizes the problems of frequency and power control because its range to participating earth stations is nearly constant and its range-rate is very small.

The SSB/PM technique requires accurate control of frequency not only to meet C.C.I.T.T. criterion of no more than 2 Hz shift in the end-to-end connection (see Report 214-2), but also to compensate for any Doppler frequency shift which may occur in the up-path.

2.1.3 Multiple radio-frequency carriers with demodulation in the repeater

For a discussion of one approach to this technique, see [Lutz and Dorosheski, 1966].

2.2 Time-division multiple access (TDMA)

Time-division multiple access (TDMA) is a multiple access technique whereby stations communicate with each other on the basis of non-overlapping transmission bursts through a common satellite repeater. Although the satellite repeater is only amplifying the signal of one earth station at any instant, a small amount of power back-off may still be applied because of the non-linearity effects at saturation.

Time-division multiple access is characterized by the durations of the time-frame and the time-slot (see Fig. 2). 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 time-division multiple access, each participating earth station is assigned 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 traffic to be transmitted. The smallest increment in time-slot duration is governed by the duration of the basic channel unit.

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 in all earth stations. However, slightly different radio-frequency carriers may be used.

Considerations of synchronization and timing associated with the use of time-division in a multiple-access system in the fixed satellite service 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 many pulses are transmitted during each time-slot. Duration of the time-frame is limited by maximum permissible transmission delay, and duration of the time-slot is limited by the number of stations and the guard time. 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 standpoint of access efficiency vs. buffer cost in a multiple-access system, at 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 factors, it will be assumed that the information has been sampled and converted to a pulse format.

If the duration of the time-frame is equal to the sampling interval (typically 125 μ s for C.C.I.T.T. quality of speech) or an integral divisor thereof, then no buffer store is required and the system can be operated as a "real time" system; in TDMA systems, however, preamble requirements cause a decrease in the available telephone capacity and the frame efficiency (ϵ), defined as the ratio of the usable frame capacity, decreases as the number of stations in the system increases, as shown in Fig. 3. A suitable method to limit this loss of efficiency is that of lengthening the time-frame by using buffer store circuits. This method of operation called the "multi-frame" mode offers increasing advantage, as the number of stations per frame and the preamble length per station increase. Generally, the gain in efficiency increases with increasing frame length from 125 μ s to 500 μ s, after which the gain in efficiency is much less pronounced as shown in Fig. 4 [Quaglione *et al.*, 1972]. Therefore, a suitable time-frame length for a TDMA system could be equal or higher than 500 μ s. However, for special types of uses a buffer store seems to offer a number of advantages and under certain conditions is necessary.

For most TDMA concepts, guard time between successive transmission to the satellite must not be less than the minimum time associated with satellite range rate after acquisition. The time-frame and time-slot durations will fix the maximum number of simultaneous users in the system.

Within the time-frame (Fig. 2) the first time-slot is designated the reference time-slot.

A reference time is provided to permit sequential interleaving of time-slots. This reference time is a coded signal originating in one of the following:

- the satellite,
- a selected earth station and relayed by the satellite,
- an earth station, but precorrected for up-path effects to appear as if it originated in the satellite.

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 transmitting 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 be satisfied when the TDMA system is operated only 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;
- in case 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, and the transmitting timing of the TDMA signal which is operating with the spot beam antenna can be slaved to that of the global beam antenna by adopting the common frame synchronization over the whole TDMA system;
- 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].

The method of modulation and modulation rate within a particular time-slot is independent of the others except for frame synchronization and addressor-addressee compatibility.

In multiple-access systems for satellite 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 PSK signals of a burst mode 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.

For this reason, an appropriate number of synchronization bits is normally assigned to the beginning of each burst and the reference carrier and clock timing are recovered during this synchronization time interval. For example, in one PCM/TDMA system [Michishita *et al.*, 1971], 6 to 40 bits are used for synchronization.

PSK modulation with coherent detection presents the intrinsic problem of resolving at the receiving end which of the “*n*” possible phase states of the recovered reference carrier is the reference state. The most suitable way to resolve this problem is to differentially encode the data bit stream prior to the modulation process. Differential encoding as a means of resolving phase ambiguities in CPSK

modulation is a commonly used method in TDMA systems already developed or under development, for its intrinsic merits of low power requirement, hardware simplicity, and flexibility to meet traffic variations, with respect to other known methods.

Recently a new PCM/TDMA system, especially suitable for a geostationary satellite, has been developed which effectively utilizes the full frame and avoids decrease in the information transmission capacity due to guard time. To implement a system without guard time the transmitting clock of each station in the network is controlled by clock pulses received from a reference station through the satellite; in this way the earth-station time-slots will be perfectly synchronized at the satellite. In each time-slot two sets of 7 bits are transmitted for supervisory information; the rest of the time-slot is used for the communication information.

In the first set of seven bits, the first bit allows for overlap of the carrier burst, the next bit is used as a reference for PSK delay detection, and the remaining five bits are used for control in demand-assigned multiple access. The next seven bits are used for synchronization of the time-slot and for station identification.

In this system acquisition is achieved by the use of a pseudo-random noise code. Initially, the pseudo-random noise (PN) code pulses are transmitted from a slave station continuously at a level 15 to 25 dB lower than normal. Its PCM clock pulses are then synchronized by comparing the PN code clock pulses with the clock pulses of the master station received through the satellite. After the synchronization has been established, the level of the pulses transmitted by the earth station is raised to normal, and the connection is achieved. [See Takada and Doi, 1969; Inoue, 1969; Kondo, 1969; Kutami *et al.*, 1969.]

2.2.1 *Orbit considerations*

Time-division multiple-access (TDMA) techniques are applicable to satellites at medium altitudes as well as to geostationary satellites. However, the interleaving of time-slots from various earth stations at the satellite requires accurate knowledge of the range and range-rate. While quadratic-range prediction has been explored and is, in fact, commonplace in the technology of launch guidance, the associated equipment is more complex than that required for linear prediction, which can be implemented using equipment readily available at present. With linear prediction, the guard-time necessary between transmissions from various participants to accommodate uncertainties in range measurement, is of the order of the maximum change in range expected over the interval of time corresponding to the round trip from satellite to earth station.

2.2.2 *Channel arrangements and supervisory control*

In a TDMA system any time-slot in the frame is available to any station. This flexibility, especially in a demand-assigned system where the number of traffic channels within the time-slot can be varied, limited only by the overall capacity of the system, 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 (of the order of 0.5%).

2.2.3 *Speech interpolation technique in TDMA systems*

TDMA systems can take full advantage of the application of digital speech interpolation as shown in the Annex to Report 211-3.

2.2.4 *Operation with stations having different sensitivities*

In a TDMA system, the full power of the satellite repeater is available at a particular instant of time for the repeating of signals from any earth station, independent of all the others; the satellite repeater output is a constant envelope signal. Because of this, a variety of types of station may be mixed in an operating system. Stations with different receiving sensitivities (ratio of antenna gain to system noise temperature) and/or transmitter powers can employ the same repeater, provided they transmit at rates appropriate to the sensitivities of the intended receivers. With the consideration that the frame synchronization signal must be receivable by all stations, each station of a given size may communicate with other stations of the same size, independent of the existence of larger or smaller stations. Further, communications between stations of differing size can be achieved by adjusting the average power received from the satellite repeater (by adjusting the width and rate of the pulses in a constant envelope signal) to values commensurate with the receiving sensitivity of the smaller station. The basic frame parameters such as guard time and burst synchronization should be compatible with the lowest sensitivity station sharing the repeater.

2.2.5 *Intermodulation*

In an infinite bandwidth time-division multiple-access system the signal is theoretically completely orthogonal. With bandwidths commensurate with the bit rates involved the degree of orthogonality obtained is near perfect and therefore this system is not characterized by baseband noise resulting from the previous burst emissions using the same satellite transponder.

The absence of intermodulation noise is offset to some extent by another noise-producing phenomenon occurring in most time-division systems.

In most practical implementations of time-division multiple-access, digital modulation will be used, and some form of sampling and quantization will be applied, resulting in quantization distortion (or noise, as it is commonly called). Delineation of acceptable standards for PCM quantization distortion is a necessary precursor to quantitative comparison of digital systems such as time-division multiple-access with others which utilize analogue modulation.

2.2.6 *Status*

TDMA by its inherent flexibility provides highly economical solutions to demand assignment of channels. It also provides for the variation of the traffic volume from an earth terminal without the requirement for a network control station.

Implementation of a time-division multiple-access system is considered feasible using present-day components and techniques as derived in the fields of communications and computers. Experiments have been conducted and operational systems are now being planned. The areas of importance in these tests are, in general, high speed logic, wideband power amplification, wideband modulation and demodulation, and time synchronization.

2.3 Common spectrum multiple access

2.3.1 General

Common spectrum systems are those in which signals from all of the participating earth stations accessing a satellite make common use of the time-frequency domain. Signal processing is employed to detect a wanted signal in the presence of others, thus providing a multiple-access capability. Three typical approaches utilizing these techniques are:

- spread spectrum,
- frequency-time matrix,
- frequency-hopping.

2.3.1.1 Spread spectrum

The spread-spectrum system makes use of a deterministic noiselike signal structure to spread the normally narrow-band information signal 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, and a coded signal entering a receiver using a different code will not be correlated. Because the generated codes in a spread-spectrum 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.

2.3.1.2 Frequency-time matrix

The frequency-time matrix system is one which requires the simultaneous presence of energy in more than one time or frequency assignment to produce an output signal. The requirement for presence in several time and/or frequency slots reduces the probability of mutual interference when a number of users are simultaneously transmitting.

2.3.1.3 Frequency-hopping

In a frequency-hopping system the transmitted frequencies are switched at a rate equal to or lower than the sampling rate of the information transmitted. Selection of the particular frequency to be transmitted can be made from a fixed sequence or can be selected in a pseudo-random manner from a set of frequencies covering a wide bandwidth. The intended receiver would frequency hop in the same manner as the transmitter in order to derive the desired information.

2.3.2 Orbit considerations

The influence of the orbit upon common spectrum multiple-access systems is greatest in those approaches requiring synchronization between transmitter and receiver. In addition to the expected requirement that all frequency apertures be wide enough to accommodate Doppler frequency shifts, the requirement for synchronization means that uncertainties in both time and frequency must be resolved in the process of acquisition. Synchronization in common spectrum systems can be relieved by the use of timing signals emanating from the satellite, in which case only propagation difference errors from the satellite to the earth stations in question need be resolved. In a common spectrum multiple-access system once a link is established between two earth stations, these stations may employ the link to establish with great accuracy both the propagation delay and the relative clock discrepancies. In this manner the entire system may

maintain an accurate accounting of timing errors, and system synchronization problems are greatly reduced.

2.3.3 Intermodulation

In addition to thermal noise in common spectrum systems, random interference will occur due to signals generated by other system users, and system distortions. The basic considerations for self-interference are different for the several types of common spectrum systems. In a frequency-hopping system false pulses are received when the set of interfering sources produces certain frequency-time patterns. In addition, cancellation errors will be evident in systems of this type. In synchronous spread spectrum systems all interference tends to become Gaussian as a result of receiver processing and the interfering signal levels are reduced by the gain or bandwidth-time product.

3. Conclusions

The type of multiplexing technique employed has an effect on the multiple-access capabilities of a system in the fixed satellite service. Conversely, the choice of multiplexing techniques will be influenced by the operational configuration of a multiple-access system in terms of the number and characteristics of the participating earth stations, the variability of traffic requirements among the participating stations, and other factors. There are technical problems in all proposed systems, and some of the systems described have not yet been tried in operation. Therefore, no order of preference can be given at this time.

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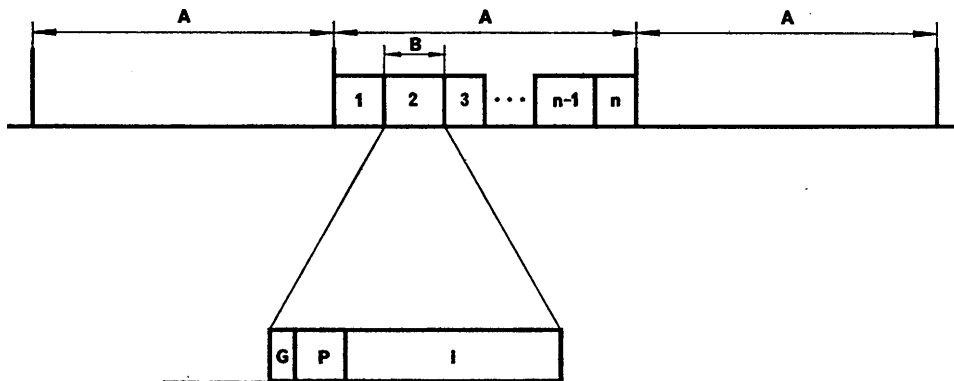


FIGURE 2

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

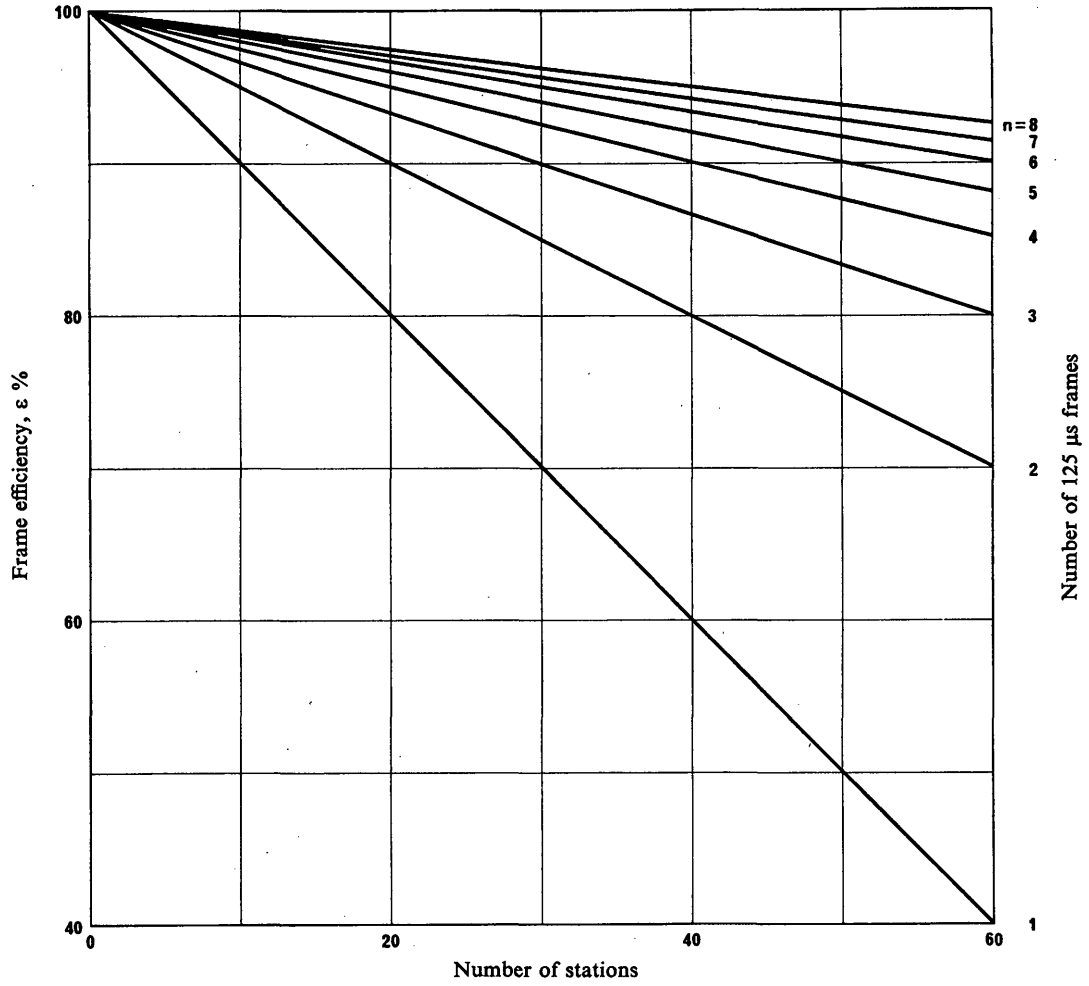


FIGURE 3
Frame efficiencies in TDMA systems

Preamble length: 80 bits

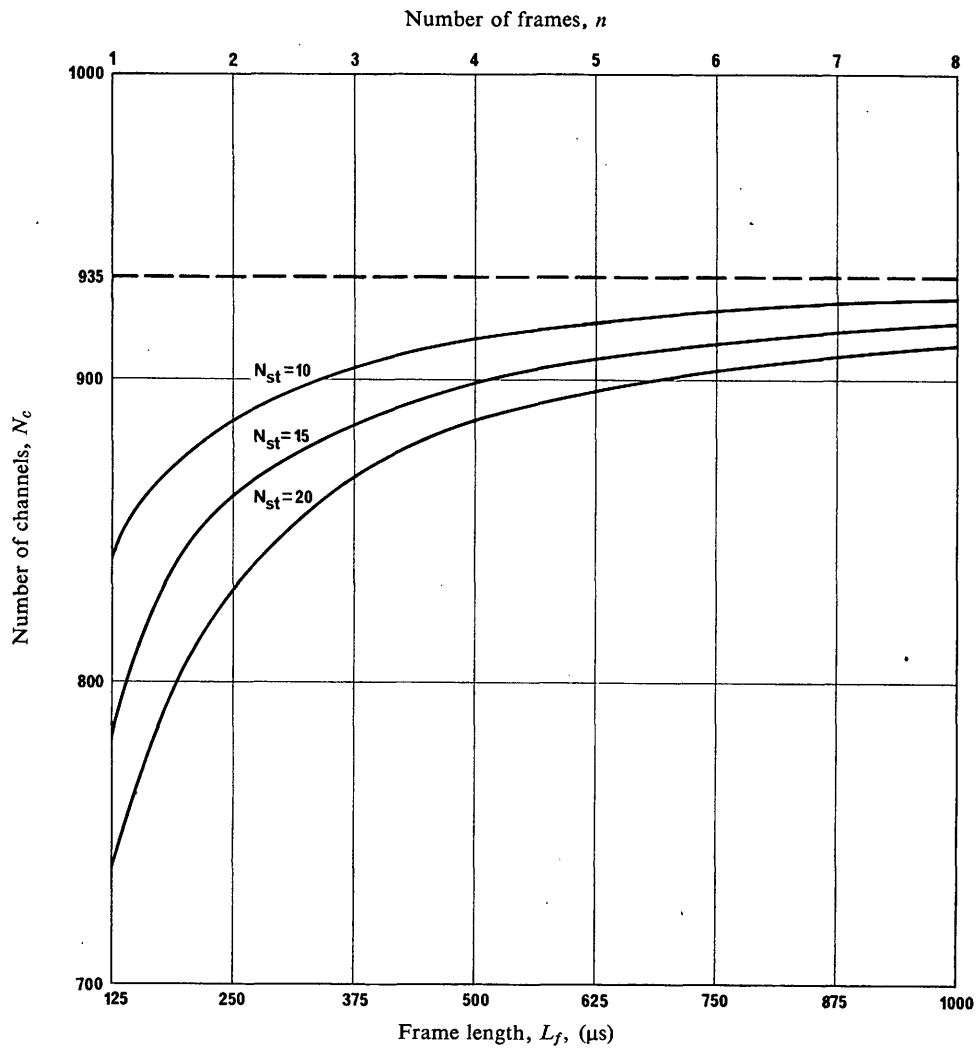


FIGURE 4

Net channel capacity of a TDMA system on a 36 MHz satellite transponder vs. frame length (L_f)

Average preamble length: 80 bits

Link bit-rate: 60 Mbit/s

N_{st} : Number of stations in the system

SECTION 4E: CHARACTERISTICS AND MAINTENANCE OF EARTH STATIONS

RECOMMENDATIONS AND REPORTS

Recommendations

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 C.C.I.R.,

CONSIDERING

- (a) that, for coordination studies and for the assessment of mutual interference between radiocommunication-satellite systems and between earth stations of such systems and stations of other services sharing the same 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 391-2) 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 rotationally 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 suggest that the reference radiation pattern as shown in Fig. 1 could provisionally be used also for frequencies in the range 10–30 GHz.

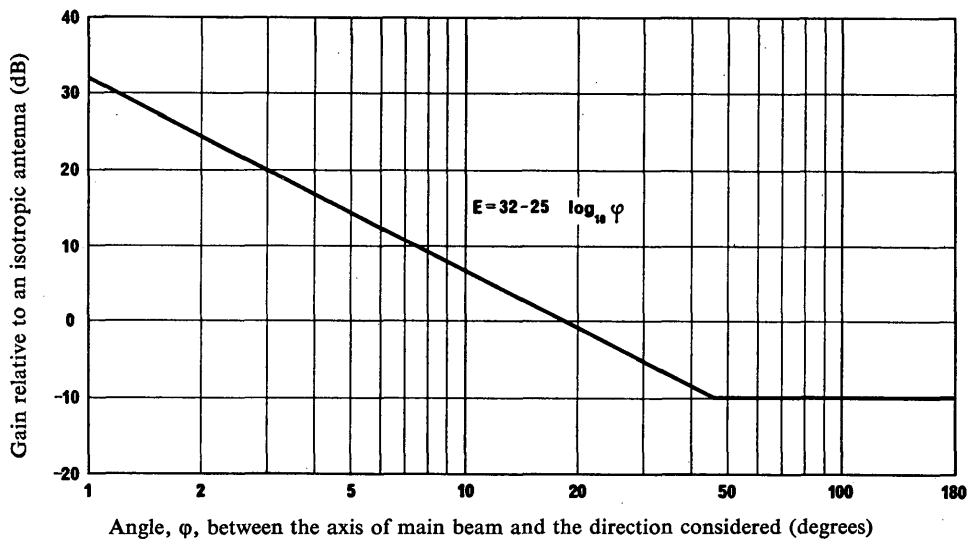


FIGURE 1

Provisional reference radiation diagram
 $E = 32 - 25 \log_{10} \phi$

4E: Reports

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-2/4)

(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 results are at present inconclusive; pending more definitive results, general guidance may be obtained from Report 339-1 (New Delhi, 1970).

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.

* Adopted unanimously.

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 382-2 for the determination of coordination distance and in Report 448-1 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 244-2 (New Delhi, 1970) is recommended for computation of the predicted basic transmission losses.
- 3.3 Instrumentation would appear to be appropriate in those cases where the emitter 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 an emitter, not necessarily on the earth-station site.
- 3.4 After the terrain profile of the great circle path from the earth station to an emitter 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 emitters.
- 4.2 Avoid locating the earth station with less than a 5° discrimination angle at the emitter between the great-circle path to the earth station and the direction of the main antenna beam of the emitter.
- 4.3 Maintain a minimum distance of about 50 km from emitters 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 emitter'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 C.C.I.R. 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 359-3, 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 obstructions 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.

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REPORT 390-2 *

EARTH-STATION ANTENNAE FOR THE FIXED SATELLITE SERVICE

(Question 1-2/4)

(1966 – 1970 – 1974)

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:

$$\text{loss of gain (dB)} = 0.00761 e^2 f^2$$

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.

* Adopted unanimously.

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.

For smaller antennae operating with geostationary satellites, manual positioning at infrequent intervals might suffice.

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. The effects of rain on radomes were discussed in [C.C.I.R., 1970].

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 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.

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 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 would be of the order of 140 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:

$$G/T = 10 \log_{10} \left[\frac{\text{antenna power gain}}{\text{system noise temperature (K)}} \right]$$

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 logarithmic units.

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 focused 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 and noise temperatures are 48 K and 68 K at 4 and 18 GHz respectively, at an angle of elevation of five degrees.

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ANNEX I

RADIATION CHARACTERISTICS OF ANTENNAE OF
EARTH STATIONS OUTSIDE THE MAIN BEAM

In 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 can be used to obtain low side-lobe levels such as tapered illumination.

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 the sub-reflector

To illuminate the sub-reflector of a 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 spill-over from the feed and to diffraction at the sub-reflector. In the case of large antennae, the influence of the sub-reflector on the side-lobe level is considerably lower than that of other phenomena.

1.3 Influence of the supports

A plane wave originated by the main reflector excites the supports of a feed or sub-reflector 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.

The effect of the supports on the side lobes adjacent to the main lobe is serious because the large, uniformly orientated scatter surfaces of the supports yield fairly high gains. Here the influence of the scattered energy resulting from the main reflector predominates, since much of this energy is radiated near the direction of the main beam of the antenna.

This interference effect can be reduced by decreasing the gain of the support radiation (decrease of the scattering cross-section by changing the geometry of the supports). Moreover, antenna construction without supports which disturb the beam has to be taken into consideration. Generic antenna types which do not have significant physical blockage are, e.g., conical horns or offset paraboloids.

1.4 *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.

1.5 *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.

1.6 *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.

2. **Quantitative contributions of major contributors**

The side-lobe levels at a given angle for a large Cassegrain type 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.

3. **Comparison of earth station antenna types**

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:

$$\frac{G(\varphi)}{G} = \frac{1}{1 + \left(\frac{\varphi}{\varphi_0}\right)^n} \quad 2 < \frac{\varphi}{\varphi_0} < 100$$

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 off 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., $\frac{\varphi}{\varphi_0}$, 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.

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 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 , on the order of 600 [C.C.I.R., 1970-1974]. Fig. 3 shows the gain of the antenna relative to isotropic, taken on an arc some 30 m distant from the rear of the antenna. Fig. 4 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 on the order of those indicated by both the near-field theoretical calculations, and by the far-field radiation patterns for such antennae.

4.2 *Artificial pit shielding for earth stations*

A pit was constructed to encircle a 10 m diameter antenna which could operate with satellites in a segment of the geostationary satellite orbit. Measurement of the shielding properties of the antenna-pit combination were made in the 4 and 6 GHz communication-satellite bands. Fig. 5 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.

REFERENCE

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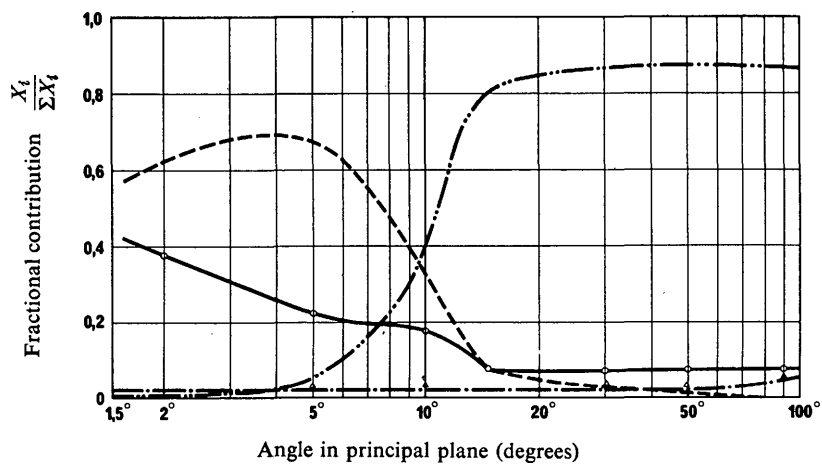


FIGURE 1

Relative contribution of various parts of 600 λ Cassegrain antenna to wide angle gain envelope

- Main annular aperture
- Feed (including diffraction around subreflector)
- Struts in principal plane
- Struts in plane normal to principal plane

$$G = 20 \log_{10} (X_1 + X_2 + \dots + X_n) \text{ dB}$$

Feed term

Main aperture term

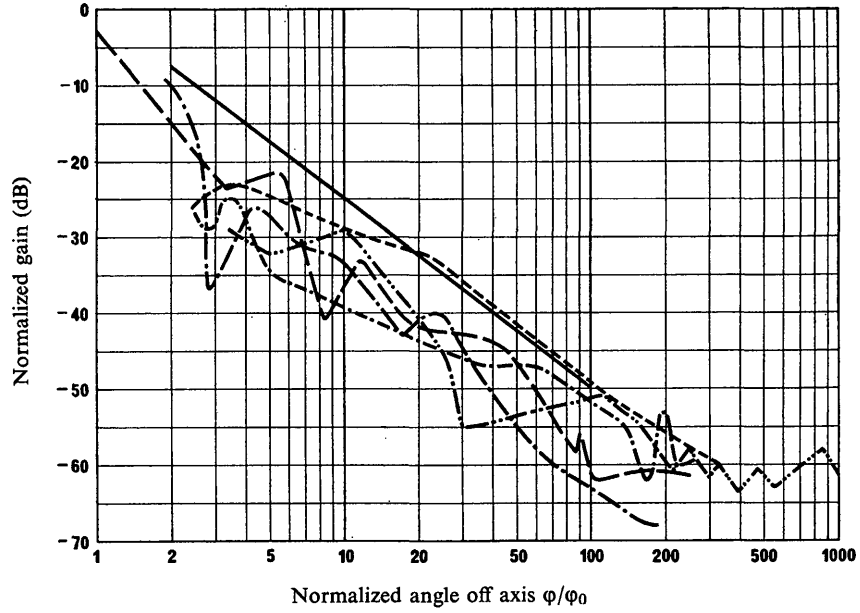


FIGURE 2

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)

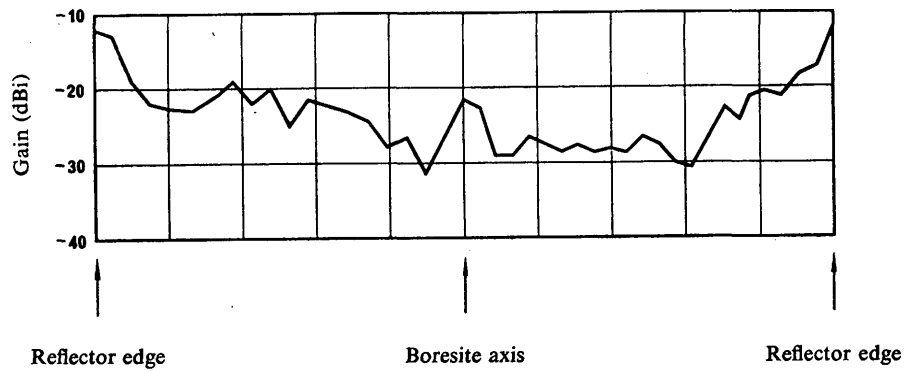


FIGURE 3

Ground level measurements on arc about 30 metres distant behind the antenna

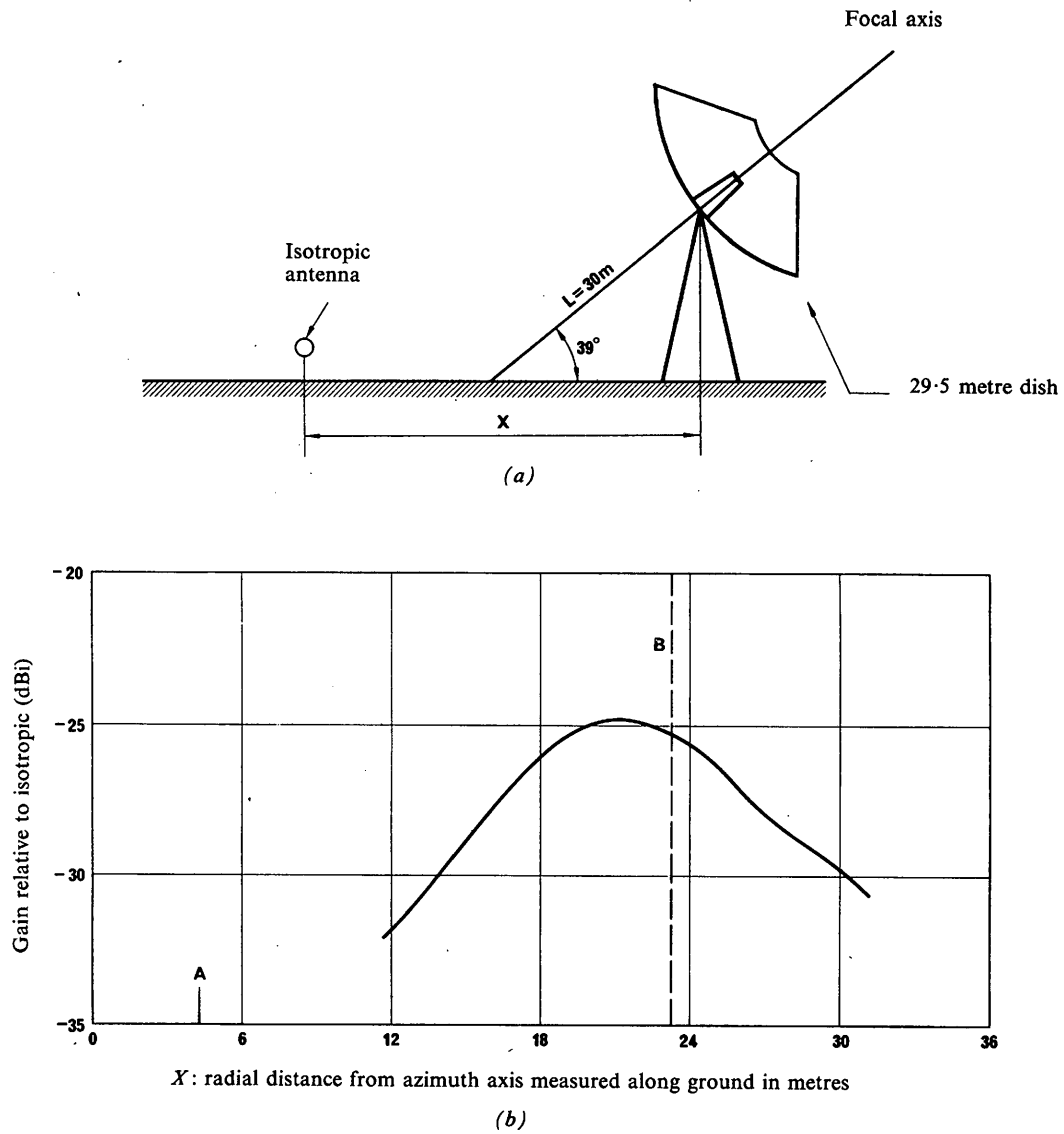


FIGURE 4

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

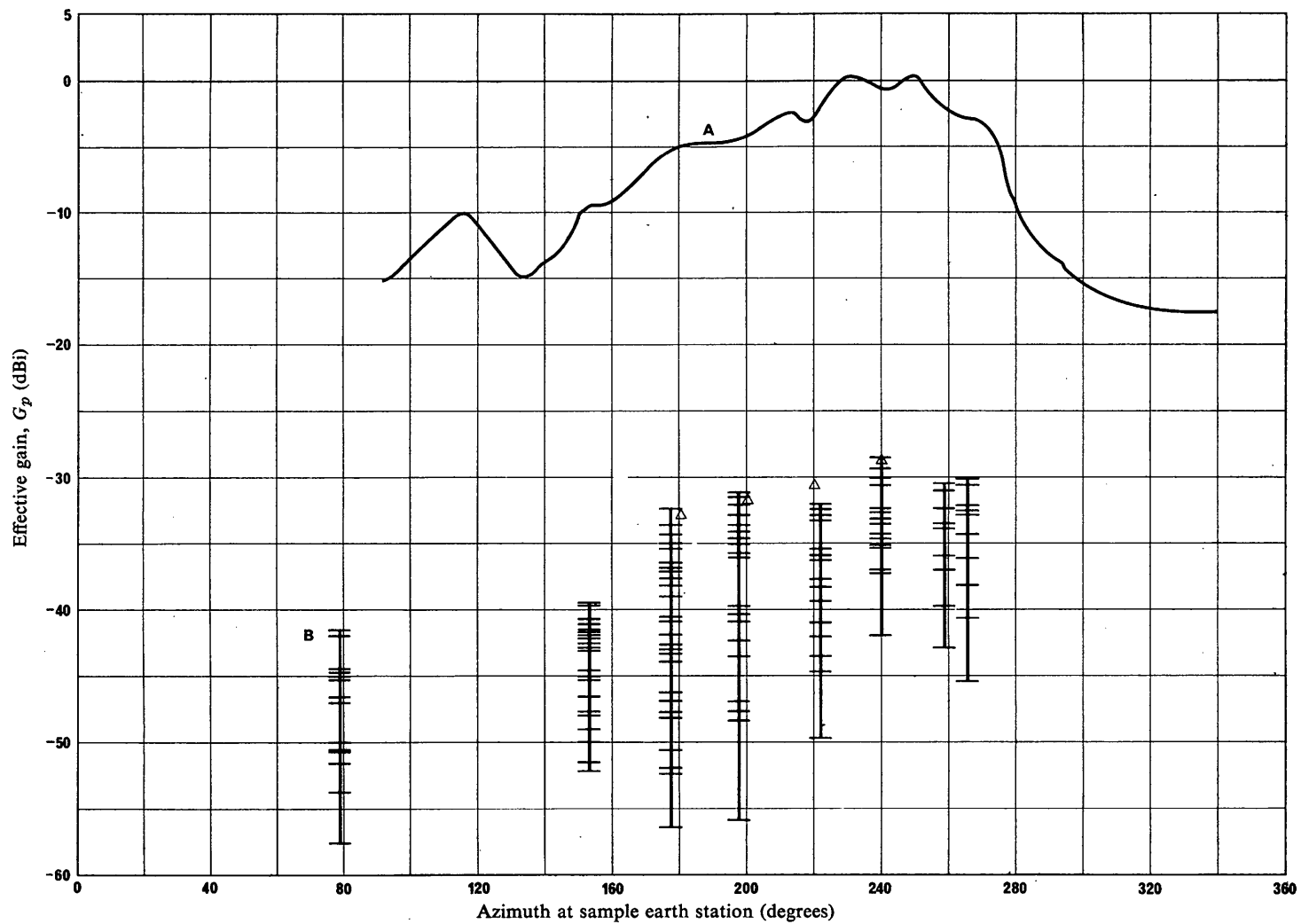


FIGURE 5

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)

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, 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 [C.C.I.R., 1963-1966].

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 coordinates. 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.

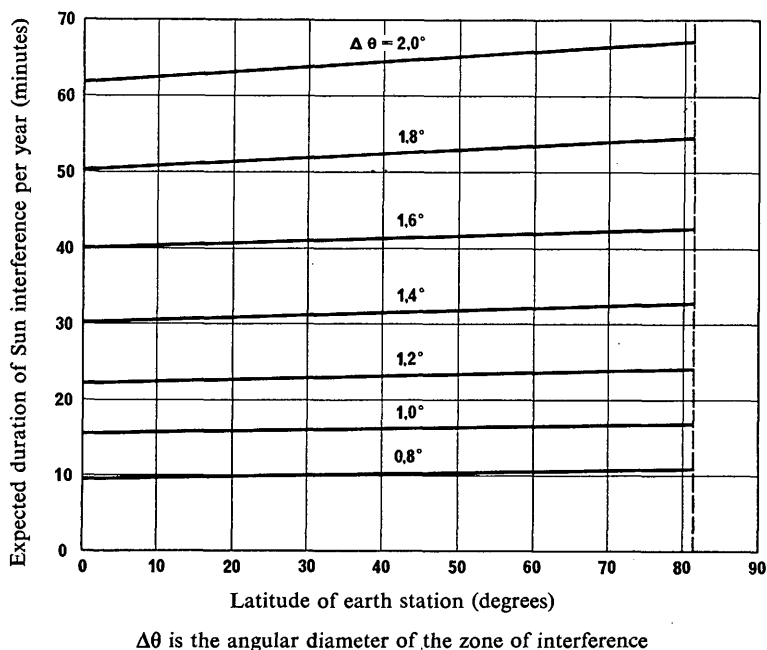


FIGURE 6

Expected duration of interference due to the Sun for a satellite in the geostationary orbit

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 [C.C.I.R., 1966–1969] the results of which are shown in Fig. 6.

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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:

$$\frac{G}{T} = \frac{(8\pi k)(r-1)}{[\lambda^2\Phi(f)]} \quad (1)$$

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 (1), 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 as 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 provisional values of the flux-density of the radio stars indicated.

TABLE I
Flux-density of radio stars

Radio star	Cassiopeia A	Taurus A	Cygnus A
$\Phi(4)$ Flux-density at 4 GHz ($\text{Wm}^{-2} \text{Hz}^{-1}$)	1065×10^{-26} ⁽¹⁾	717×10^{-26}	488×10^{-26}
$\Phi(f)$ Flux-density at f GHz	$\Phi(4) \left(\frac{f}{4}\right)^{-0.75}$ ⁽²⁾	$\Phi(4) \left(\frac{f}{4}\right)^{-0.25}$ ⁽²⁾	$\Phi(4) \left(\frac{f}{4}\right)^{-1.19}$ ⁽³⁾

(1) Value for January, 1968 (see § 4.3).

(2) Where f is between 3 and 32 GHz.

(3) Where f is between 3.7 and 4.2 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 that their solid angle is

very small giving rise to negligible correction errors due to angular extension. The flux-density $\Phi(f)$ is expressed by:

$$\Phi(f) = \frac{4\pi k Tb(f)}{\lambda^2} (1 - \cos \psi) \quad (2)$$

where

$Tb(f)$: brightness temperature of a planet (K),

ψ : semi-diameter.

The value of $\Phi(f)$ derived from equation (2), is substituted in equation (1) to obtain the value of G/T of an earth station. The value of ψ can be found elsewhere [U.S.A.]. 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:

$$(G/T)_c = G/T + C_1 + C_2 + C_3 + C_4 \quad (3)$$

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 at 4 GHz for angles of elevation above 5°, is given by:

$$C_1 = \frac{0.036}{\sin \alpha} \text{ dB}$$

where α is the angle of elevation.

The dependence of attenuation on frequency is shown in Fig. 7.

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. 8.

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:

$$\frac{G(\varphi)}{G} = 2^{-\left(\frac{\varphi}{\varphi_0}\right)^2}$$

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 is 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].

4.3 Change of flux with time

Cassiopeia A is subject to a reduction of flux with time. This correction may be obtained by the factor $C_3 = 0.989^n$ where n is the number of years elapsed ($n = 0$ in January 1968).

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:

$$\frac{\Delta(G/T)}{G/T} = \frac{\Delta\Phi(f)}{\Phi(f)} + \frac{\Delta r}{r} \times \frac{r}{(r-1)} \quad (3)$$

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 dB
Taurus A	37 dB
Cygnus A	39 dB

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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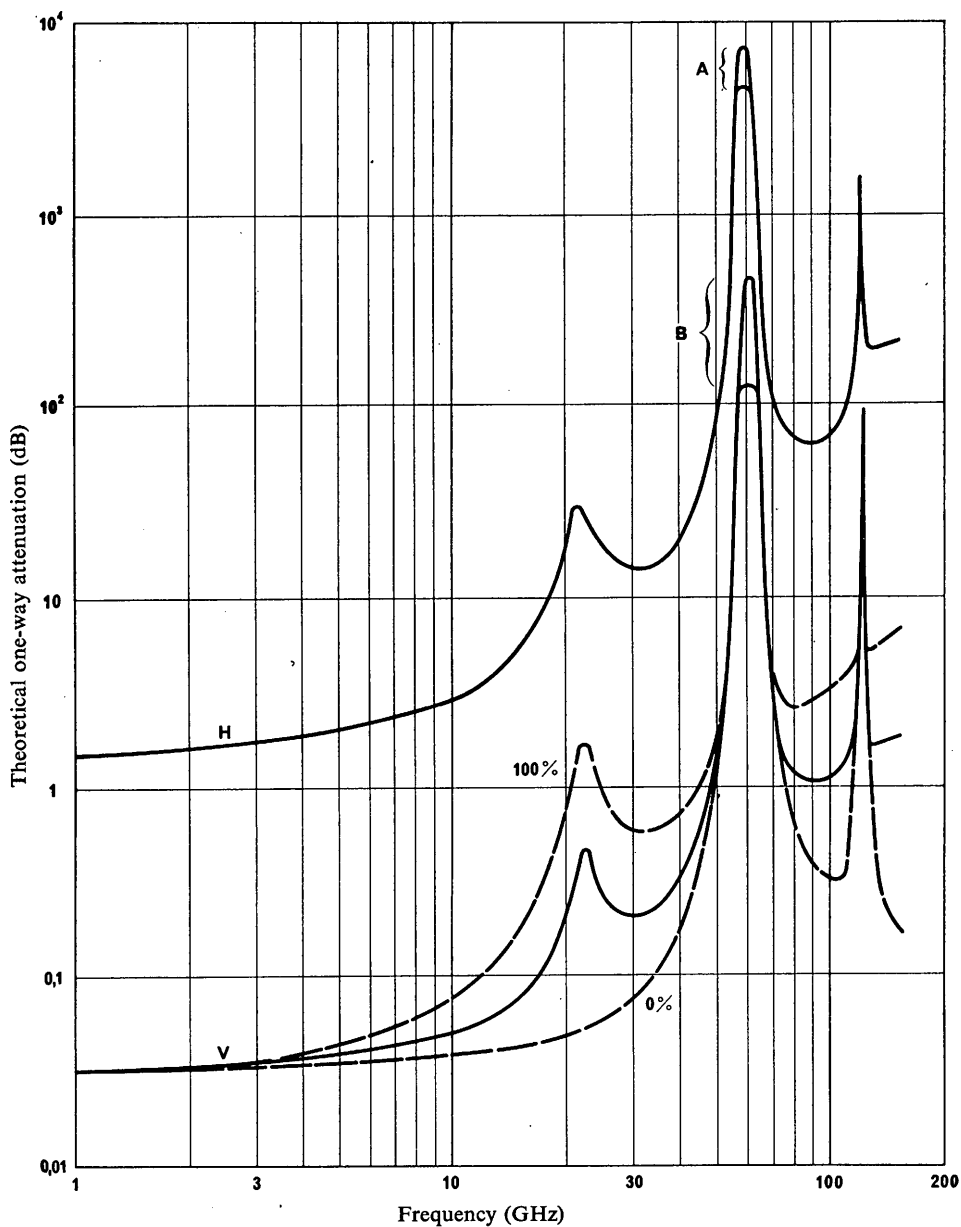


FIGURE 7

Theoretical one-way attenuation for vertical and horizontal 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	H: Horizontal
B: Limits of uncertainty	V: Vertical

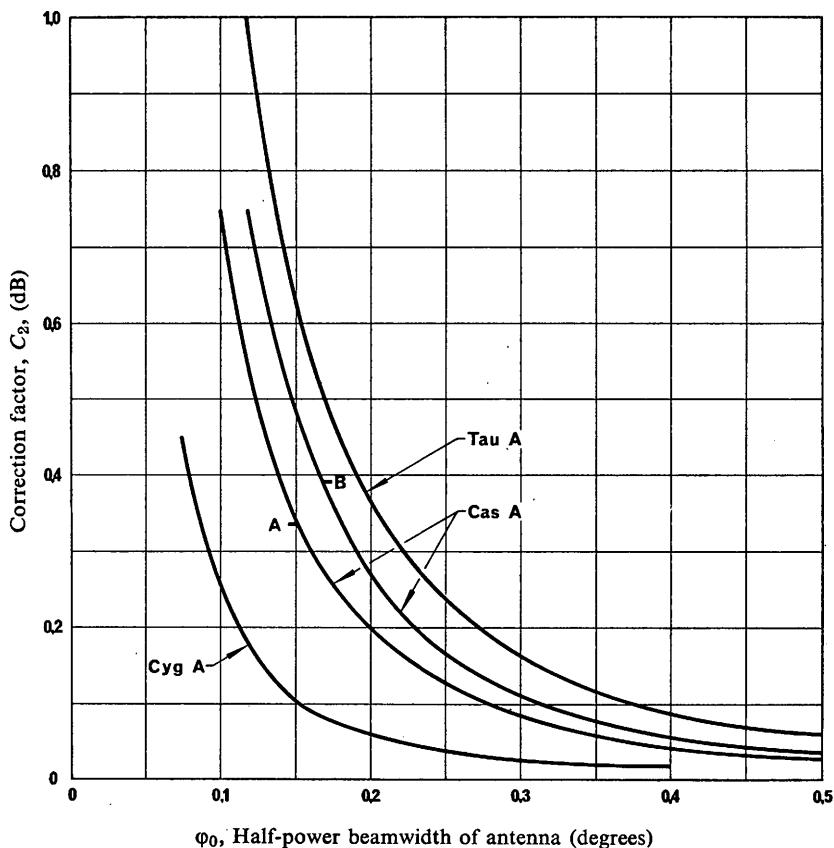


FIGURE 8
Correction factor for the angular extension of radio stars

REPORT 391-2 *

**RADIATION DIAGRAMS OF ANTENNAE FOR EARTH STATIONS IN THE
FIXED SATELLITE SERVICE FOR USE IN INTERFERENCE STUDIES**

(Question 1-2/4)

(1966 – 1970 – 1974)

1. Introduction

In the determination of coordination distance or for the assessment of interference between earth stations and radio-relay stations and for coordination 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.

* Adopted unanimously.

2. Characteristic radiation patterns of antennae

For coordination 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 coordination 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 wave-length ratio ($D/\lambda > 100$) by a reference radiation diagram*

At the final Study Group 4 meeting in 1974, information was submitted concerning the statistical distribution of the side-lobe peaks for six large diameter antennae, measured at 4 and 6 GHz (Docs. 4/185, 4/206, 4/258 and 4/263).

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:

$$G = 32 - 25 \log_{10} \varphi \text{ dB}$$

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 $20 \log_{10} (D/\lambda) \approx G_0 - 8$, 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 data presented in the reference documents also indicate that 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 degree and that, within this angular region, some of the largest peaks may exceed the reference diagram by 10 dB.

2.2 *Reference radiation pattern for $D/\lambda < 100$*

Theoretical considerations and the available data concerning radio-relay antennae (Report 614) 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:

$$G = 52 - 10 \log_{10} (D/\lambda) - 25 \log_{10} \varphi \text{ dB}$$

As long as there are no experimental data available, this simple formula may be used.

Further details about the theoretical background for such a formula can be found in the Annex to Report 614. 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 $20 \log_{10}(D/\lambda) \approx G_0 - 8$, where G_0 is the main lobe antenna gain in dB.

2.3 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 systems. 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.

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 coordination and mutual interference studies between earth stations and either terrestrial stations or space stations.

Because of the wide variety of applications where sharing of frequency bands is involved, studies are continually needed, especially for antennae with $D/\lambda < 100$, so that the most useful and practical reference radiation diagram is available. Annex I to Report 390-2 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.

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. 2). 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.

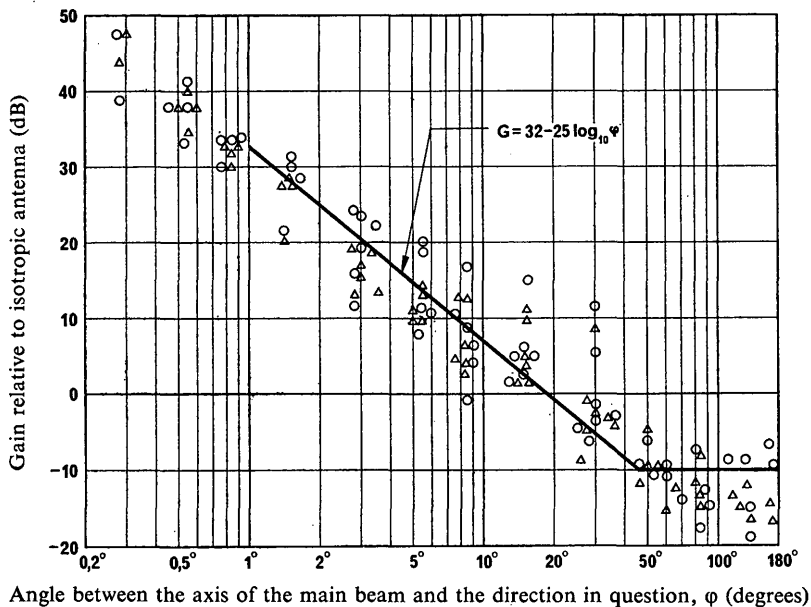


FIGURE 1

Statistical data from some large earth-station antenna diagrams at 4 and 6 GHz

Levels exceeded by 10% of the side-lobe peaks: $D/\lambda \approx 400$ and 600 respectively. Δ : 4 GHz, \circ : 6 GHz

Note.— It should be noted that the various points in the figure may represent different angular sample widths and number of peaks. Some of the points which consistently exceeded the level of the curve relate to a particular antenna.

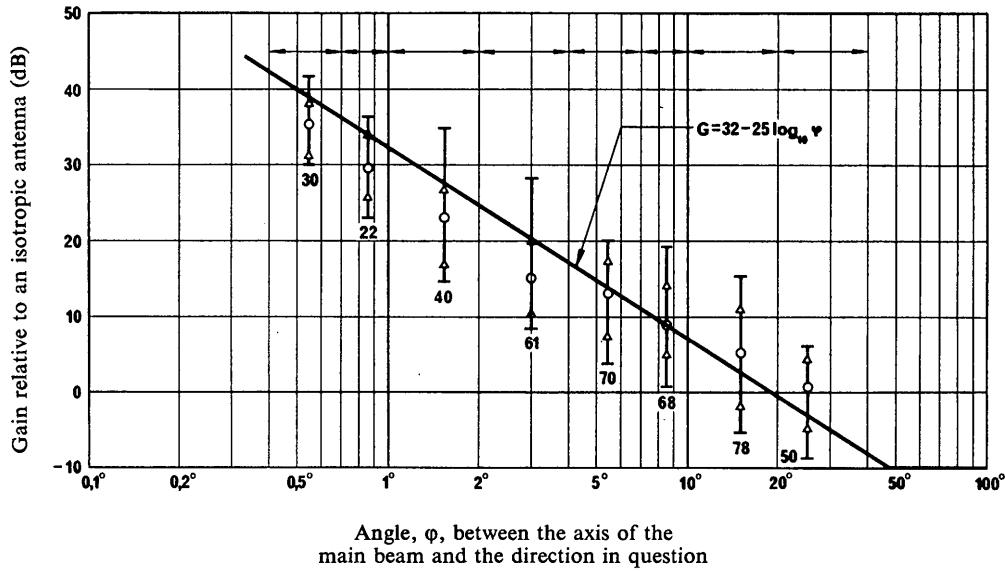
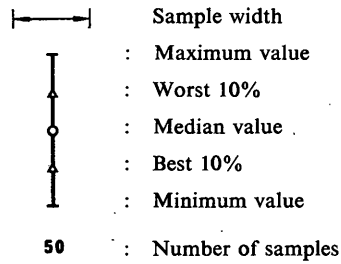


FIGURE 2
Example of distribution of side-lobe peaks



REPORT 554 *

THE USE OF A TRANSPORTABLE EARTH STATION WITH A SMALL ANTENNA
FOR RELIEF OPERATION IN THE EVENT OF NATURAL DISASTERS AND
SIMILAR EMERGENCIES

(Question 22/4)

(1974)

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, high quality international communications immediately following a natural disaster would prove helpful in saving lives by virtue of improved relief activity coordination.

* Adopted unanimously.

This Report discusses a presently 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, high-power amplifier requirements, as well as antenna system 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 be available for transportation to, and installation at, the disaster area with access to an existing satellite system.

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 C.C.I.R. 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 standard earth station*

The transportable earth terminal could operate with any suitable standard 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 Report 211-3 and Report 509-1, a station of this type might employ frequency division multiplex FM, or single-channel per carrier 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 ($\Delta M/PSK$) 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 bandwidth required for FDM/FM and 64 kbit/s PCM-4 Φ PSK single-channel per carrier systems are shown in Table I. Only some of the satellite e.i.r.p.'s shown in Table I are available in current satellite systems.

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 dB to 23.5 dB 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 degrees, these values correspond to antenna diameters in the range 2.5 m to 5 m approximately.

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 for 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 sufficient 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 ± 5 degrees.

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. **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 disasters 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.

TABLE I
Examples of transmission system parameters
for 6 channels in 6/4 GHz band

G/T ratio (diameter) (dB)	Type of modulation	Bandwidth (MHz)	Satellite e.i.r.p. (dBW)	Earth station e.i.r.p. (dBW)	Transmit power (W)	Circuit quality (clear sky condition)
17.5	FDM-FM	0.2	15	60	80	$\frac{S}{N}$ 30 dB
		1.0	21	66	320	$\frac{S}{N}$ 50 dB
(2.5 m)	SCPC 64 kbit/s PCM-4ΦPSK	0.3	18	68	500	Error-rate 10^{-4}
			21.5	70.5	900	Error-rate 10^{-6}
23.5	FDM-FM	0.2	9	60	20	$\frac{S}{N}$ 30 dB
		1.0	15	66	80	$\frac{S}{N}$ 50 dB
(5 m)	SCPC 64 kbit/s PCM-4ΦPSK	0.3	12	68	130	Error-rate 10^{-4}
			15.5	70.5	225	Error-rate 10^{-6}

Note 1. — It is assumed that in FDM-FM systems the margin is 4 dB, the threshold level improvement is 5 dB.

Note 2. — Values 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, which the small earth station is communicating with, have G/T of 40.7 dB.

Note 3. — Total thermal noise/down-link thermal noise = 1.5.

Note 4. — Satellite transponder characteristics are similar to those of the INTELSAT IV global beam transponder. (Gain step No. 3 for FDM-FM, No. 4 for SCPC.)

SECTION 4F: SHARING OF FREQUENCIES BETWEEN NETWORKS OF THE FIXED
SATELLITE SERVICE AND GEOSTATIONARY-SATELLITE ORBIT
UTILIZATION

RECOMMENDATIONS AND REPORTS

Recommendations

RECOMMENDATION 466-1

**SYSTEMS IN THE FIXED SATELLITE SERVICE FOR TELEPHONY
USING FREQUENCY-DIVISION MULTIPLEX**

**Maximum permissible levels of interference in a telephone channel of a geostationary-satellite network
in the fixed satellite service employing frequency modulation, caused by other networks of this service**

(Study Programme 2C-1/4)

(1970 – 1974)

The C.C.I.R.,

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 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 the mean interference noise power should be an appropriate fraction of the total noise power permitted in the hypothetical reference circuit;
- (j) 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;
- (k) that the level of interference between geostationary-satellite networks in the fixed satellite service operating in frequency bands below 10 GHz are not expected to exhibit 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 such networks, should not exceed:
 - 1.1 1000 pW psophometrically weighted mean power in any hour;
 - 1.2 1000 pW psophometrically weighted one-minute mean power for 20% of any month;
2. that the following Notes should be regarded as part of this Recommendation:

Note 1. — The way in which the above values are to be taken into account in the general noise objectives for networks in the fixed satellite service is defined in Note 6 of Recommendation 353-2.

Note 2. — 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 §§ 1.1 and 1.2 above, 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.

Note 3. — In segments of the geostationary satellite orbit not likely to be crowded, interference allowances less than those recommended in §§ 1.1 and 1.2 above, may be utilized, allowing a corresponding increase in other noise contributions within total acceptable noise limits.

RECOMMENDATION 483

**SYSTEMS FOR TELEVISION USING FREQUENCY MODULATION
IN THE FIXED SATELLITE SERVICE**

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 2C-1/4)

(1974)

The C.C.I.R.,

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 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. — 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.

Note 3. — 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 484 *

STATION-KEEPING OF GEOSTATIONARY SATELLITES USING FREQUENCY BANDS ALLOCATED TO THE FIXED SATELLITE SERVICE

(Study Programme 2J-1/4)

(1974)

The C.C.I.R.,

CONSIDERING

- (a) that the geostationary-satellite orbit is of unique usefulness to telecommunications services;

* The Administration of the People's Republic of China reserves its position with respect to this Recommendation.

- (b) that 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 the present to satellites located at or near stable points of the geostationary-satellite orbit;

RECOMMENDS

that space stations on geostationary satellite using frequency bands allocated to the fixed satellite service:

1. shall have the capability of maintaining their positions within $\pm 1^\circ$ of the longitude of their nominal positions, but efforts should be made to achieve a capability of maintaining their positions at least within $\pm 0.5^\circ$ of the longitude of their nominal positions;
2. shall maintain their positions within $\pm 1^\circ$ of longitude of their nominal positions irrespective of the cause of variation; but
3. need not comply with § 2 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 § 2;
4. 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 practicable.

4F: *Reports*

REPORT 453-1 *

**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-1/4)

(1970 – 1974)

1. Introduction

This Report responds to Study Programme 2J-1/4 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.

The first meeting of the Interim Working Party was in Ottawa, from 10 to 13 June, 1969, and the report is given in Doc. IV/334 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 Doc. 4/1, 1970–1974. 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 Docs. 4/252 and 4/299, 1970–1974, respectively. 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 coordination of frequencies assigned to space and earth stations. Articles 7 and 9A of the Radio Regulations refer. See also C.C.I.R. Report 454-1.

* Adopted unanimously.

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 388-2, 390-2 and 455-1 as well as Reports 555, 556, 557, 558, 559 and 561.

The contents of this Report are as follows;

2. Factors determining the relationship between the nominal angle of separation and carrier-to-interference ratio
 - 2.1 Radiation diagrams of earth-station antennae
 - 2.2 Polarization discrimination advantage
 - 2.3 Frequency re-use by means of narrow-beam satellite antennae
 - 2.4 Satellite station-keeping
 - 2.5 The use of frequency bands allocated for the fixed satellite service for both up-paths and down-paths
3. Relationship between input carrier-to-interference ratio and baseband performance
 - 3.1 Co-channel carriers
 - 3.2 Interleaved carriers
4. Allowance for inter-system interference noise
5. The effect of modulation characteristics on orbit/spectrum utilization
6. System homogeneity
7. Use of multiple frequency bands
8. Quantitative analyses of the effects of the technical factors upon orbit utilization
 - 8.1 Orbit spacing studies using specific system characteristics
 - 8.2 A homogeneous parametric study
 - 8.3 The effect of station-keeping accuracy on orbital capacity
 - 8.4 Optimization of heterogeneous orbit utilization
9. Frequency re-use by geosynchronous satellites in inclined orbits
10. Other factors affecting the number and locations of geostationary satellites
 - 10.1 Economic, operational and technical considerations affecting the capacity of individual satellites
 - 10.2 Power flux-density at the surface of the Earth
 - 10.3 Influence of traffic patterns
 - 10.4 Additional frequency bands
 - 10.5 Satellite-to-satellite relay
 - 10.6 Flexibility in the positioning of satellites
 - 10.7 Miscellaneous technical factors
11. Criteria of efficiency in the use of the geostationary-satellite orbit and the frequency spectrum
12. Review of possible future C.C.I.R. Recommendations for improving efficiency of orbit utilization

References

- Annex I. Illustrative examples of spacing required between geostationary satellites of different networks
- Annex II. Methodology for relating orbit/spectrum utilization measures to system parameters.

2. Factors determining 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 is 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 390-2.

In order to stimulate the provision of antennae with higher performance standards, it would be desirable for the C.C.I.R. to establish a design objective for new antennae, with side lobes as low as practicable. It would not be appropriate to use for this purpose the reference pattern in Recommendation 465-1, because that pattern was prepared to indicate the performance of antennae in current service. The preparation of the design objective is under study in the C.C.I.R.; see Study Programme 1A-1/4.

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.

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 2C-1/4. 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 link, have been studied [C.C.I.R., 1970-1974a] 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.

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. 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.

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.

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.

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. This is considered further in § 8.3 of this Report. The factors affecting the positioning of satellites and the accuracy of station-keeping that is technically feasible at present are considered in Report 556.

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.

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.

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.

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 388-2 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*

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.

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 the case of systems employing a variety of modulation and satellite multiple-access techniques, the maximum interleaving advantage may only be achieved by appropriate coordination 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, 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.

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, it is estimated that the total capacity of a busy arc of the orbit might be increased by at least 75% if the inter-system interference noise component were raised from the 10% of total noise recommended for systems using FM in Recommendation 466-1 (for FDM telephony) and in Recommendation 483 (for television) to about 50% of total noise.

To increase now the inter-system interference noise allowance beyond that recommended in Recommendations 466-1 and 483, so that it forms a substantial proportion of the total channel noise would have serious disadvantages, for example:

- the capacity of individual satellite networks would be reduced. This would increase costs, more particularly for satellite systems used to provide international links for the public network;
- interference would be sensitively dependent upon such factors as:
 - satellite station-keeping,
 - satellite attitude control,
 - side-lobe characteristics of satellite and earth-station antennae,
 - cross-polarization response of antennae.

C.C.I.R. studies of most of these factors are, as yet, in an early stage. While inter-system interference noise is only a small part of the total noise, uncertainties about these factors do not give rise to serious fears that system designers will lose effective control of system performance. However, there would be little confidence at present that performance targets would be achieved if the interference component were large.

In the interest of preserving efficient use of the geostationary orbit, it is desirable that the interference noise value specified in Recommendation 466-1 should continue to apply for the time being to systems using earth-station antennae with directional properties in the plane of the geostationary-satellite orbit above some minimum specified standard.

At some time in the future, it may be found desirable to increase the recommended inter-system interference noise component beyond the proportion of total noise currently recommended in order to increase the communications capacity made available by the geostationary-satellite orbit. This increase might be made selectively, applying in particular to the busier arcs of the orbit. If arcs of the orbit should be occupied by satellites serving earth stations with antennae below minimum specified performance values, which would have to be agreed, these systems might have to be designed so as to tolerate larger interference noise contributions if close satellite spacing should be required.

It appears necessary to continue studies on this matter especially in the following areas:

- the suitable inter-system interference noise allocation for transmissions other than FDM-FM telephony and television, e.g., PCM-PSK telephony;
- a possible relationship between the interference noise allowance and the degree of congestion of the geostationary orbit;
- a suitable inter-system interference noise allowance for use at frequencies above 10 GHz.

5. The effect of modulation characteristics on orbit/spectrum utilization

Studies have been made [C.C.I.R., 1970-1974 b, c, d] 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.

The relationship between modulation characteristics and other factors that affect orbit utilization is considered in more detail in Report 559. See also § 8.

6. 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.

Many facets of this problem have been considered and some of the observations that can be made at this time include:

- a reasonable efficient orbit utilization may result if a low e.i.r.p. satellite working with earth stations having high gain antennae were placed between the already-existing satellites of systems with high down-path e.i.r.p. and earth stations with low values of figure of merit (G/T);
- with different types of satellite in orbit, efficient orbit utilization might be obtained through a suitable choice of transmission parameters and through adjustment of the interference noise allowances, the relative power levels and the orbital positions of satellites in the different systems;
- when space networks with significantly different down-path e.i.r.p. share the orbit, it is generally advantageous to cluster several low e.i.r.p. satellites together; the size of such clusters should have some form of inverse relationship with the difference in satellite e.i.r.p.

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. This matter is examined further in § 8.4 below.

7. Use of multiple-frequency bands

Radiocommunication satellites use frequency bands in pairs, one band for the up-path and the other for the down-path. Up to the present time, for example, many systems have paired the use of the 4 and 6 GHz bands because they were allocated early and they provide good propagation conditions. In the future, new frequency bands allocated at the World Administrative Radio Conference for Space Telecommunications, 1971, to various space radiocommunication services will be put into use, and

the different propagation conditions obtaining at these different frequency bands and the differences in available bandwidth may lead to preferred pairings of these new bands. It may be desirable for the C.C.I.R. to define preferred pairings for frequency bands to avoid wasteful use of the spectrum and the geostationary satellite orbit (see Study Programme 2J-1/4).

The following text deals with the use of more than one pair of frequency bands in satellites used entirely for the fixed satellite service. The problems that arise when other services are provided by satellites which also make use of frequency bands allocated for the fixed satellite service have received preliminary study [C.C.I.R., 1970-1974e]. See Study Programmes 2K-1/4 and 2M/4.

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 coordination 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.

This latter problem has been examined [C.C.I.R., 1970-1974 f, e]. It is found that significant differences in the angular separation required may arise even from differences in the propagation margin required in different bands, and the situation might be aggravated by differences in type of modulation, transmission parameters, antenna characteristics and so on. It is evident that the problem will not be significant in parts of the orbit where few satellites use more than one pair of frequency bands, but it could have a substantial adverse effect on orbit/spectrum utilization efficiency where there are several multi-band satellites in adjacent orbital locations. There is insufficient information at this time to quantify this effect in general terms. It can certainly be stated that the analysis of the effect of using multi-band satellites in the fixed satellite service relative to orbit/spectrum utilization is complex.

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.

8. Quantitative analyses of the effects of the technical factors upon orbit utilization

The various technical factors reviewed in §§ 2, 3, 4, 5, 6 and 7 of this Report will interact in complex ways to influence the capacity of satellites and the angular spacing required between them

when they use the same frequency bands. No analysis embracing all parameters has been completed yet, but several studies of some parameters have been made, and the results are summarized below.

8.1 *Orbit spacing studies using specific system characteristics*

Annex I gives details of two studies 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 *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. 1 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 $N_I = 1000$ pW0p, which is the value currently stipulated in Recommendation 466-1. Similarly, Fig. 2 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.

The impact of the modulation parameters can be observed in Fig. 3. The abscissa is given in terms of 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. 3 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.

Fig. 1 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. 4 where \bar{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. 1 to 4. 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.

First, it may be seen from Fig. 1 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 30 : 1 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. 2 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. 3 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. 4 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. 1, that greater total orbital capacity is potentially available if a successively larger fraction of the noise budget is allocated to interference.

8.3 *The effect of station-keeping accuracy on orbital capacity*

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 [C.C.I.R., 1970-1974g]. Some of the results are shown in Fig. 5. 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.

8.4 *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 [C.C.I.R., 1970-1974 h, j, k].

In [C.C.I.R., 1970-1974j] this analytical technique was 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 coordination. 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° - 3° orbital spacing.

[C.C.I.R., 1970-1974k] 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.

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.

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 387-2.

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.

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 205-3, 233-3 and 234-3;
- 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 *Satellite-to-satellite relay*

A preliminary study has been made of the factors involved in relaying information directly from one satellite to another. This technique might be used to connect two earth stations which do not use the same satellite without requiring relaying at a third earth station which has access to both satellites.

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;
- only two paths would be required between space and earth, instead of the four needed for use via the third earth station, thus saving bandwidths in the Earth-space bands (the frequencies assigned to the space-space links could be located in parts of the spectrum which are unsuitable for use between Earth and space);
- 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;
- the number of earth stations could be reduced.

It should be recognized that the implementation of inter-satellite links may complicate the satellites to an extent which cannot yet be assessed; moreover, a study of trunking, switching and modulation within a satellite-to-satellite relaying space segment is required.

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 is recognized, however, that such design 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.

Further study of this important matter is required, and this may lead to a Recommendation on flexibility in the positioning of satellites.

10.7 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

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. However, three possible approaches have been suggested:

- (a) a reference satellite system (or systems) might be defined, against which calculations could be performed. This concept needs further study;
- (b) where the satellite is to employ antennae giving global coverage, an approach which gives an indication of the efficiency with which the orbit would be utilized by a group of such systems is to calculate the angular separation at which a predetermined small amount of interference would arise between the proposed system and an identical hypothetical system. The method of calculation is identical with that set out in Report 454-1, but extended to evaluate directly the angular separation α , as follows:

$$25 \log_{10} \alpha = 32 + 10 \log_{10} \left[\frac{1}{k\Delta T} \left(\frac{P'_s g'_3(\eta_e)}{l_a} + \frac{\gamma P'_e g_2(\delta_e)}{l_u} \right) \right]$$

The symbols have the same meaning as those set out in Report 454-1; e.g. $g'_3(\eta_e)$ is taken to represent the gain of the hypothetical interfering satellite antenna in the direction of the earth station and $g_2(\delta_e)$ is the gain of the antenna of the satellite in the direction of the hypothetical interfering earth station;

- (c) a method is being developed for relating transmission capacity to the spectrum and orbital arc occupied. See Annex II of this Report. So far, the method has been developed for homogeneous systems of satellites used for FDM/FM telephony but it is potentially general in its application.

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. Undoubtedly certain of the terms likely thus to be involved require careful choice and precise definition and even when this is done, it may not be possible to reach a satisfactory way of expressing the efficiency of use of these resources in a meaningful and useful way. Nevertheless, it is generally considered that the subject requires further investigation which would be an appropriate task for Interim Working Party 4/1.

It is evident that the definition of a reference system as suggested in (a) above for comparison purposes will itself raise some problems. If used, however, it would enable the efficiency of other systems to be compared in a relative way. Methods (b) and (c) have the advantage that they do not require a separate reference system and therefore need to be explored further. Possibly approaches via method (a) and via methods (b) and (c) will be of value. 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 make a simple answer impossible. The question of the extent of territory and the number of earth stations covered by any particular system should, if possible, also be reflected in some way in the results.

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.

It is considered that a generalized systems approach to this problem should be made but that the continuation of this work should be reviewed when it is possible to determine whether useful results are likely to be achieved.

12. Review of possible future C.C.I.R. 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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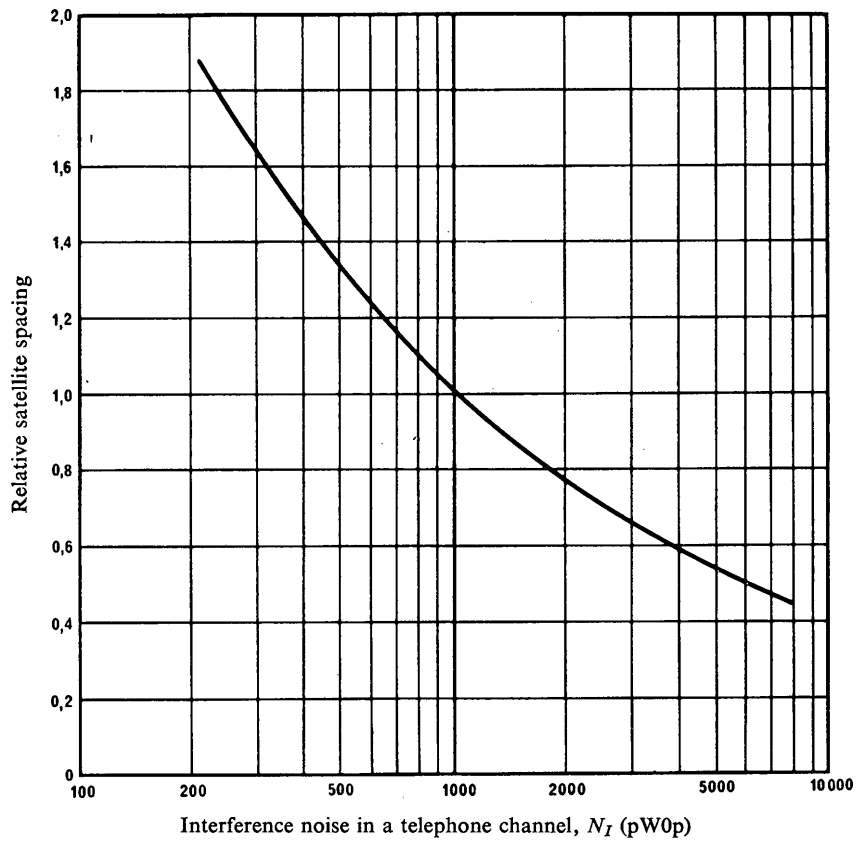


FIGURE 1

Satellite spacing as a function of interference noise

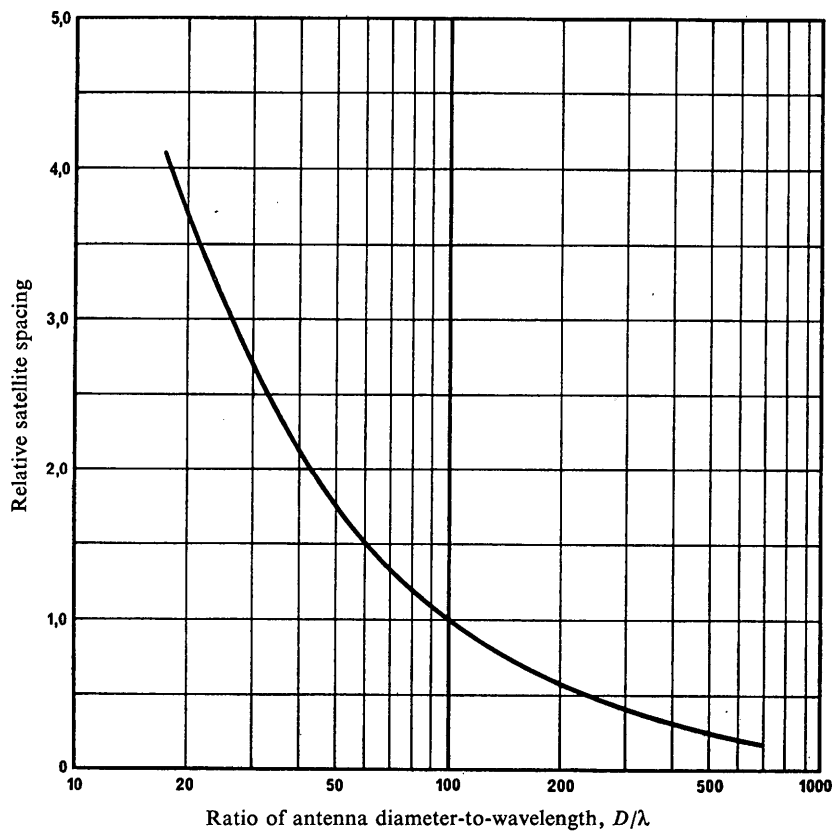


FIGURE 2

Satellite spacing as a function of earth-station antenna size

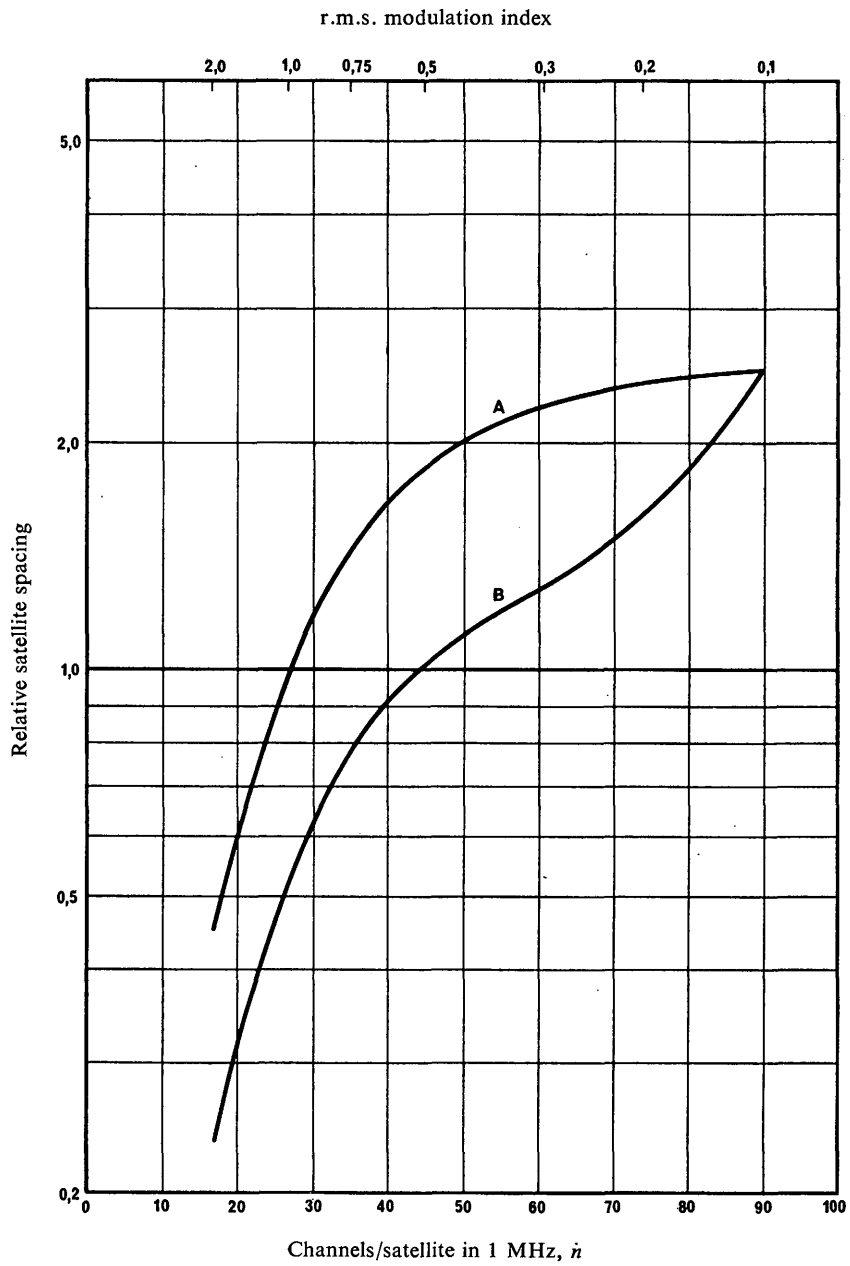


FIGURE 3
Satellite spacing as a function of modulation index
A: Co-channel
B: Interleaved

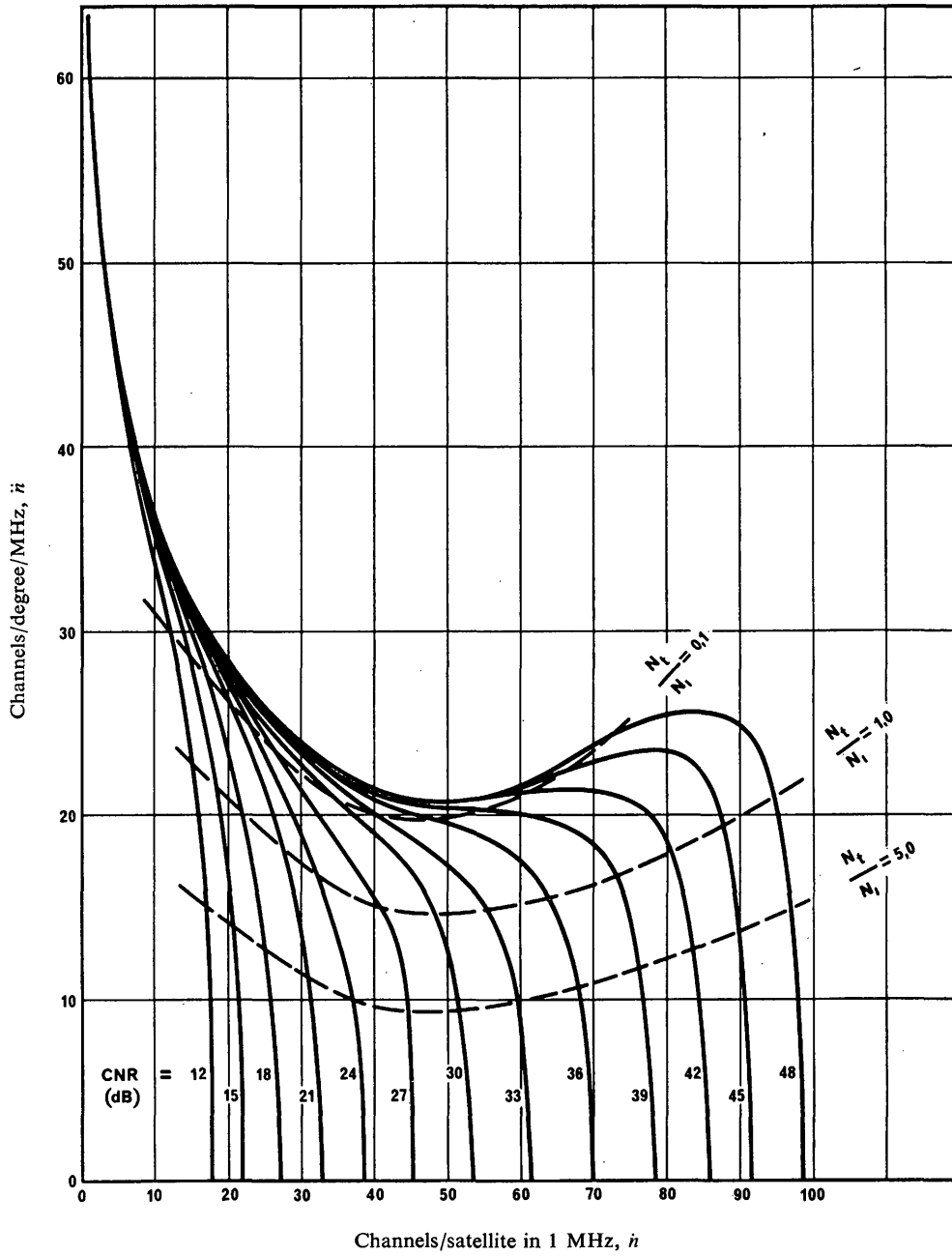


FIGURE 4
Orbit/spectrum utilization as a function of channels per satellite
($D/\lambda = 300, N_t + N_r = 7500$)
(Interfering carriers are assumed to be co-channel)

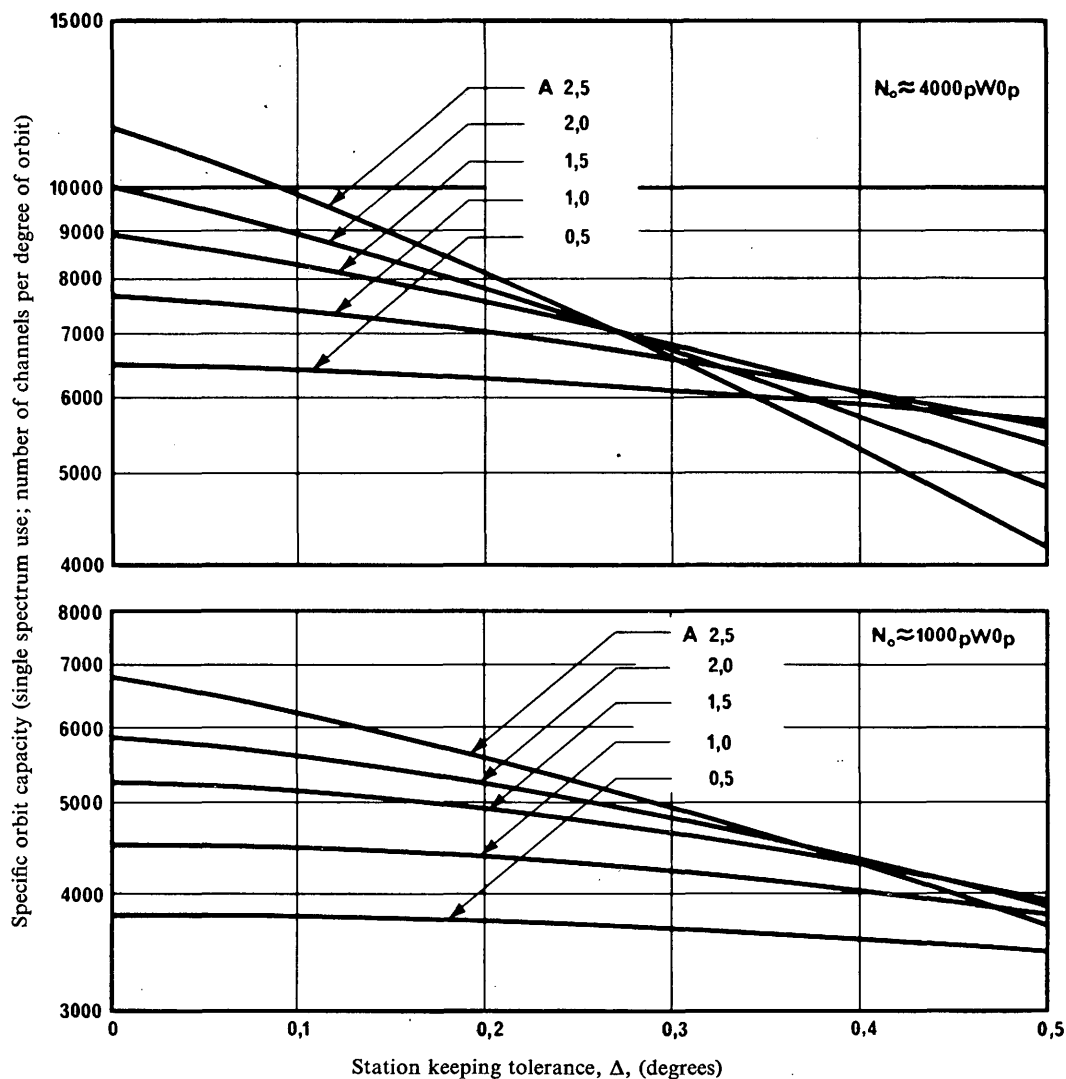


FIGURE 5

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)
- C.C.I.R. earth-station reference antenna pattern
- Bandwidth = 500 MHz.
- A: R.m.s. Modulation index

ANNEX I

ILLUSTRATIVE EXAMPLES OF SPACING REQUIRED BETWEEN
GEOSTATIONARY SATELLITES OF DIFFERENT NETWORKS

This Annex shows the results of two studies of the spacing required between satellites of networks with various characteristics.

1: Study A

Three basically different types of system are assumed with characteristics chosen to be reasonably representative. Frequency modulation with FDM telephone basebands are assumed in all cases.

System I is a high capacity system employing high e.i.r.p. satellites, large earth-station antennae and relatively low index frequency modulation.

System II is a medium capacity system employing medium e.i.r.p. satellites, large earth-station antennae and high index frequency modulation.

System III is a medium capacity system employing high e.i.r.p. satellites, medium earth-station antennae and high index frequency modulation.

In order to show the effect of the relative capacities of the wanted and interfering carriers but with other parameters (modulation index, e.i.r.p. per channel, etc.) unchanged, a *System Ia* is also defined which is identical to *System I* except that it has a number of 300 channel carriers instead of a single large carrier.

The detailed characteristics assumed are given in Table I.

TABLE I
System characteristics

System	I	II	III	Ia
Earth-station antenna gain at 4 GHz (dB)	59	59	52	59
Earth-station receive noise temperature (K)	50	50	200	50
Satellite e.i.r.p./35 MHz (dBW)	34	21.1	34	34
Satellite e.i.r.p./carrier (dBW)	34	21.1	34	26.2
Satellite antenna receive gain (dB)	15	15	15	15
Satellite receive noise temperature (K)	1000	1000	1000	1000
Earth-station available transmitter power per carrier (dBW)	31.4	20.3	27.3	23.6
Capacity of carriers (channels)	1800	900	900	300
Multi-channel r.m.s. deviation (MHz)	3.15	4.36	4.36	0.522
Interference power (pW0p)	1000	1000	1000	1000
Antenna pattern (dB above isotropic)	32-25 log ₁₀ θ			
Multi-channel peak/r.m.s. ratio (dB)	10			
Baseband top frequency (Hz)	4200 n			
Pre-emphasis advantage (dB)	4			
Polarization advantage	none			

The required satellite separation angles with co-channel carriers, considering a single interference entry, are given in Table II.

TABLE II
Minimum separation angles (degrees)

Interfering system	Wanted system			
	I	II	III	Ia
I	4.8°	4.5°	3.4°	6.0°
II	1.6°	1.5°	< 1°	2.0°
III	4.4°	4.3°	2.8°	5.3°

The values given are based on the assumption that carriers are fully loaded. If it is assumed that under different loading conditions and with energy-dispersal the spectral density rises by a maximum of 3 dB above the full load value, then the above spacings would need to be increased by up to 30%.

If there are a large number of interfering satellites at regular spacings on both sides of the wanted satellite then the minimum separation angles would be approximately 50% greater than those given in Table IV.

2. Study B

This study considered two types of system. Both use digital transmission, with PCM and 4-phase PSK modulation but in other respects the basic system descriptions given for Study A, *Systems I and III*, apply broadly to Study B and it is convenient to designate these systems with these numbers also. The system assumptions and characteristics are as shown in Table III, interference

TABLE III
System characteristics

System	I	III
Modulation and demodulation	PCM-4-PSK coherent detection	
Repeating system	heterodyne	
Bit-rate/channel	64 kbit/s/channel	
Symbol rate	32 MegaBauds	32 MegaBauds
Capacity of carrier (channels)	960	960
Error-rate	median	less than $10^{-7}/1$ reference circuit
	0.3%	less than $10^{-4}/1$ reference circuit
Polarization advantage	None	
Allowable interference from other systems	28 dB for one earth-station to earth-station link	
<i>Earth station</i>		
Antenna gain (dB)	59	52
Receive noise (K)	50	200
Transmitter power per carrier (dBW)	22	28.6
Antenna pattern (dB above isotropic)	32 - 25 log ₁₀ θ	
<i>Satellite</i>		
Antenna receive gain (dB)	15	
Receive noise (K)	1000	
e.i.r.p./carrier (dBW)	24.0	36.6

calculation having been made using only the power ratio of the desired and the undesired carrier, without considering the dispersion of the PSK spectrum and the improvements to be obtained by filtering. The minimum satellite separations found to be necessary are shown in Table IV.

TABLE IV
Minimum separation angles (degrees)

Interfering system	Wanted system	
	I	III
I	1·1	1·1
III	3·4	1·1

ANNEX II

METHODOLOGY FOR RELATING ORBIT/SPECTRUM UTILIZATION MEASURES TO SYSTEM PARAMETERS

1. Introduction

This Annex presents a general methodology which may be used to derive numerical results relating orbit/spectrum utilization measures to system parameters.

There are two main technical problems:

- 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 455-1;
- 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 388-2.

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:

$$\left(\frac{S}{N}\right)_t = \left(\frac{C}{N}\right)R_t \quad (1)$$

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 characteristic) 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 (1) through:

$$N_t = 10^9 (S/N)_t \text{ pW} \quad (2)$$

and it may be shown that

$$R_t = 380 M_{\text{rms}}^2 (\sqrt{\Lambda} M_{\text{rms}} + 1), \quad n \geq 240 \quad (3a)$$

and

$$R_t = 15 n^{0.6} M_{\text{rms}}^2 (\sqrt{\Lambda} M_{\text{rms}} + 1), \quad 12 \leq n < 240 \quad (3b)$$

where

M_{rms} : multi-channel 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 (3) also includes a 4 dB pre-emphasis advantage as well as a 2.5 dB psophometric weighting, and was, further, based on Carson's rule for FM bandwidth, i.e.:

$$W = 8400 n (\sqrt{\Lambda} M_{\text{rms}} + 1) \text{ Hz} \quad (4)$$

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:

$$\left(\frac{S}{N}\right)_j = \left(\frac{C}{I}\right)_j R_j \quad (5)$$

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 455-1.

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 388-2 may be used to compute the numerical values of R_j .

$$\text{Baseband noise } N_{Ij} = 10^9 / (S/N)_j \text{ pW} \quad (6)$$

Since $(C/I)_j$ is directly related to the spacing between the wanted and unwanted satellites for a given set of system parameters, equation (6) 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:

* 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.

$$N_T = N_t + \sum_{j=1}^K N_{Ij} \quad (7)$$

where K is the number of interference entries.

Using equations (1), (2), (5) and (6):

$$N_T = 10^9 \left\{ \frac{1}{(C/N)R_t} + \sum_{j=1}^K \frac{1}{(C/I)_j R_j} \right\} \text{ pW} \quad (8)$$

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 (8) is quite general. For an arbitrary, given set of parameters, 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

The assumptions collectively referred to as the homogeneous model, in § 8.2 of this Report, permit reasonably straightforward computation of the trade-offs of interest, as shown below. In this present Annex, however, for slightly greater generality, the last assumption in the model is removed, i.e., both up- and down-path contributions are considered.

Consider the evaluation of the quantity channels/degree/MHz. First, 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 (8) 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 C.C.I.R. Special Joint Meeting, Geneva, 1971, it can be shown that:

$$R_0 \approx 76 (1 + 9.5 M_{rms}^3), \quad n \geq 240 \text{ channels} \quad (9a)$$

$$R_0 \approx 3n^{0.6} (1 + 9.5 M_{rms}^3), \quad 12 \leq n < 240 \quad (9b)$$

The equation (9) includes psophometric weighting and C.C.I.R. pre-emphasis.

Next, it is convenient to separate up-path and down-path contributions, as follows:

$$\left(\frac{C}{N}\right) = \left(\frac{C}{N}\right)_d \left(\frac{1}{1 + \alpha}\right) \quad (10)$$

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:

$$\left(\frac{C}{I}\right)_j = \left(\frac{C}{I}\right)_{dj} \left(\frac{1}{1 + \alpha_j}\right) \quad (11)$$

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:

$$G(\Delta\theta) = A/(\Delta\theta)^{2.5}; (A = 10^{3.2}) \quad (12)^*$$

it may be shown, to a good approximation, that

$$\alpha_j = \alpha_0; \quad (13)$$

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 (8) may then be written, using equations (9) and (13):

$$\sum_{j=1}^K \frac{1}{(C/I)_j R_j} = \frac{1 + \alpha_0}{R_0} \sum_{j=1}^K \frac{1}{(C/I)_{dj}} \quad (14)$$

and it may further be shown, for co-channel, co-polarized transmissions, that:

$$\sum_{j=1}^K \frac{1}{(C/I)_{dj}} \approx \frac{2A}{G_{0d} (\Delta\theta)^{2.5}} \sum_{k=1}^{\infty} k^{-2.5} \approx \frac{2.7A}{G_{0d} (\Delta\theta)^{2.5}} \quad (15)$$

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 (10), (14) and (15) into equation (8) yields:

$$\frac{1}{\Delta\theta} = \left\{ \left(\frac{N_T}{10^9} - \frac{1 + \alpha}{(C/N)_d R_t} \right) \frac{R_0 \eta (\pi D/\lambda)^2}{2.7A (1 + \alpha_0)} \right\}^{0.4} \quad (16)$$

From equation (4)

$$\dot{n} = 119/(\sqrt{\Lambda} M_{rms} + 1) \text{ channels/MHz}$$

and hence the quantity sought is

$$\ddot{n} = \frac{119}{(\sqrt{\Lambda} M_{rms} + 1) \Delta\theta} \text{ channels/degree/MHz} \quad (17)$$

Introducing equation (16) into equation (17) gives an explicit equation relating a measure of orbit and spectrum utilization to all major system parameters. Fig. 4 of the Report 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 C.C.I.R. pre-emphasis.

* In principle $\Delta\theta$ is the topocentric angle, but since it approximates to the geocentric angle, these two angles are used interchangeably.

REPORT 454-1 *

USE OF THE GEOSTATIONARY-SATELLITE ORBIT

Method of calculation to determine whether two geostationary-satellite systems require coordination

(Study Programme 2J-1/4)

(1970 – 1974)

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 based on the concept that the noise temperature of the system receiving interference undergoes an apparent increase due to the effect of the interference. It 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 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. Calculation of the increase in noise temperature of the satellite link receiving interference

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 also 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.

2.1 Case I

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);

* Adopted unanimously.

- $g_3(\eta)$: 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 : geocentric angular separation between two satellites (degrees). **

The parameters ΔT_s and ΔT_e are given by the following equations:

$$\Delta T_s = \frac{p'_e g'_1(\theta) g_2(\delta_{e'})}{k l_u} \quad (2)$$

$$\Delta T_e = \frac{p'_s g'_3(\eta_e) g_4(\theta)}{k l_d} \quad (3)$$

* To simplify the calculation it was assumed that:

— basic transmission loss on the down-path is the same regardless of the satellite and earth station considered;
 — basic transmission loss on the up-path is the same regardless of the earth station and satellite considered.

** The angle θ is used as a good approximation of the angle under which an earth station would see the two satellites under consideration.

In the foregoing equations, the gains $g'_1(\theta)$ and $g_4(\theta)$ are those of the earth stations concerned. In the event that precise numerical data relating to earth-station antennae are not 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:

$$\Delta T = \gamma \Delta T_s + \Delta T_e \quad (4)$$

Hence

$$\Delta T = \gamma \frac{p'_e g'_1(\theta) g_2(\delta_{e'})}{kl_u} + \frac{p'_s g'_3(\eta_e) g_4(\theta)}{kl_a} \quad (5)$$

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:

$$\Delta T = \gamma \frac{p'_e g'_1(\theta) g_2(\delta_{e'})}{kl_u} + \frac{\bar{p}'_s \bar{g}'_3(\eta_e) g_4(\theta)}{kl_a} \quad (6)$$

If there is a change of modulation in the wanted satellite then it may be necessary to treat up- and down-paths separately using equations (2) and (3).

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:

$$\Delta T'_{s'} = \frac{p_e g_1(\theta) g'_2(\delta_e)}{kl_u} \quad (7)$$

$$\Delta T'_{e'} = \frac{p_s g_3(\eta_{e'}) g'_4(\theta)}{kl_a} \quad (8)$$

When both satellites share the same translation frequency, then

$$\Delta T' = \gamma' \frac{p_e g_1(\theta) g'_2(\delta_e)}{kl_u} + \frac{p_s g_3(\eta_{e'}) g'_4(\theta)}{kl_a} \quad (9)$$

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}):

$$\Delta T' = \gamma' \frac{p_e g_1(\theta) g'_2(\delta_e)}{kl_u} + \frac{\bar{p}_s \bar{g}_3(\eta_{e'}) g'_4(\theta)}{kl_a} \quad (10)$$

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.

2.2 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 coordination procedures analogous to those used for coordination 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.

3. 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. These 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 388-2 and 455-1.

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 C.C.I.R. 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.

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 unfavourably sited transmitting earth station of the interfering satellite 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 unfavourably sited transmitting earth station is the one in the direction of which the satellite receiving antenna gain of the network interfered with is the greatest.

The most unfavourably sited receiving earth station of the network suffering interference should be determined in an analogous manner for each "space-to-Earth" service area of that network. The most unfavourably sited receiving earth station is the one in the direction of which the satellite transmitting antenna gain of the interfering network is the greatest.

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 455-1 *

**FREQUENCY SHARING BETWEEN NETWORKS
OF THE FIXED SATELLITE SERVICE**

(Question 2-2/4, Study Programme 2C-1/4)

(1970 – 1974)

1. Introduction

The extent to which the same frequencies may be used, without causing harmful interference, by different satellite networks of the fixed satellite service, is a subject of considerable importance, bearing as it does on the efficient use of the frequency spectrum and the geostationary-satellite orbit.

The possible use of frequency sharing may be affected by:

- the number of satellites sharing a given frequency band channel;
- the radiation pattern of the earth-station and space-station antennae;
- any difference in polarization between wanted and interfering signals;

* Adopted unanimously.

- 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.

2.2 Channel 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:

$$10 \log_{10} \frac{1 \text{ mW test tone}}{\text{Unweighted interference power in a telephone channel of 3.1 kHz bandwidth}} = \left(\frac{C}{I}\right) + B \quad (2)$$

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").

$$\left(\frac{C}{I}\right) = \text{the wanted-to-interfering carrier power ratio at the input to the receiving system (dB).}$$

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.

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 presently known. Another difficulty is that the nature of digital detection makes it impossible to define the interference performance independently of the thermal noise performance (in contrast to analogue signals above threshold). Reference should be made to Report 388-2 which sets out the techniques for calculating interference noise in systems carrying multi-channel 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 interference resulting 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. **Separation of satellites in space and time domains**

3.1 *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.

3.2 *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° – 6°) in most cases. Larger separations are, however, required in the case of multi-channel systems with low modulation indices, or single-channel systems. Illustrative examples of the spacing required between geostationary satellites of different systems are given in Annex I of Report 453-1.

3.3 *Interference between geostationary and non-geostationary systems*

3.3.1 *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.

3.3.2 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.

4. 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., size 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.

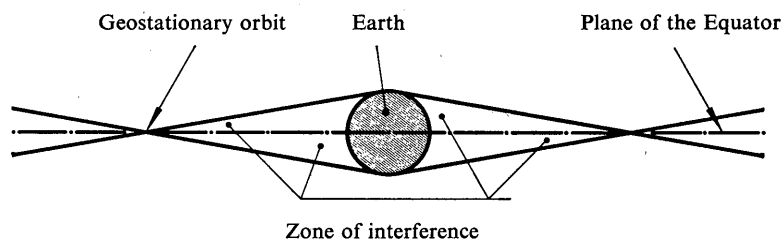


FIGURE 1

Zone of interference between geostationary and non-geostationary satellites

ANNEX

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 388-2.

2. Method

The interference geometry between two satellite networks is shown in Fig. 1. 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.

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. 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; this is 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. 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 that 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:

$$(C/I)_U = P_t + G_1 - \Delta L_U - M_U - p_t - g_1(\theta) + \Delta G_2 + Y_u \quad \text{dB} \quad (1)$$

and

$$(C/I)_D = E + G_4 - \Delta L_D - e - G_4(\theta) + Y_D \quad \text{dB} \quad (2)$$

where

- $(C/I)_{U,D}$ = up- and down-path wanted-to-interfering carrier ratios (dB);
- P_t, p_t = 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 and e should be determined recognizing variations of path geometry with time. 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.

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:

$$(C/I)'_u = P_t + G_1 - M_u + \Delta G'_2 - e' + Y' + 20 \log \theta' - 35.2 \text{ dB} \quad (3)$$

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,

$$\Delta G'_2 = G_{2 \text{ wanted}} - G_{2 \text{ interfering}} \text{ dB};$$

e' = satellite e.i.r.p. of the interfering carrier in the direction of the wanted satellite (dBW);

Y' = minimum polarization discrimination between the interfering-satellite carrier and the wanted-satellite receive antenna (dB);

θ' = geocentric minimum angular satellite spacing for the wanted earth station (degrees).

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. 2 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 (1) from that of equation (2). This correction term is used as follows:

$$(C/I)_{link} = (C/I)_D - \Delta I \text{ dB} \quad (4)$$

For Case II, use simply:

$$(C/I)'_{link} = (C/I)'_u \text{ dB} \quad (5) *$$

3. Interference effects

§ 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.

* Interference between earth stations needs to be considered separately since different propagation conditions and different criteria apply.

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 (1), (2) or (3) 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 (1), (2) or (3);
- 4.4 determine the network wanted-to-interfering carrier ratio in accordance with equation (4) or (5), 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 388-2 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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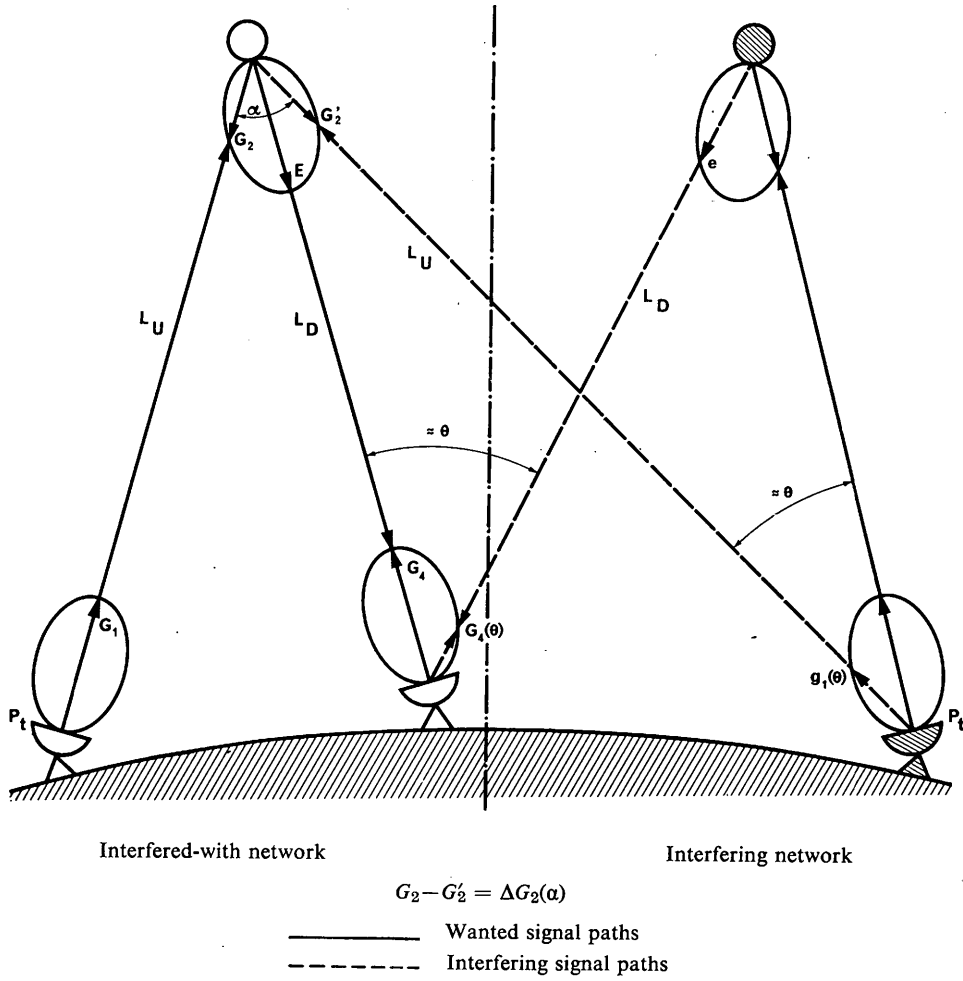


FIGURE 1a

Interference geometry between two satellite networks, Case I

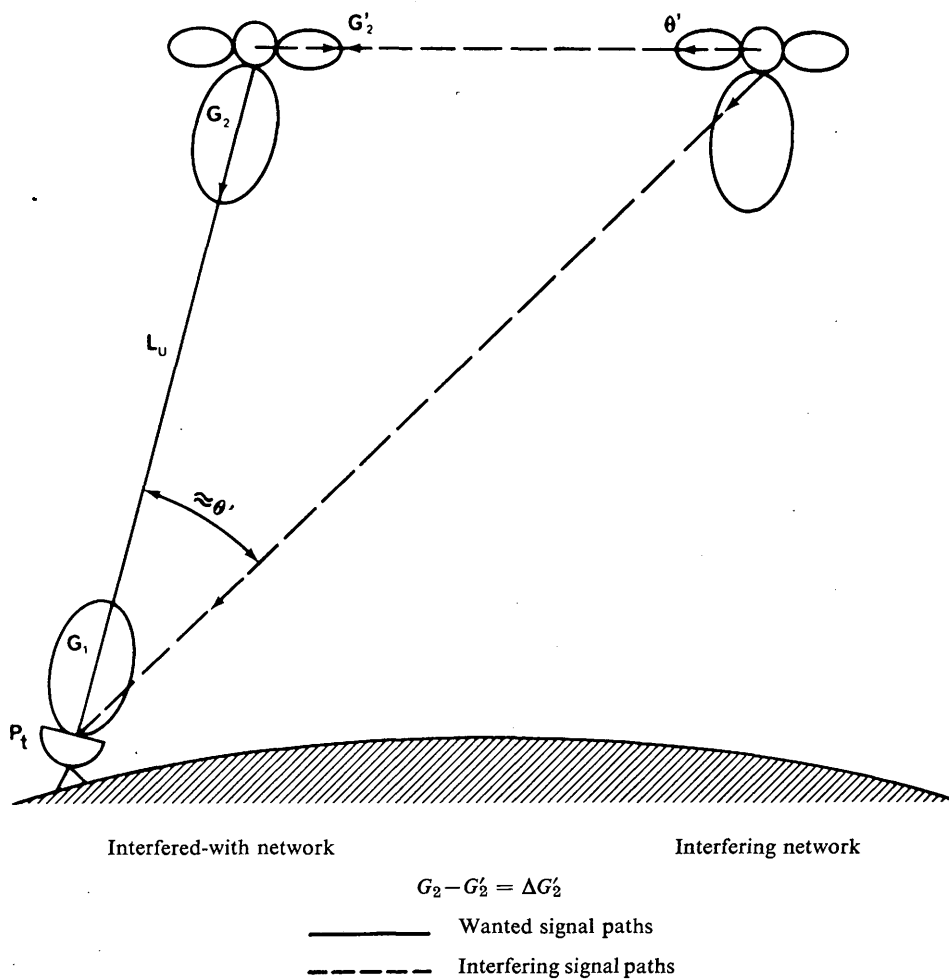


FIGURE 1b
Interference geometry between two satellite networks, Case II

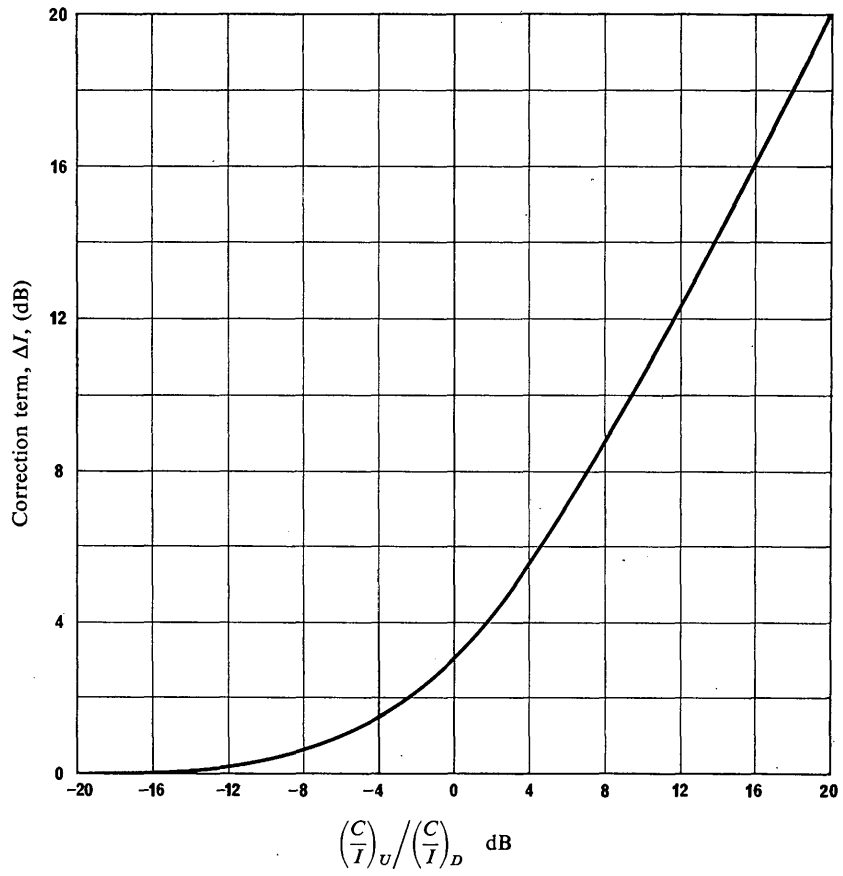


FIGURE 2

Correction term ΔI for up-path to down-path wanted carrier to interfering carrier ratios, $(C/I)_U / (C/I)_D$

REPORT 555 *

**POLARIZATION DISCRIMINATION BY MEANS OF
ORTHOGONAL CIRCULAR AND LINEAR POLARIZATION**

(Study Programmes 1B/4 and 1C/4)

(1974)

1. Introduction

The use of orthogonal polarization can provide an effective way of increasing the capacity of the geostationary-satellite orbit. 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.

Antennae can transmit and receive linearly polarized waves without having polarizers in their feed circuits, but require polarizers for the generation of circular polarization. Earth stations utilizing linear polarization may have adjustable polarizers incorporated in order to align the direction of their electric vectors to that of the satellite antenna. Alternatively, linearly polarized antennae without polarizers must incorporate mechanical rotation of the feed for polarization tracking purposes.

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.

The data referred to in this Report were mostly obtained at 4 and 6 GHz, although the general principles are applicable to the higher frequency ranges. In some cases the data were obtained from equipment not designed for maximum polarization discrimination, and some projection has been made for further improvements.

2. Antennae

In this section the polarization properties of antennae alone are considered, i.e. the effects of polarizers are excluded.

For earth-station antennae, in the case where frequencies are re-used within one satellite, the main beam centre is the most important region, because the beam centres of all earth station antennae are always directed to the satellites by tracking. The -3 dB region is only important in the case of satellite tracking failure. The region defined by the outer region of the main beam, well beyond the -3 dB points, should be given attention from the standpoint of permissible satellite spacing, especially in cases where frequencies are re-used in adjacent satellites. For satellite antennae the region of interest coincides with the beam coverage and extends to at least the -3 dB contour.

Polarization discrimination characteristics in various regions of antennae beams depend principally on the type of antennae. Calculation of polarization discrimination was made on several types of antennae in and near the main beam. Some of the results are summarized in Table I. Among

* Adopted unanimously.

the antennae considered, conical horns and horn-reflectors are suitable for satellite antennae. Fig. 1 shows the measured cross-polarization levels using linear polarization for these antenna types.

It should be noted that, for both circular and linear polarizations, front-fed reflector type antennae have a polarization discrimination a little inferior to horn types, particularly when the reflector antennae have blockage due to the primary radiators. It should also be noted that more complicated problems have to be taken into account in the case of multiple beam antennae. The polarization discrimination in the main beam of the Cassegrain antennae used for earth stations depends mainly upon their primary radiators.

For linear polarization the frequency characteristics of the polarization discrimination of two earth station antennae at Raisting are shown in Fig. 2. The variation of the polarization discrimination in linear polarization across the main beam was also measured on the No. 3 antenna at Pleumeur-Bodou and was found to exceed 37 dB over the -1 dB region, and 25 dB over the -3 dB region at all frequencies of measurement.

Based on a limited amount of measured data and on limited theoretical considerations, the following conclusions can be reached:

- in the centre of the main beam, up to the -1 dB region, large reflector earth-station antennae could provide in excess of 35 dB of discrimination for both circular and linear polarization;
- in the region up to the -3 dB contour, satellite antennae with beam patterns having near perfect rotational symmetry about the focal axis would provide 40 dB of discrimination for both circular and linear polarization. Satellite antennae with aperture blockage may provide somewhat less discrimination in certain regions within the -3 dB contour.

When the beam cross-section is elliptical in shape, special designs utilizing gratings or cylindrical reflectors may have to be used to maintain high values of linear polarization discrimination. 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;

- well outside of the main beam (several side lobes away), linear polarization will have better performance than that of circular, provided alignment can be maintained. Some examples of wide angle pattern measurements using linear polarization with relatively small size earth-station antennae without polarizers are shown in Figs. 3 and 4. It is expected that little more than 10 dB of polarization discrimination will be dependably obtained in this region.

3. Polarizers

For satellites, the polarizers required for the generation of circular polarization can be designed so as to achieve excellent polarization discrimination. For example, polarizers with an ellipticity ratio of 0.2 dB corresponding to about 39 dB of polarization discrimination will be realizable throughout a 500 MHz bandwidth in the 4 GHz or 6 GHz band.

At an earth station, a common feed system is usually used for transmission and reception. Consequently, any polarizer incorporated should cover both the transmission and reception bandwidths, so that a polarizer with wide bandwidth characteristics is required. In addition, earth-station feed systems, as distinct from those of satellites, are normally required to carry high microwave power

levels while meeting the requirements of low noise temperature performance. It is generally difficult to obtain polarizers with high discrimination characteristics to operate under these conditions.

Fig. 5 also shows, as a function of frequency, the polarization discrimination of earth-station polarizers specially designed for the purpose of frequency re-use. It should be noted that polarizers for circular polarization with less than 0.3 dB of ellipticity ratio (more than 35 dB of polarization discrimination), covering both the 4 and 6 GHz bands with a noise temperature contribution of about 2 K, could be made available. For linear polarization a polarizer with limited angular tracking could be built with about 35 dB discrimination and a temperature contribution of about 3 K.

4. Antenna systems

In this section the overall performance of an antenna system consisting of antenna and polarizer is considered. Linearly polarized antennae without polarizers but with mechanical rotation may be utilized, and will give performance as discussed in § 2.

Within the -1 dB beamwidth, values of polarization discrimination of 33 dB for circular polarization and of 30 dB for linear polarization may be achievable with present-day technology. With future developments, the achievable polarization discrimination could be more than 35 dB for circular and more than 33 dB for linear polarization, because the values of polarization discrimination of earth-station antennae using polarizers will be influenced by improvements in polarizer design.

Fig. 6 shows an example of polarization ellipticity measured in and near the main beam of an existing antenna for circular polarization. The antenna is of the large aperture type, where the primary beam is made rotationally symmetrical by using a corrugated horn. However, the polarizer used was not optimized for orthogonal polarization.

The practical difficulties of measuring such low axial ratios as above 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 when the discrimination is in the 30–40 dB range. Such a method should be applicable to all earth-station antennae.

5. Factors affecting the polarization discrimination in satellite systems

5.1 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 planes of polarization must be provided at the earth station.

Faraday rotation is important in the case of linear polarization, but has negligible effect on circular polarization. The influence of Faraday rotation, however, will be negligible for frequencies above 10 GHz.

5.2 Position and attitude of satellites

The direction of the polarization plane of satellite antennae, viewed from earth stations, varies if satellites drift or change their orbital positions or attitudes, because the relative earth-satellite geometric relation and the sighting angle of satellites vary. This factor can be kept small if the satellite attitude and station keeping are well controlled.

5.3 Propagation

Another important factor which degrades polarization discrimination is the de-polarization of radio waves passing through rain and snow. Heavy precipitation can cause both differential attenuation and phase shift between orthogonal polarizations. Thus, elliptic polarization can result from both linear and circular polarization with serious degradation in discrimination.

The relationship between precipitation rate and the amount of cross-polarization discrimination and as a function of frequency, is not yet completely documented. Measurements over terrestrial paths with low elevation angles have been reported in Study Group 5 [Reports 233-3, 234-3 and 564].

6. Overall polarization discrimination

6.1 Polarization tracking for linear polarization

Polarization tracking may be necessary at earth stations in order to reduce the effects of the factors discussed in § 5. Earth stations receiving signals from separate beams of the same satellite, or switching to another satellite, may have to realign their plane of polarization when changing the mode of operation. However, complex techniques are required to obtain complete cancellation of the cross-polarization coupling for both 4 GHz and 6 GHz bands in practical antennae commonly used for both frequency bands, even in the case where polarization tracking is used.

The angle of the plane of polarization of an antenna may vary over its design bandwidth. Whilst this may not affect systems not employing frequency re-use, it would be a disadvantage with linear polarization in a frequency re-use system, since the overall discrimination would not then be maintained over the frequency band and could not be completely corrected with polarization tracking.

Fig. 7 shows the computed values of polarization discrimination degradation due to misalignment in the polarization plane. From this figure it will be noticed that linear polarization tracking is almost obligatory for frequencies below 10 GHz in view of the effect described in § 5.1. Although it would be desirable to construct earth stations without polarizers and polarization tracking facilities, without their use the cross-polarization isolation will possibly drop to as low as 15 dB or worse.

In polarization tracking it will be necessary to take into consideration the effect of failure or malfunction within the polarization tracking sub-system. In such cases, not only would the communication signals radiated by the malfunctioning antenna suffer, but also those signals where the frequency is shared by means of orthogonal polarization would be seriously interfered with.

6.2 Polarization discrimination achievable in satellite systems

In a one-hop satellite radiocommunication link, cross-polarization coupling in both Earth-to-space and space-to-Earth paths needs to be taken into account. Computed cross-polarization couplings on one path are shown in Figs. 8 and 9. Fig. 8 is for circular polarization and the values shown are for the worst case, where the major axes of polarization ellipticity of satellites are orthogonal to those of earth stations. Fig. 9 is for linear polarization, also for the worst case.

Fig. 10 shows the result of an actual experiment using a satellite and an antenna with circular polarization at the Ibaraki Earth Station in Japan. It should be noted that neither the satellite nor earth-station antenna is intentionally designed for frequency re-use by orthogonal polarization, although a corrugated feed horn was used at the earth station.

7. Conclusions

This Report is based on a relatively limited amount of theoretical and experimental data.

Administrations are invited to submit further experimental and theoretical studies in this area of technology.

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. 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.

The choice of whether circular or linear polarization is to be used should be considered from the above points of view.

The data available at present suggest that if antennae without polarizers were to be employed, linear polarization would provide potentially more discrimination between orthogonally polarized waves than circular polarization. However, for frequencies below 10 GHz, if polarization tracking was necessary because of the Faraday rotation effect, circular polarization might be preferable. Both circular and linear polarizations are presently in use in the fixed satellite service in the frequency bands below 10 GHz.

TABLE I
Calculated polarization discrimination (dB) near the centre of the main beam

Region	Polarization	Conventional antennae			Antennae with beam-symmetry factor of 1.05		
		(a) Horns and Cassegrain antennae fed thereby	(b) Horn-reflectors	(c) Cassegrain antennae fed by horn-reflectors	(d) Horns and Cassegrain antennae fed thereby	(e) Horn-reflectors	(f) Cassegrain antennae fed by horn-reflectors
-1 dB	Circular	31	31	32	44	36	44
	Linear	31 (39)	26 (27)	31 (33)	44 (50)	28 (30)	32 (32)
-3 dB	Circular	22	21	22	35	29	34
	Linear	22 (30)	19 (23)	21 (27)	35 (41)	24 (26)	26 (26)
-10 dB	Circular	9	9	9	22	20	22
	Linear	9 (13)	8 (18)	9 (18)	22 (25)	17 (19)	18 (19)

Note 1. — Beam-symmetry factor is defined as the ratio of beamwidths at the level of -3 dB in the orthogonal polarization planes.

Note 2. — The calculations were performed for the following assumptions:

— full flare angle: 16.5°

— D/λ 4 for (a) and (d)

16 for (b) and (e)

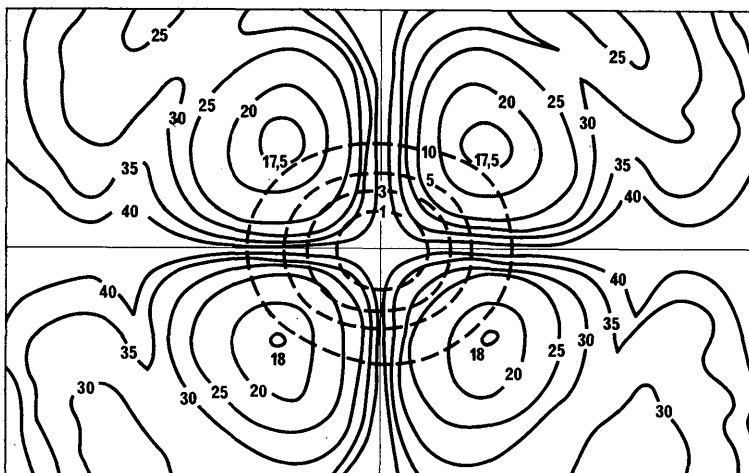
> 100 for Cassegrain antennae

— for Cassegrain antennae, the effect of aperture blockage was not taken into consideration.

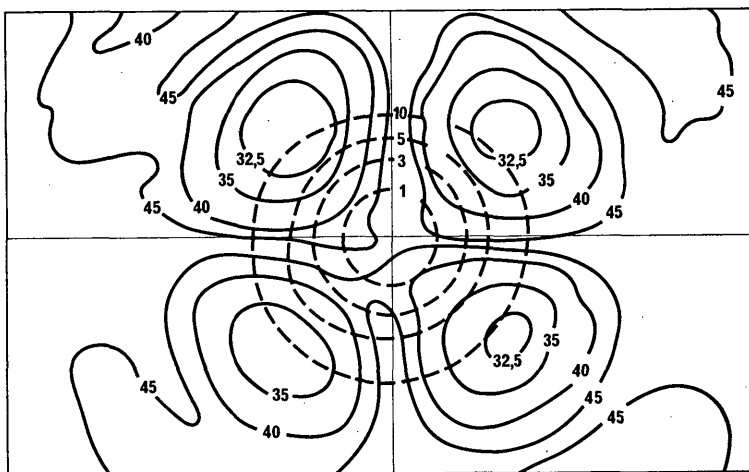
Note 3. — Figures in parentheses show the polarization discrimination with polarization tracking.

LEGEND TO FIGURE 1

- 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 except otherwise indicated.
- 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.



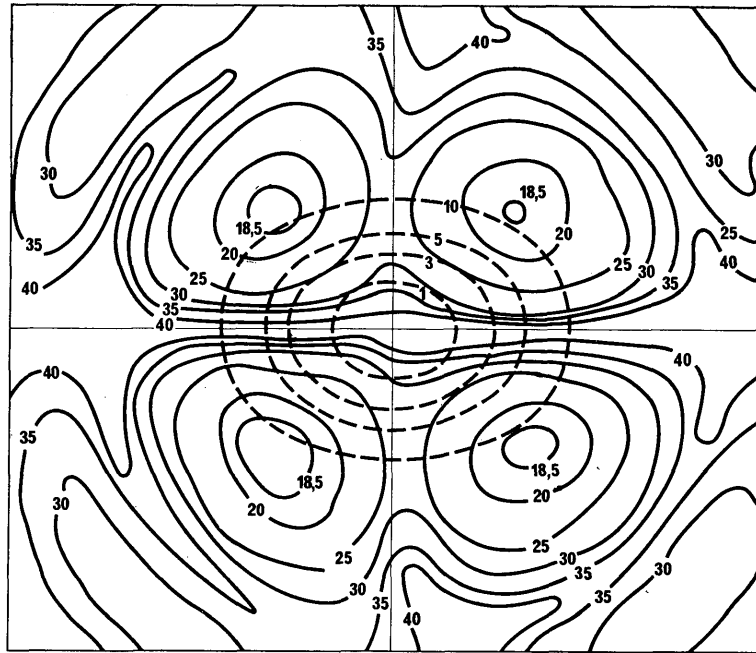
(a) Conventional conical horn



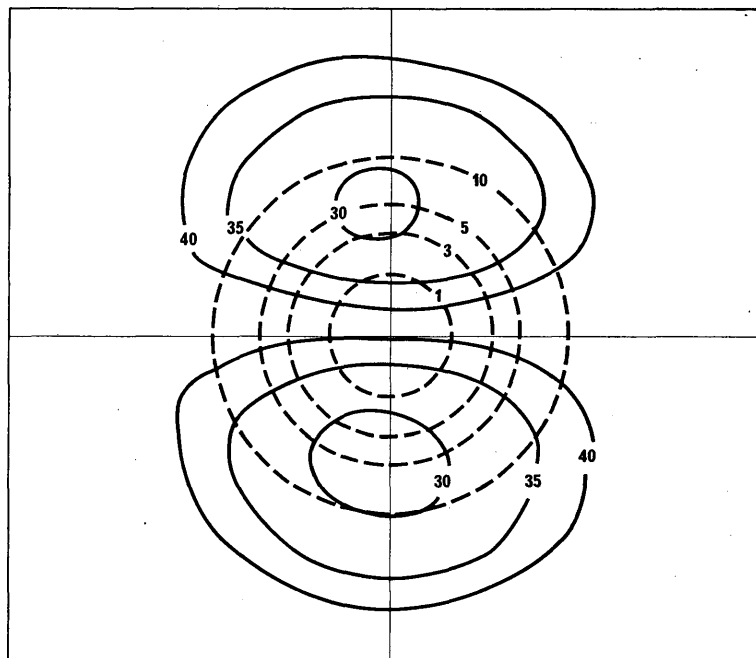
(b) Conical horn with an almost axially symmetrical beam
(Beam symmetry factor ≈ 1.05)

FIGURE 1

Measured cross-polarization levels
(linear polarization)



(c) Conventional conical horn-reflector*

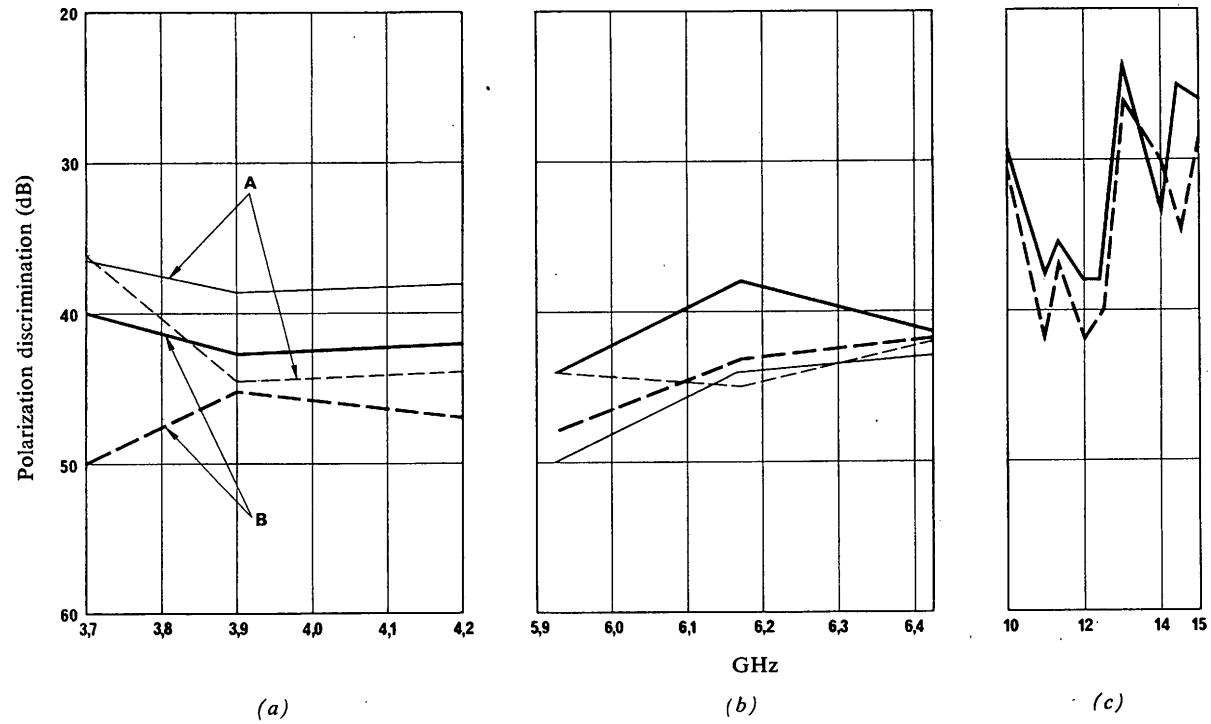


(d) Conical horn-reflector with an almost axially symmetrical beam*
(Beam symmetry factor ≈ 1.05)

FIGURE 1

Measured cross-polarization levels
(linear polarization)

* Polarization plane perpendicular to horn axis.



A: Raisting No. 2 antenna B: Raisting No. 3 antenna

FIGURE 2
Main beam linear polarization discrimination
of Raisting earth-station antennae

————— Horizontal polarization
----- Vertical polarization

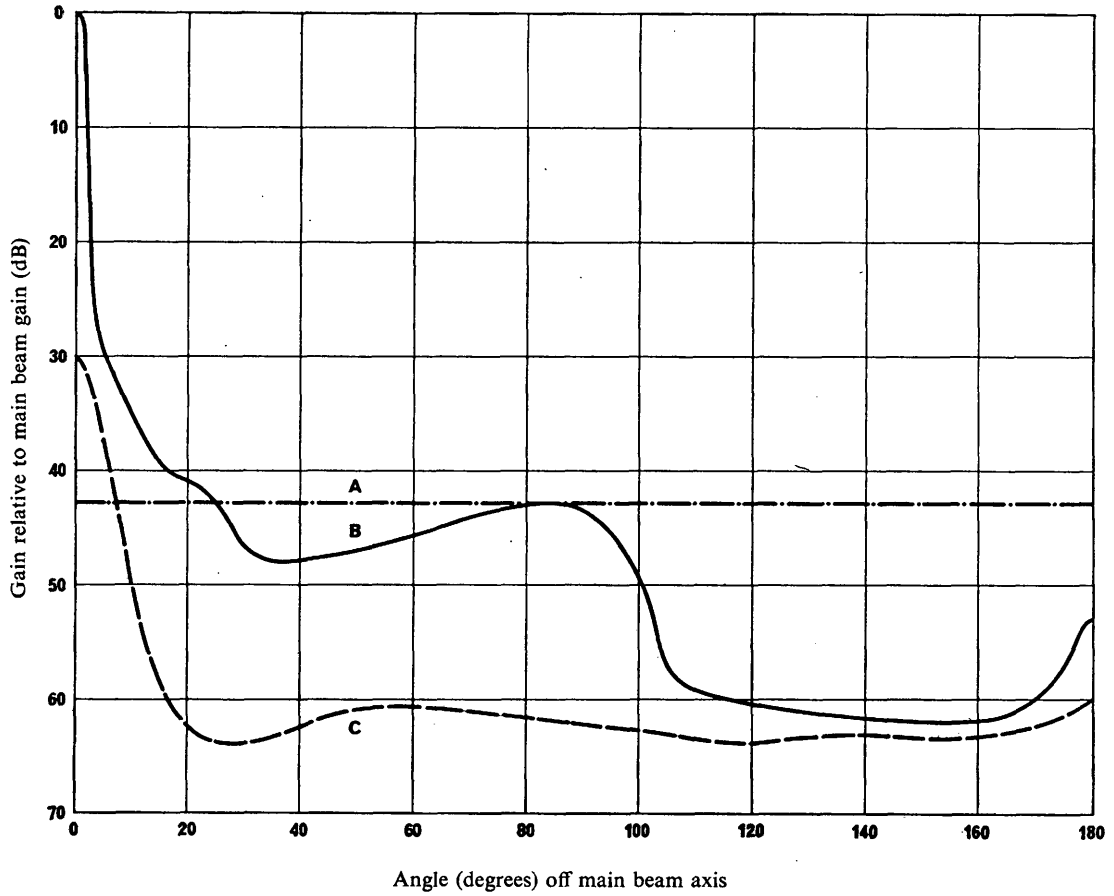


FIGURE 3

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

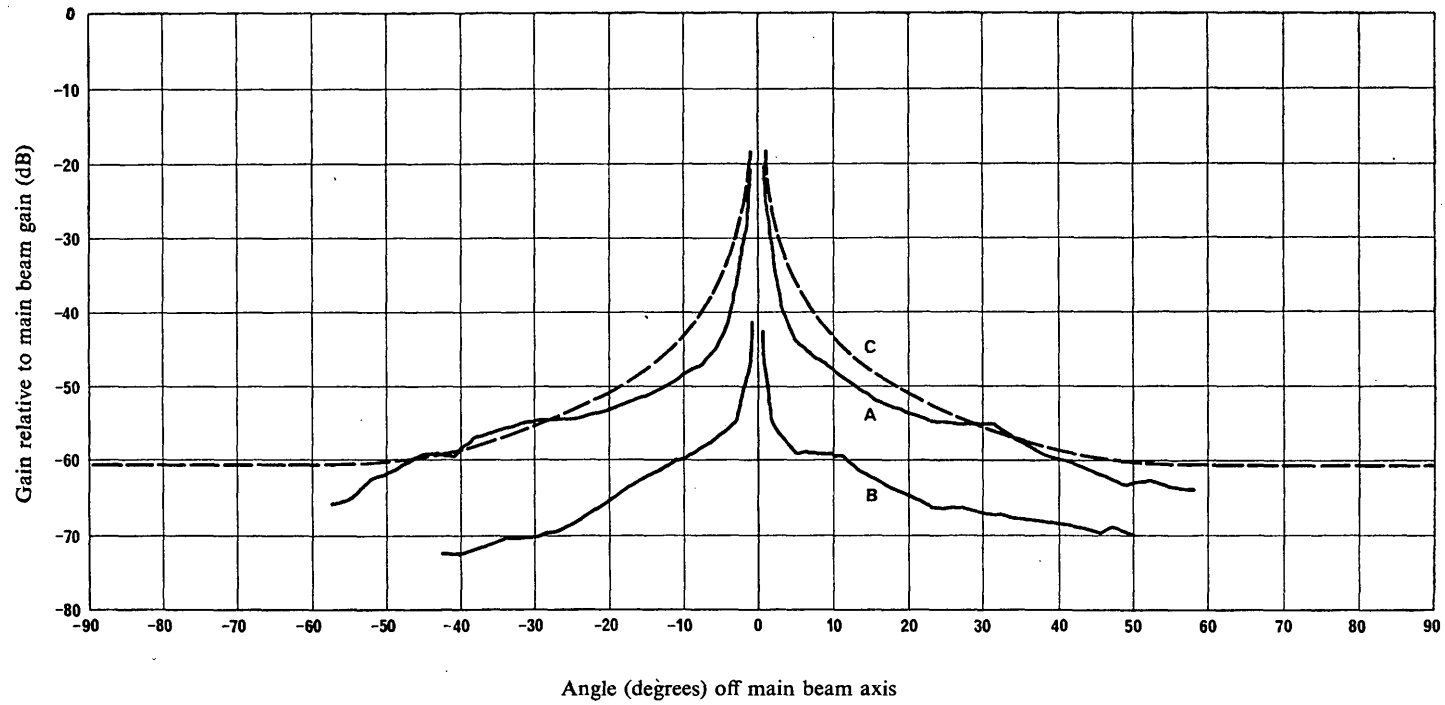


FIGURE 4

Co- and cross-polarized antenna patterns of a 12-foot (3.6 m) diameter Gregorian-fed circular reflector

12 ft. scale model

E-plane — frequency 10.5 GHz

Co-polarized plus cross-polarized overlay

A: Co-polarized

B: Cross-polarized

C: Reference pattern of Recommendation 465-1

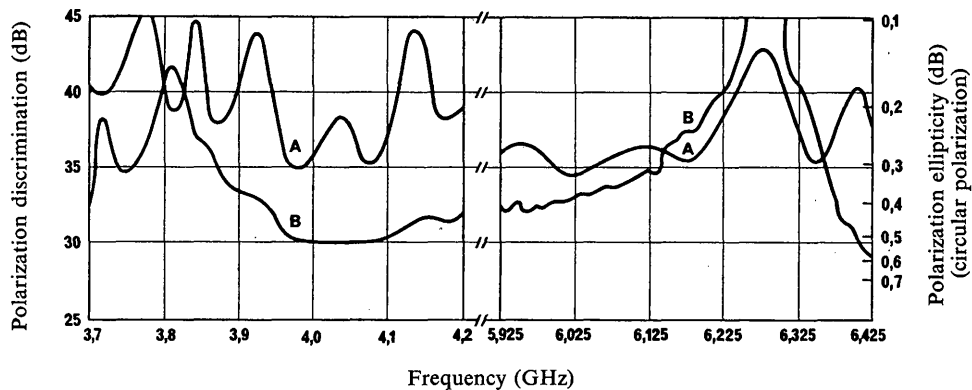


FIGURE 5

Frequency characteristics of polarizers for an Earth-station

- A: Circular polarization
- B: Linear polarization

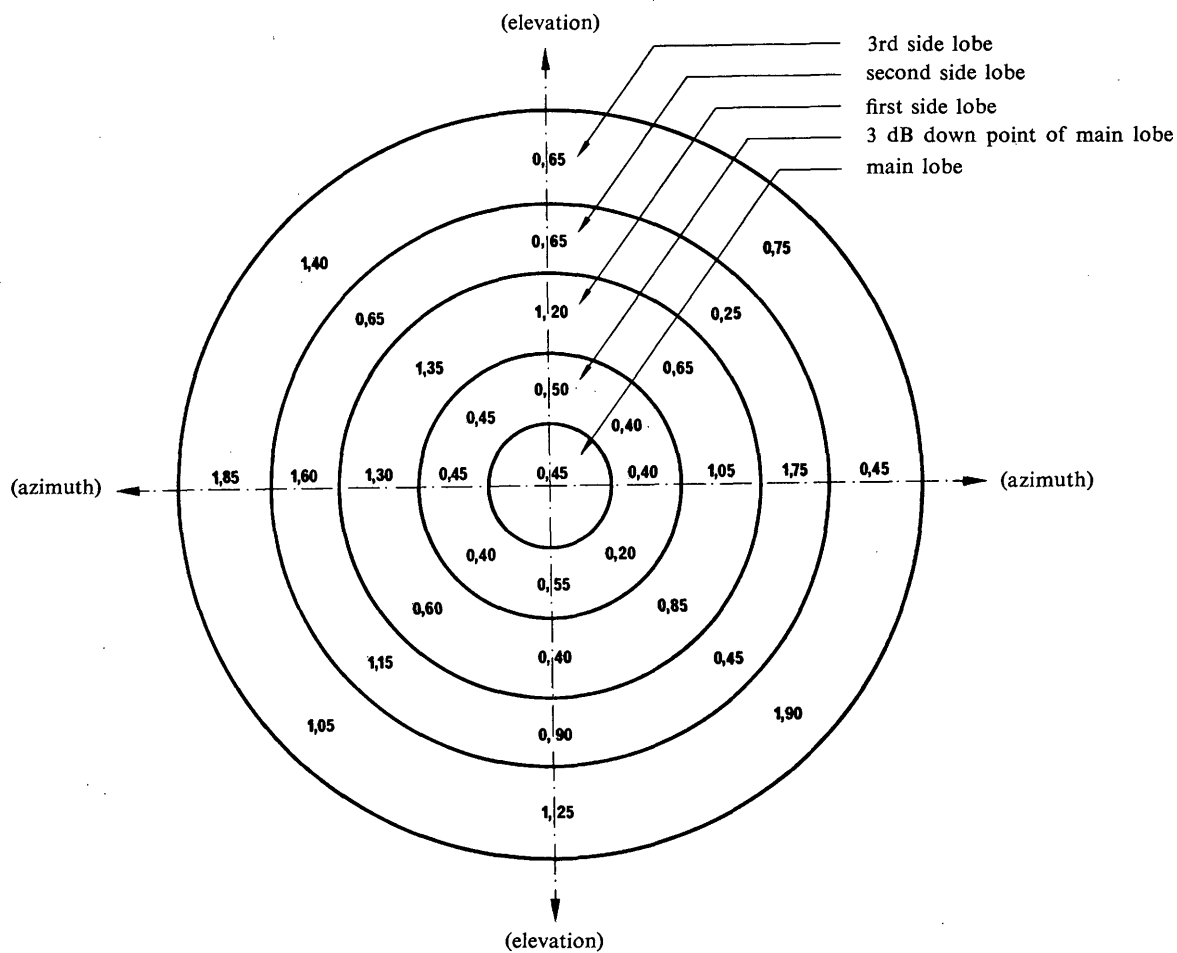


FIGURE 6

Polarization ellipticity near main beam

Note. — The measuring frequency is 6.2 GHz. The antenna is 29.6 m in diameter, Cassegrain type fed by 4 reflector beam waveguide, the feed horn being corrugated.

All ellipticity values are measured at the peak of main and side lobes respectively, and at the 3 dB down point of the main lobe: they are expressed in dB.

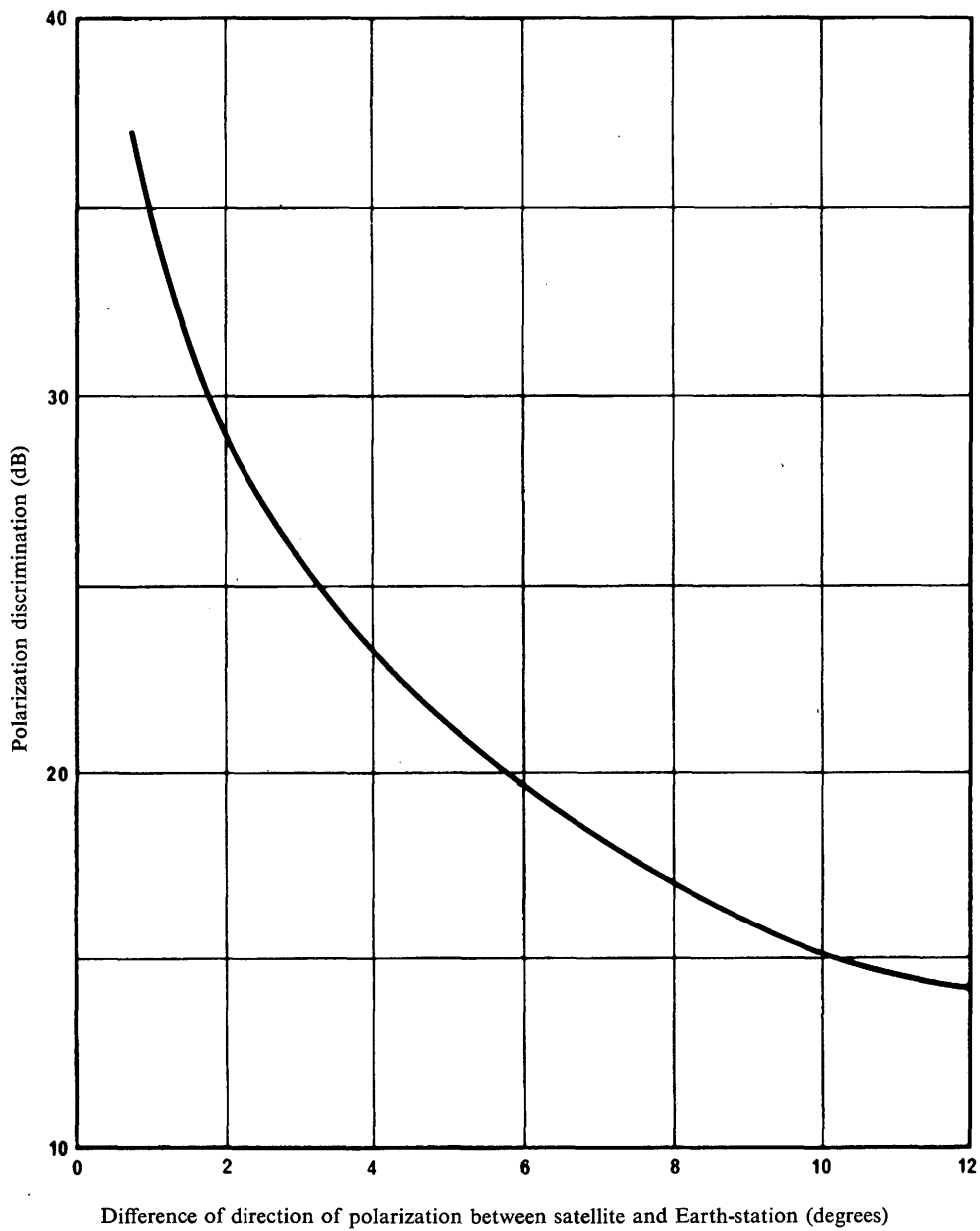


FIGURE 7

Polarization coupling due to the difference of direction of polarization between the satellite and the Earth-station

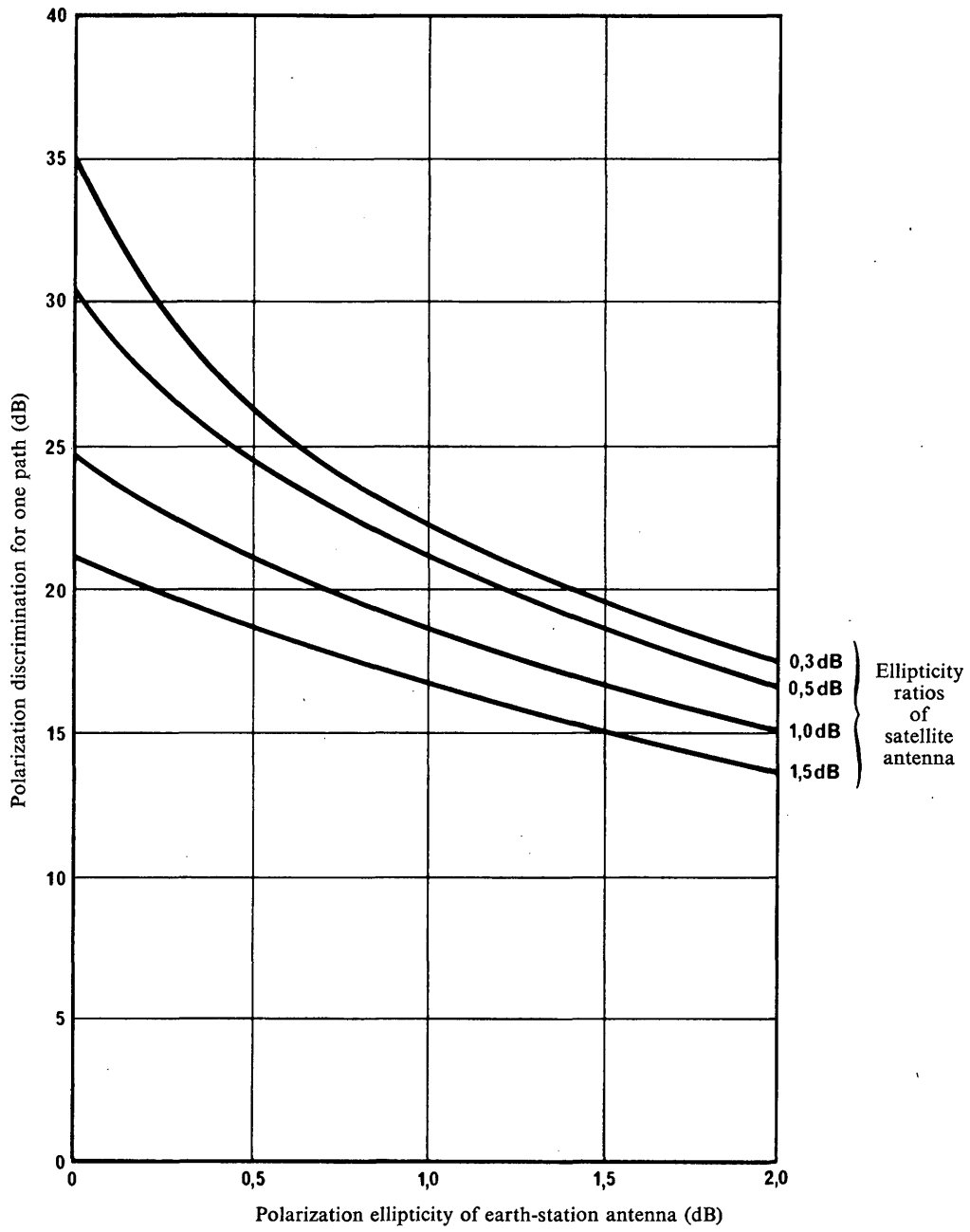


FIGURE 8

Polarization discrimination for a satellite-earth-station link (circular polarization)

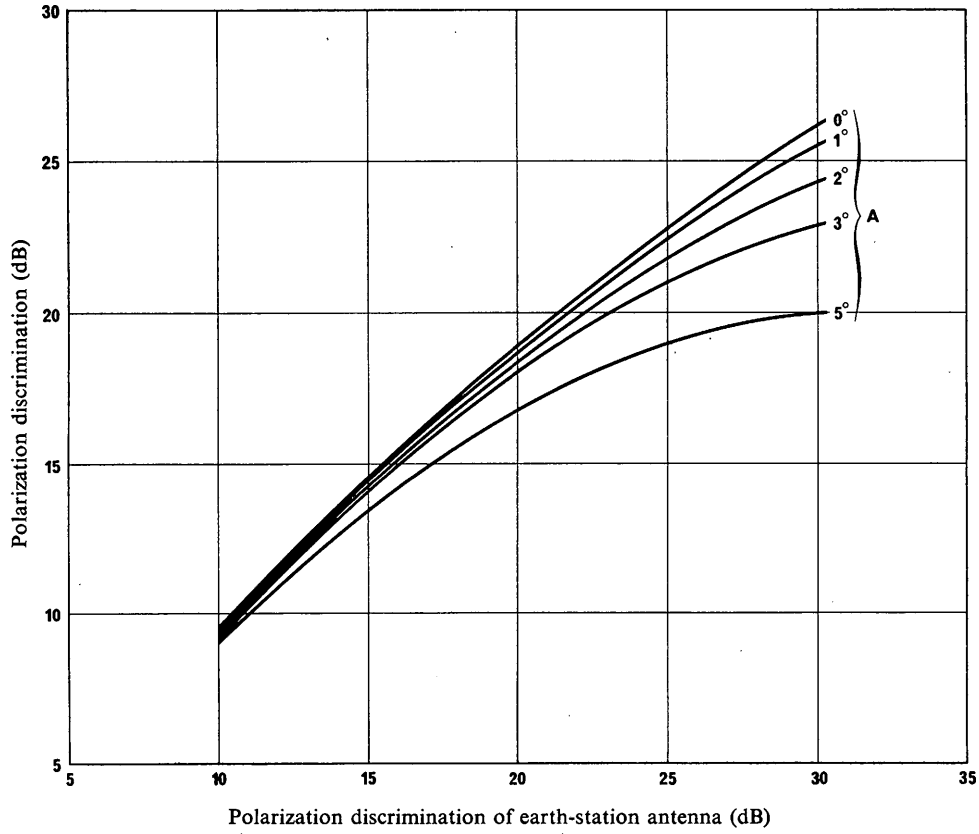


FIGURE 9

*Polarization discrimination for a satellite-earth-station link
(linear polarization)*

A: Angular difference of polarization direction between satellite and Earth-station

Polarization discrimination of the satellite antenna: 35 dB

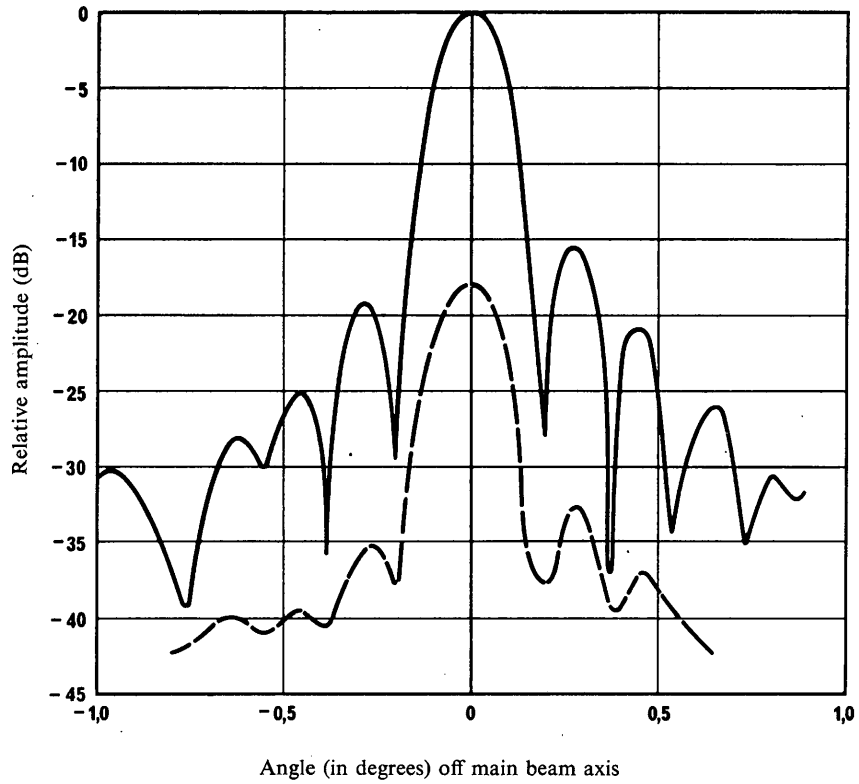


FIGURE 10

Polarization discrimination by circular polarization of satellite-earth path

———— Normal polarization pattern - - - - - Orthogonal polarization pattern

Satellite used: INTELSAT III F-4

Earth-station antenna used: Cassegrain type fed by 4-reflector 29.4 m diameter beam waveguide with corrugated feed horn

Frequency: 3701 MHz

REPORT 556 *

SYSTEMS IN THE FIXED SATELLITE SERVICE

Factors affecting station-keeping of satellites in the geostationary-satellite orbit

(Study Programme 2J-1/4)

(1974)

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 453-1, 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. 470 VC, 470 VD and 470 VE 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 orbital drift or orbital 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 [C.C.I.R., 1970–1974], 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° .

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

* Adopted unanimously.

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.

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.

2.3 *Orbit eccentricity*

Eccentricity of the satellite orbit causes a daily longitudinal excursion of apparent position. Thus an eccentricity of 0.001 causes 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 elements 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 III and the Canadian ANIK I spacecrafts 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 the computing capability and associated costs do increase somewhat with respect to those necessary for $\pm 1^\circ$ station-keeping.

This applies primarily at the present to satellites located at or near to 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.

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C.C.I.R. [1970-1974] Doc. 4/15, United Kingdom.

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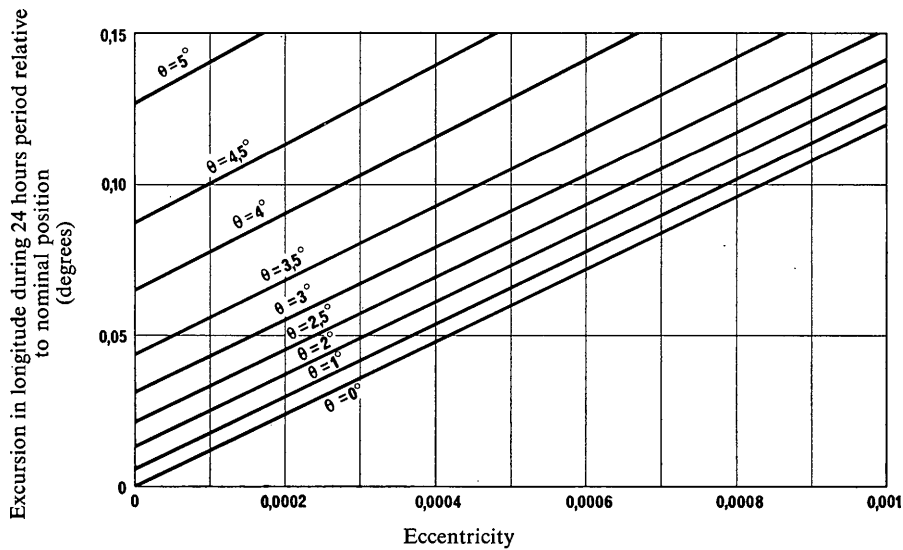


FIGURE 1

Maximum daily variation of longitude due to eccentricity and inclination of orbit

θ : Inclination

REPORT 557 *

SYSTEMS IN THE FIXED SATELLITE SERVICE

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-1/4)

(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:

$$(c/i)^{-1} \approx \frac{p'_e g'_1(\varphi) g_2(\delta)}{p_e g_1 g_2} + \frac{p'_s g_4(\varphi) g'_3(\eta)}{p_s g_4 g_3} \quad (1)$$

* Adopted unanimously.

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.

$$(c/i)_r^{-1} \approx \frac{p'_s g'_3(v) g_2(\varepsilon) l_u^*}{p_e g_1 g_2 l_0} \quad (2)$$

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 band.

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:

$$\begin{aligned} g_1(f) &= a_1 / \rho^b \\ g_4(f) &= a_4 / \rho^b \end{aligned}$$

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:

$$g_2(\varepsilon) = g_3(\nu) = 1;$$

(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 C.C.I.R. 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.

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).

* $\zeta(b)$, 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.

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:

$$i = \frac{e'_s g_a}{l_a} \quad (6)$$

where l_a is the antipodal free-space attenuation between the two space stations:

$$l_a \approx 1.27 f^2 \times 10^{19} \quad (7)$$

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:

$$T_R(f) = 1500(f/6)^{0.5} = 612 f^{0.5} \text{ K} \quad (8)$$

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:

$$i/n = \frac{e'_s g_a}{l_a k T_R B} = \frac{e'_s g_a}{1.07 f^{2.5} \times 10^5} \quad (9)$$

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 limit; i.e. towards points A and B of Fig. 3.

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.

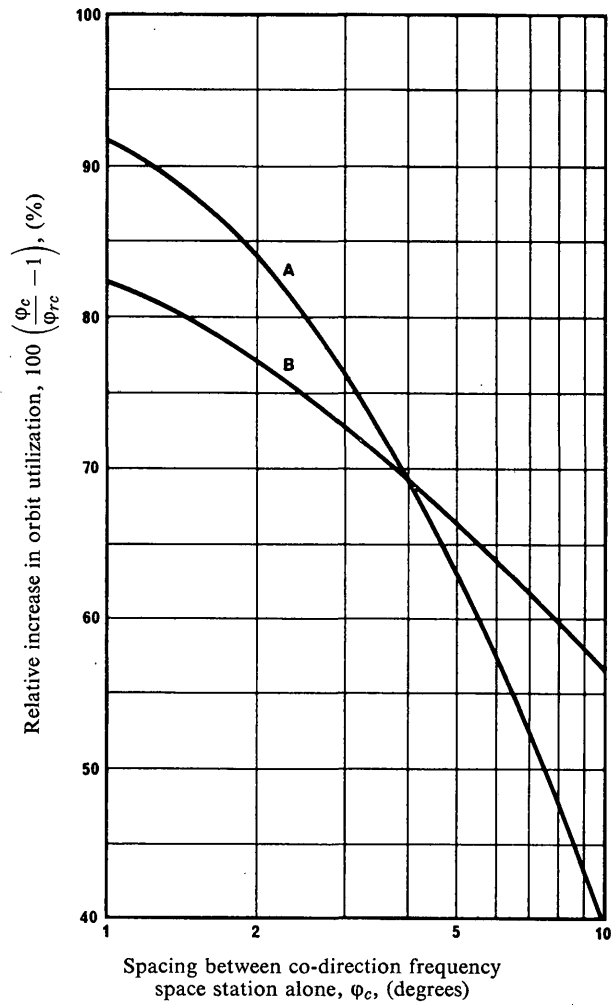


FIGURE 1

Increase of orbit utilization with reverse-direction frequency systems relative to that with co-direction frequency systems only

A	B
$a_1, a_4 = 0.016$	$a_1, a_4 = 0.063$
$b = 3.0$	$b = 2.5$
$g_1/g_4 = 2.25$	$g_1/g_4 = 2.25$

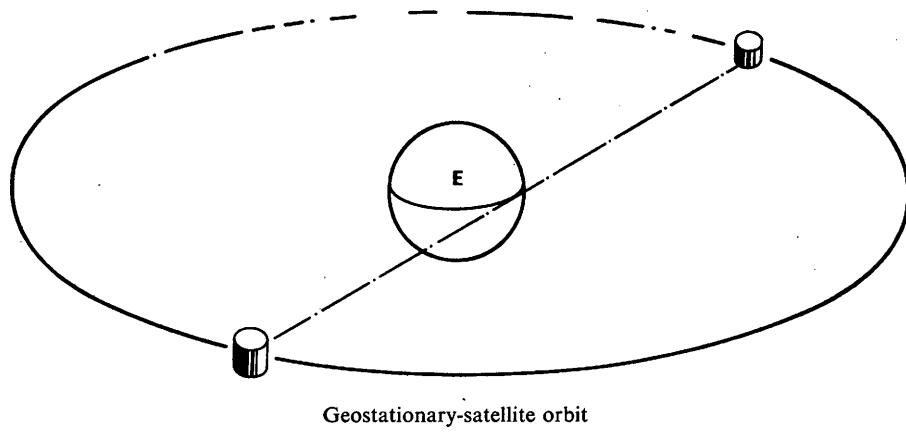


FIGURE 2
Geometry of near antipodal satellites
E: Earth

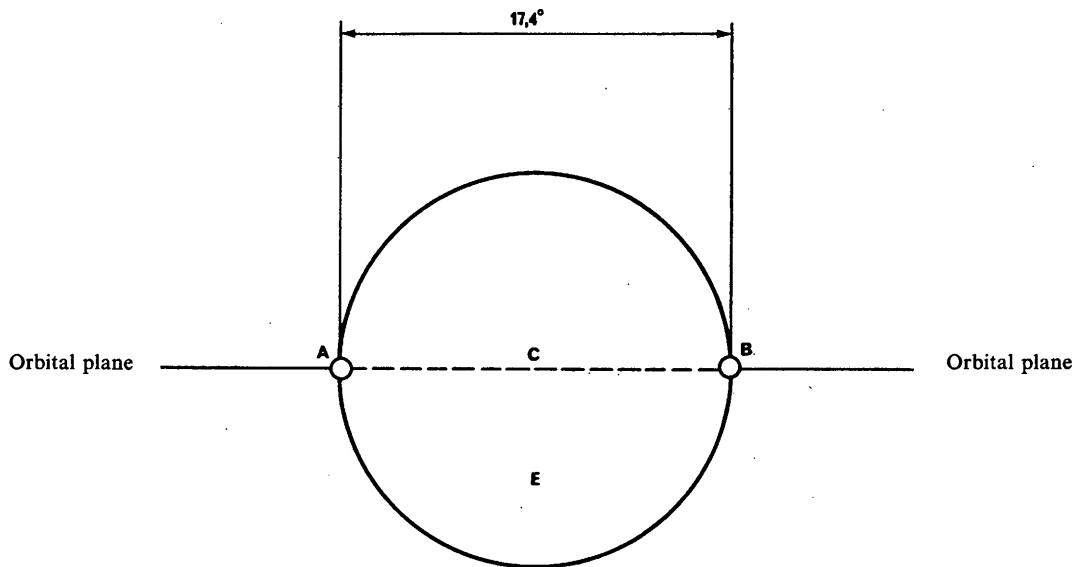


FIGURE 3
The Earth and the geostationary-satellite orbit as seen from a geostationary-satellite
C: Equator
E: Earth

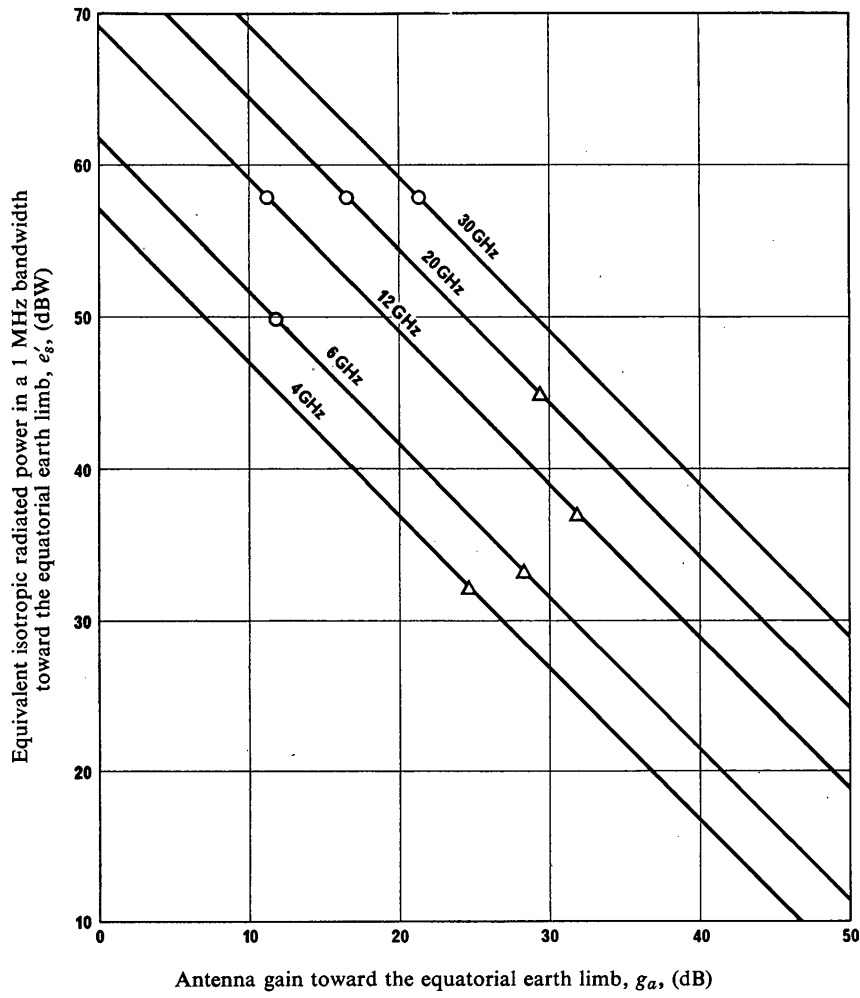


FIGURE 4

Relationship between the maximum permissible values of e_s towards the equatorial earth limb

- Terrestrial station emissions
- △ Power flux-density limits

REPORT 558 *

SATELLITE ANTENNA PATTERNS IN THE FIXED SATELLITE SERVICE

(Study Programme 2J-1/4)

(1974)

1. Introduction

Satellite antenna patterns have a significant effect on the utilization of the geostationary-satellite orbit, particularly when narrow beamwidths are employed. 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 454-1 and 455-1. This Report is a preliminary examination of the problems of 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.

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 by the pointing stability to about 50 dB on-axis gain. 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 will probably dominate operational systems in the near future. Eventually, Cassegrain and phased arrays may also be utilized. 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.

* Adopted unanimously.

2.2 Main lobe patterns

Ideally, the variation 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 $\frac{\sin^2 x}{x^2}$. 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 that 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.

On the other hand, the optimum aperture size of an antenna operating in one pair of frequency bands is 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 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 of satellite antenna patterns can be considered in relation to improving 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. toward 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 $\frac{\sin^2 x}{x^2}$ function and the sum of two displaced $\frac{\sin^2 x}{x^2}$ 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.

Beam shaping and generation of spatially separate beams by multiple feeds on a common parabolic reflector should also be considered. 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.

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 beamshaping of a narrow beam mechanically de-spun horn reflector antenna [C.C.I.R., 1970-1974a; Shinji *et al.*, 1974] is shown in Fig. 10; 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.

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. 6.

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. 7 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.

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. 11. 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. 11 for each frequency. Reference is made to [C.C.I.R. 1970-1974b] and to Report 390-2 for additional considerations on side-lobe levels. Examples of side-lobe gain characteristics are shown in Annex II.

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. 6. 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. 8 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 that 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.

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. 9 as function E.

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 $5-10^\circ$;
- 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. The side lobes may cause interference to other satellites which receive in the same frequency band.

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 or elliptical main lobes. It is also desirable to have an interim reference for these conditions for the coordination 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.

$$G(\theta) = G_m - 3 \left(\frac{\theta}{\theta_0} \right)^2 \quad \text{dB for } \theta_0 \leq \theta \leq 2.6 \theta_0 \quad (1)$$

$$G(\theta) = G_m - 20 \quad \text{dB for } 2.6 \theta_0 \leq \theta \leq 6.3 \theta_0 \quad (2)$$

$$G(\theta) = G_m - 25 \log \left(\frac{\theta}{\theta_0} \right) \quad \text{dB for } 6.3 \theta_0 \leq \theta \leq \theta_1 \quad (3)$$

$$G(\theta) = -10 \quad \text{dB for } \theta_1 \leq \theta \quad (4)$$

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. 9.

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 are 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.

Thus, it is believed that this postulated pattern represents a reasonable basis for further consideration relative to satellite reference radiation patterns.

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. over a coverage area will enhance orbit utilization. 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 presently known 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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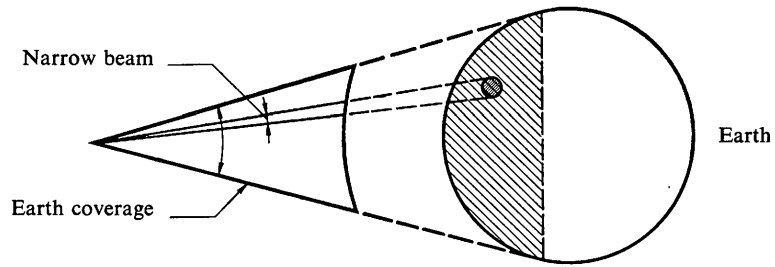
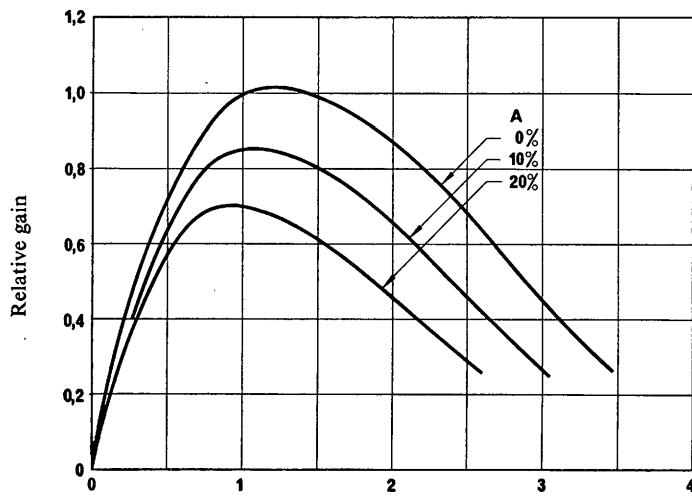


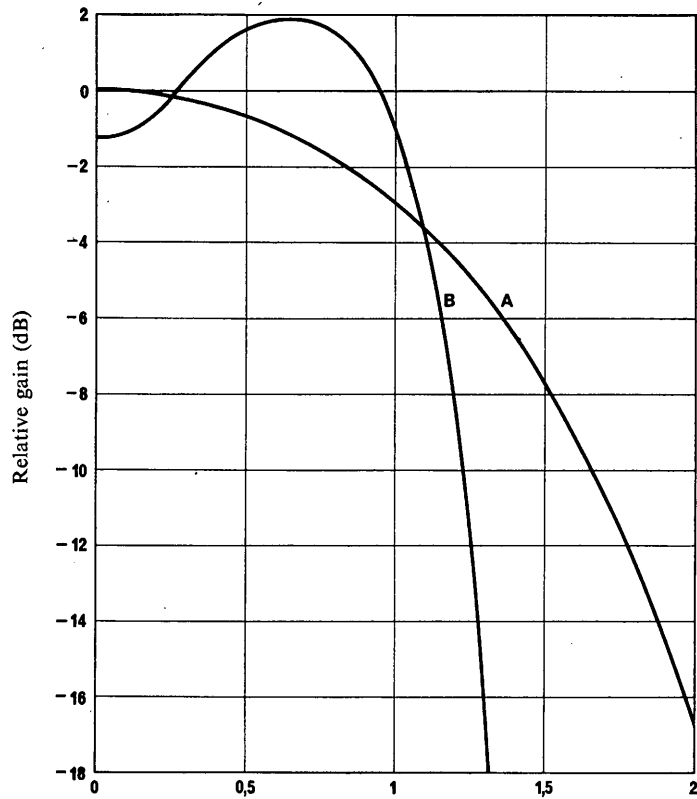
FIGURE 1
Ideal satellite antenna patterns



Ratio of actual aperture area to aperture area which provides required 3 dB beamwidth at 0%, 10% and 20% tolerance

FIGURE 2
Gain in the coverage area versus aperture area

A: Tolerance for antenna pointing errors as a percentage of 3 dB beamwidth



Off-axis angle relative to one-half the 3 dB beamwidth of conventional beam, θ/θ_0

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.

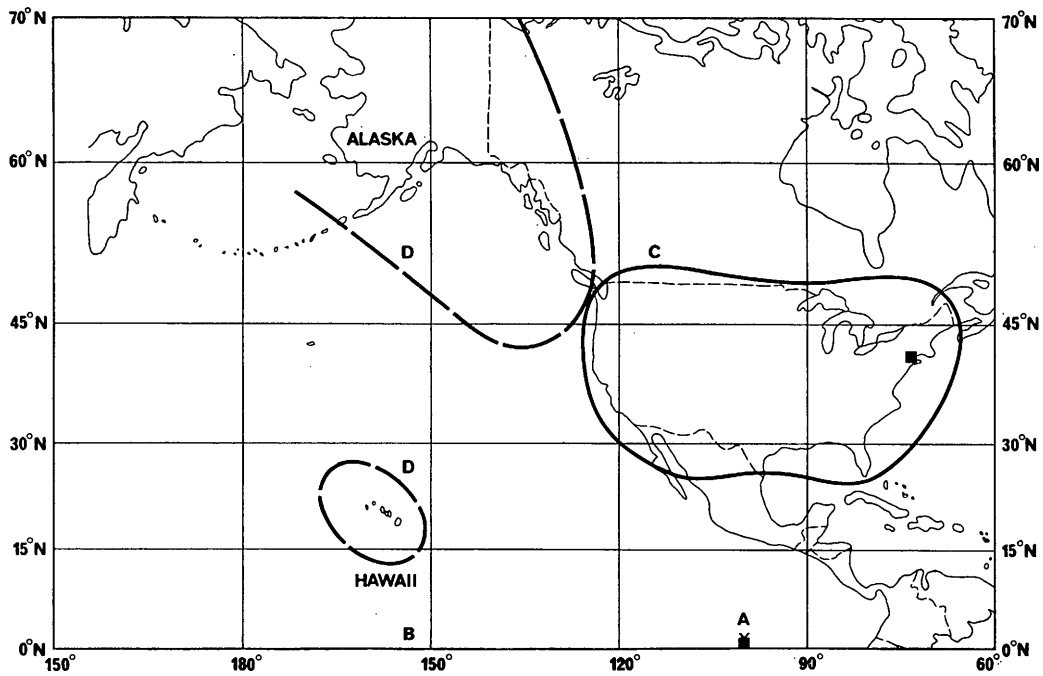


FIGURE 4

Example of antenna coverage contours

*(6.8° × 3.5° 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° × 3.5° beam D: 2.8° circular spot beams

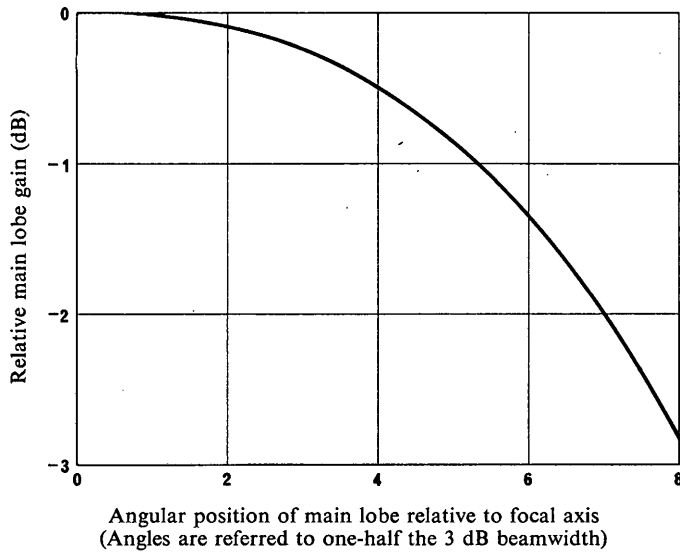


FIGURE 5

Main lobe gain versus angular position of main lobe relative to focal axis

20 dB taper, $f/D = 1$

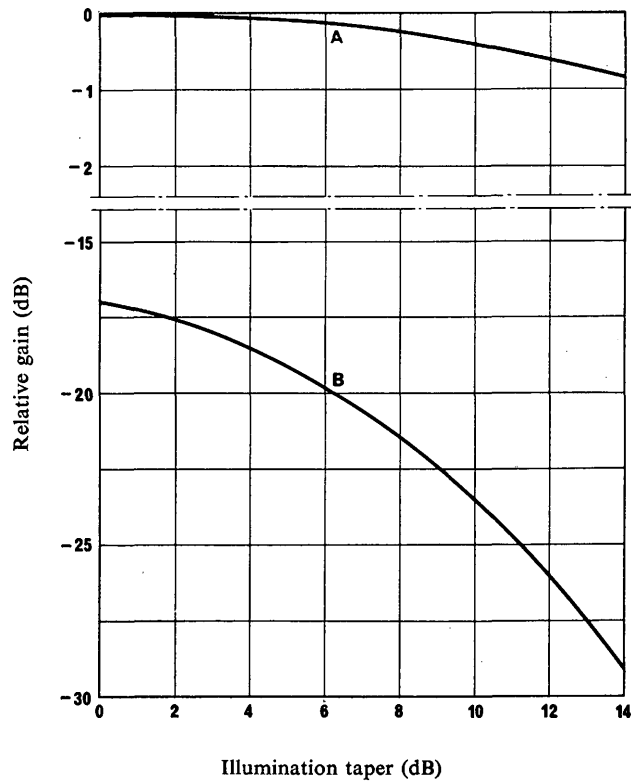
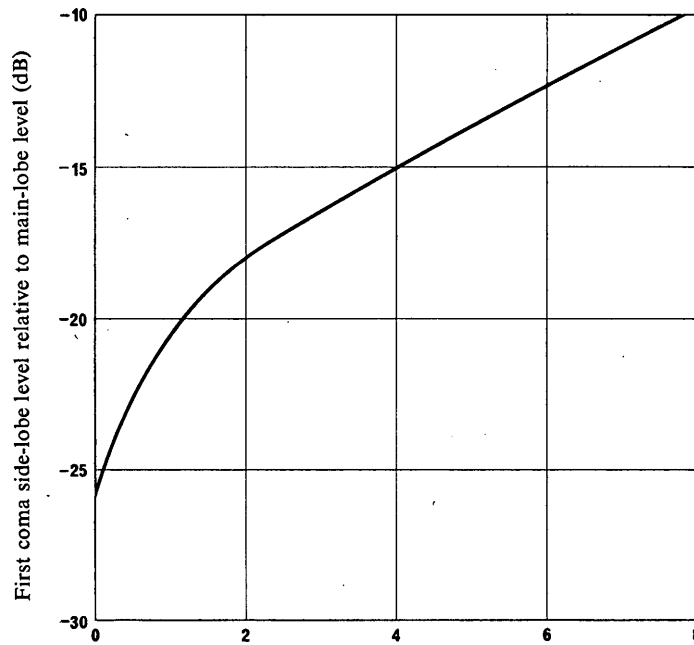


FIGURE 6
Effects of aperture illumination
A: Main lobe
B: First side lobe



Angular position of main lobe relative to focal axis
(Angles are referred to one-half the 3 dB beamwidth)

FIGURE 7

First coma side-lobe level versus angular position of main lobe relative to focal axis

20 dB taper, $f/D = 1$

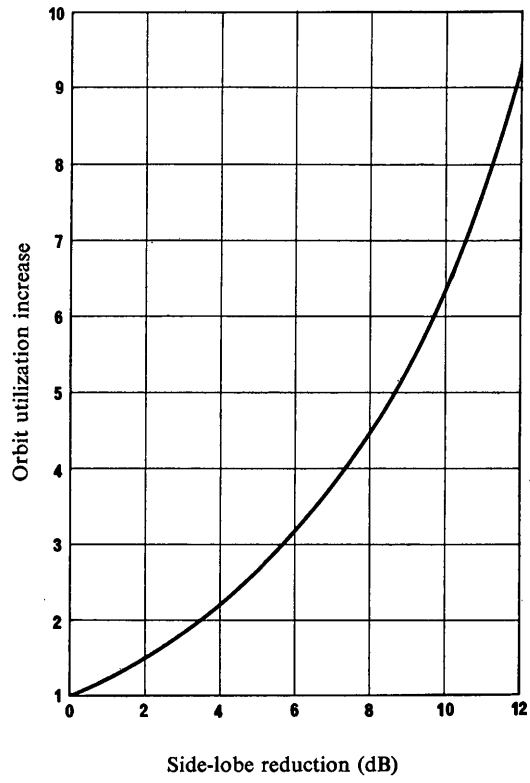
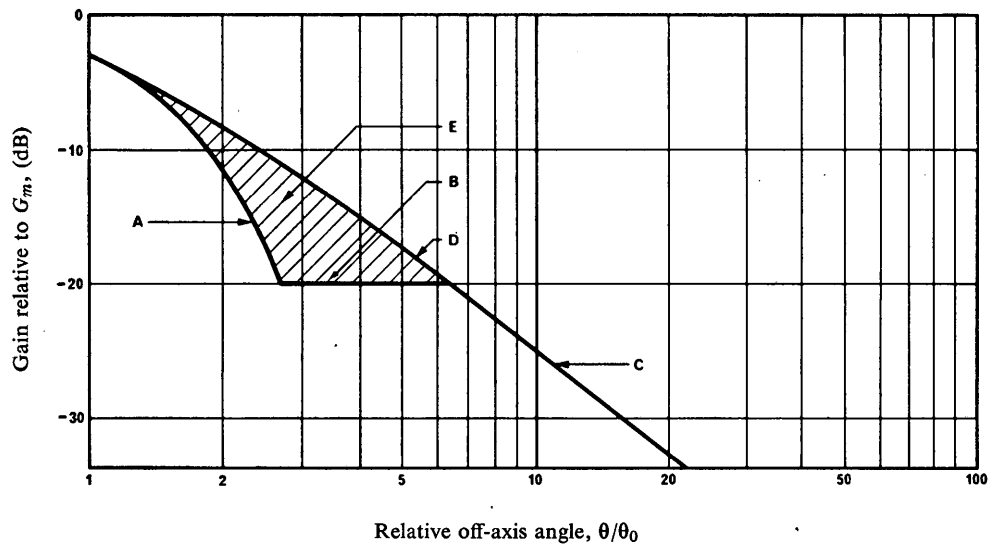


FIGURE 8

Effect of side-lobe level on orbit utilization



- Curves A: $[G(\theta) - G_m] = -3 \left(\frac{\theta}{\theta_0}\right)^2$ dB ($\theta_0 \leq \theta \leq 2.6 \theta_0$)
- B: $[G(\theta) - G_m] = -20$ dB ($2.6 \theta_0 \leq \theta \leq 6.3 \theta_0$)
- C: $[G(\theta) - G_m] = -25 \log \left(\frac{\theta}{\theta_0}\right)$ dB ($6.3 \theta_0 \leq \theta \leq \theta_1$)
- 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)

FIGURE 9

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]

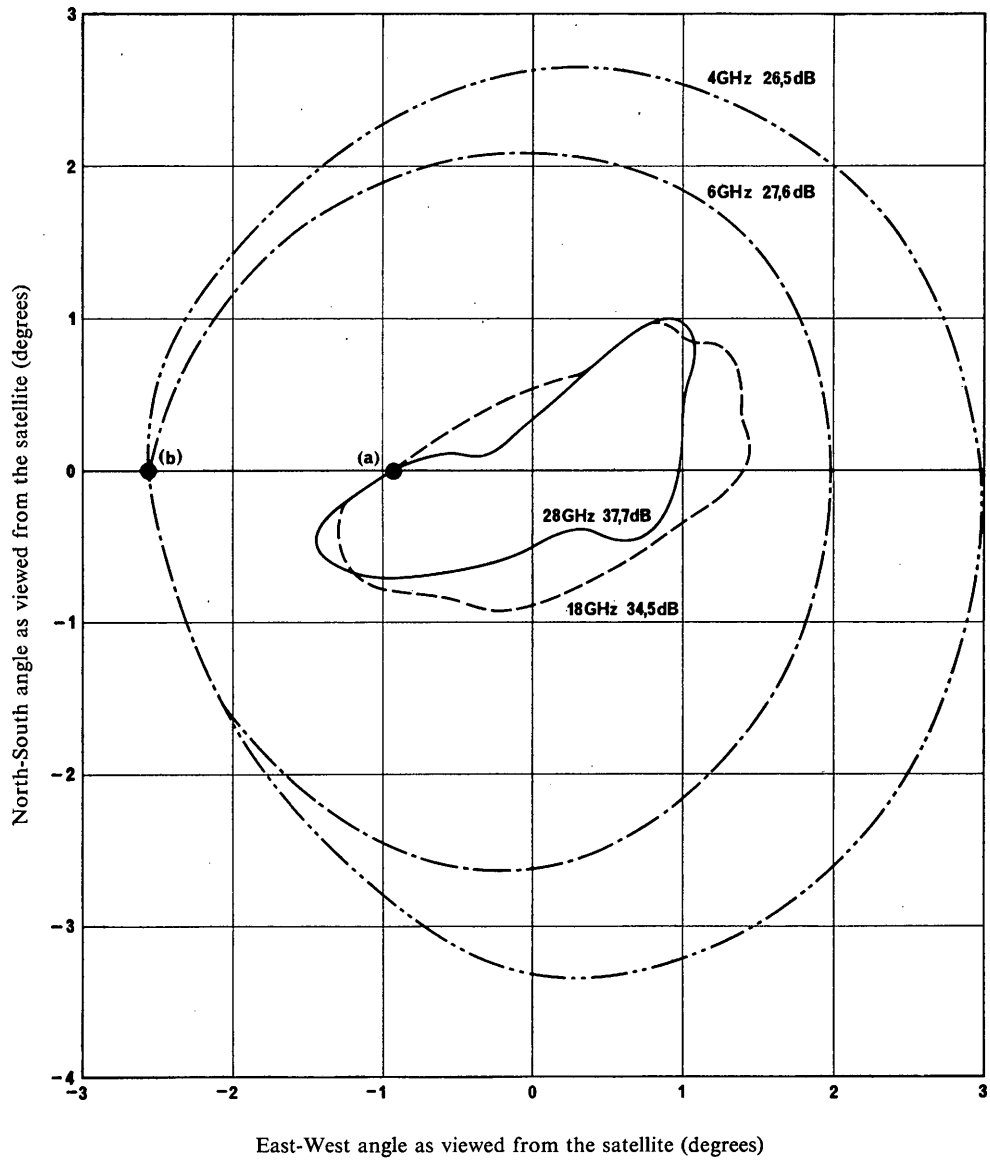


FIGURE 10
Constant gain contours of the shaped-beam horn-reflector antenna
(Which meet coverage requirements of Japan with circular polarizations)
[For (a) and (b) see Fig. 11]

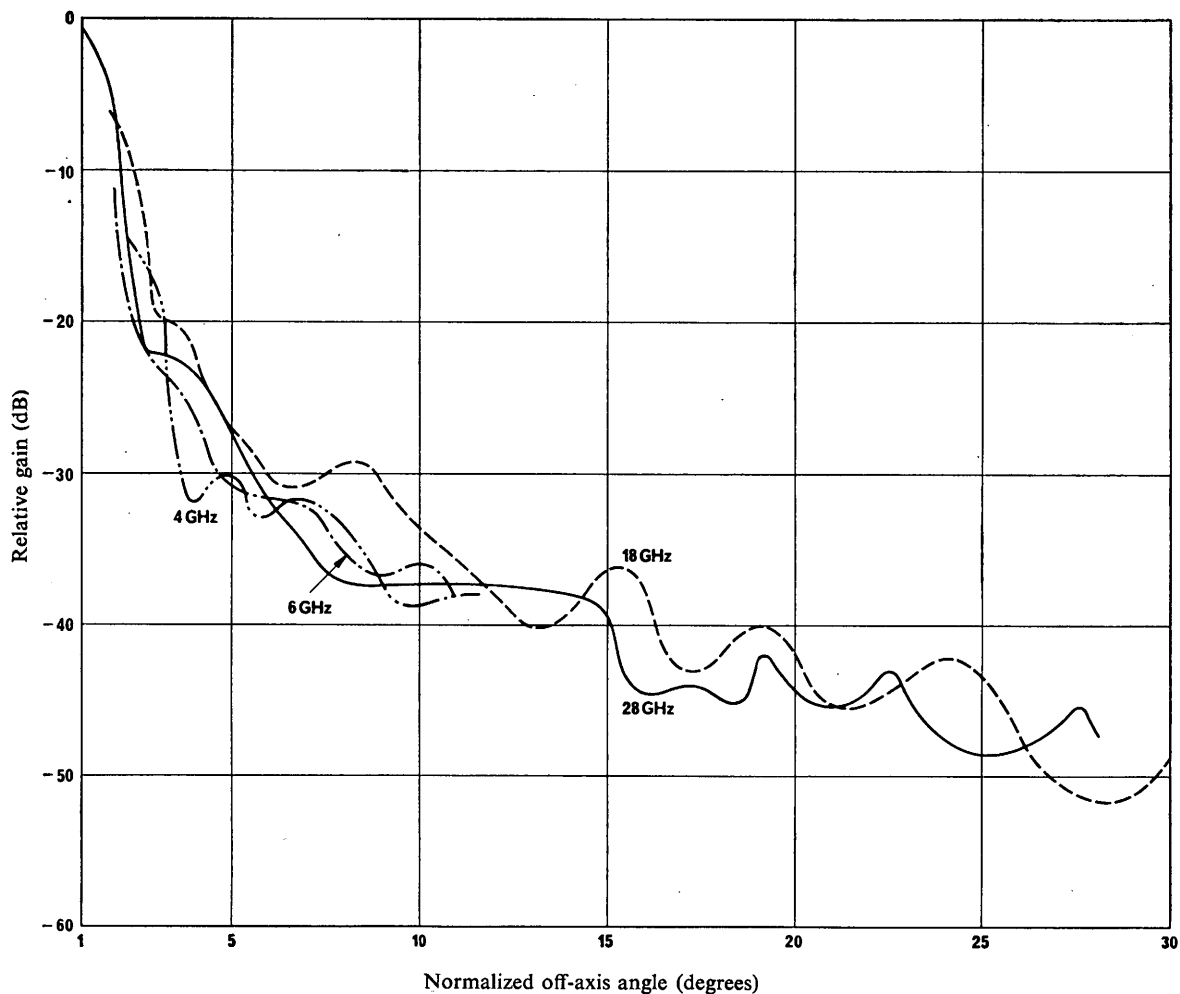


FIGURE 11

*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. 10 |
| - - - | 18.3 GHz circular (R) 1.0° | |
| - · - · - | 6 GHz circular (L) 2.7° | } see point (b) in Fig. 10 |
| · · · | 4 GHz circular (R) 2.7° | |

Note. — The off-axis angles are referred to the origin of Fig. 10 and are in the plane through points (a) and (b) of Fig. 10.

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. 12. This is the pattern of a dielectric-loaded antenna at 23.3 GHz.

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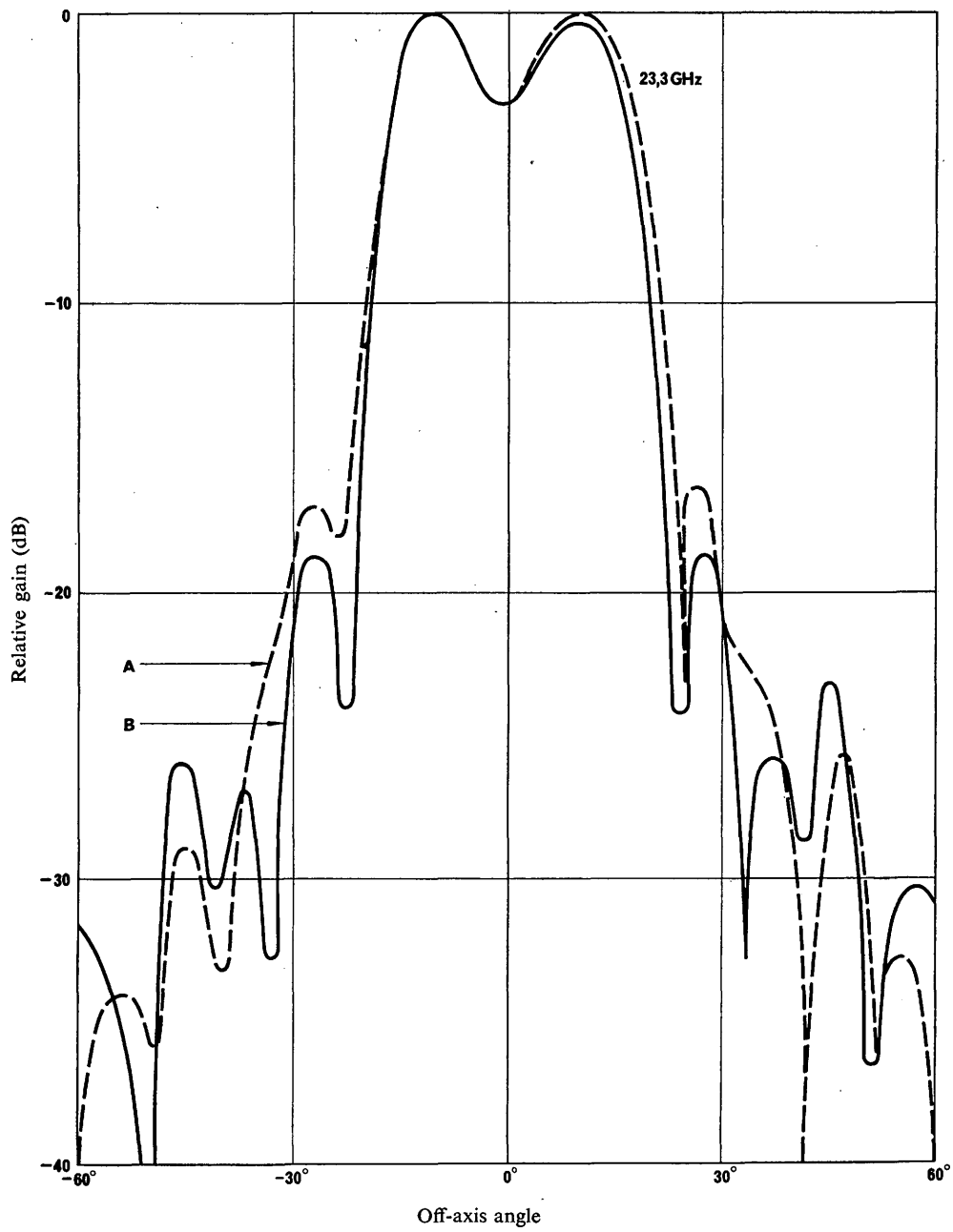


FIGURE 12

Pattern of shaped global beam given by a dielectric-loaded horn antenna

A: H-plane
B: E-plane

ANNEX II

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. 13 and 14 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 operates 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 so 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.

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. 14 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.

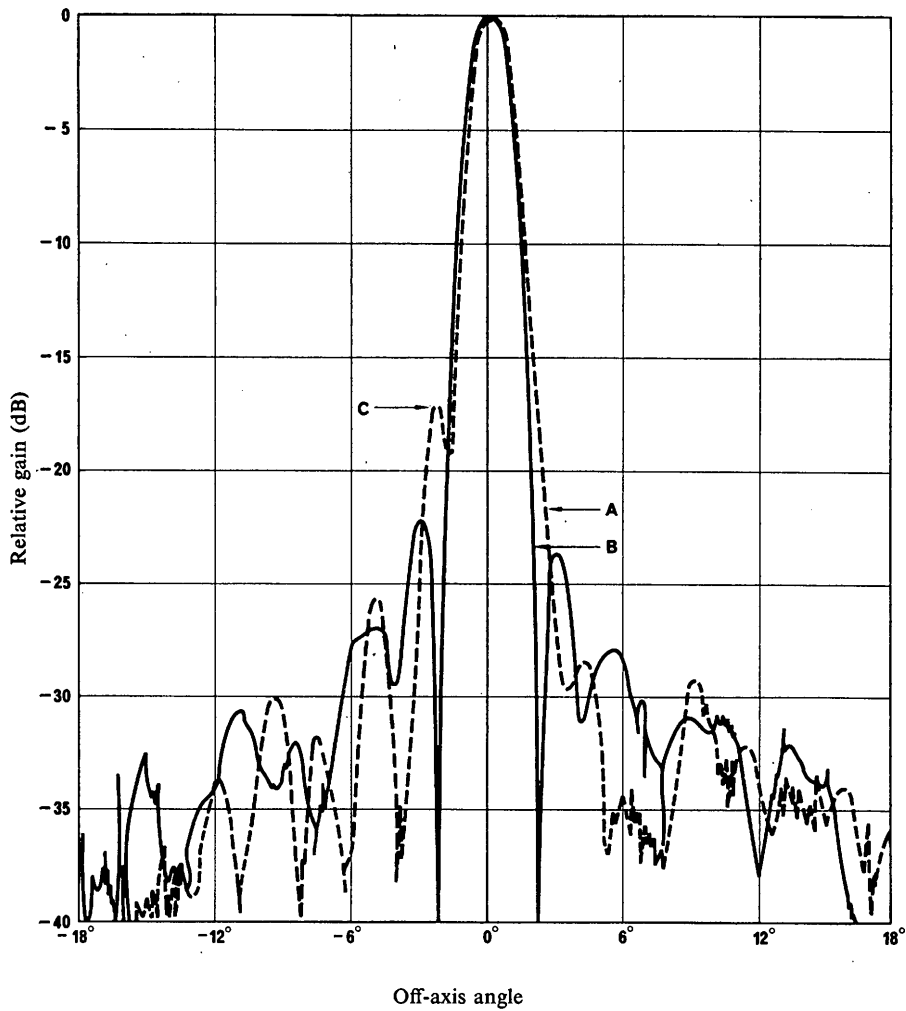


FIGURE 13

Pattern of a focus-fed paraboloid

11.7 GHz, horizontal polarization

A: H-plane B: E-plane C: ground reflection

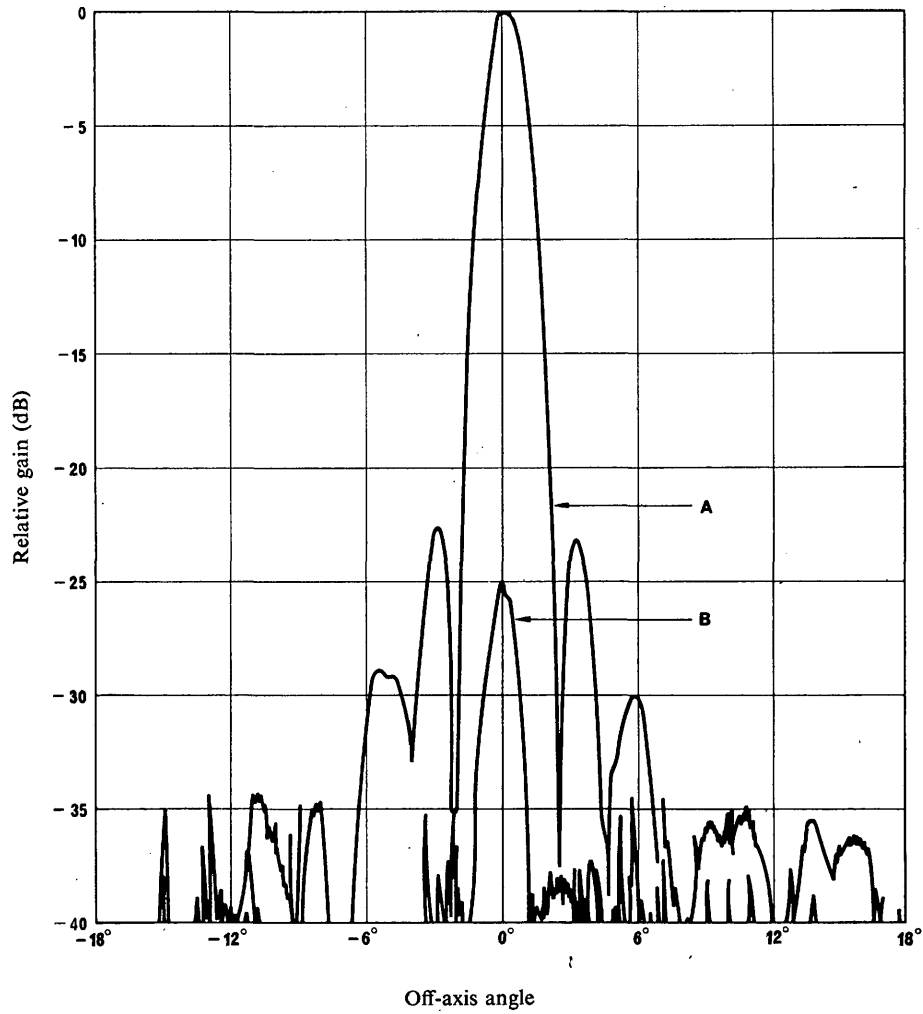


FIGURE 14

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

(Study Programme 2J-1/4)

(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 [C.C.I.R., 1970-1974a].

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.

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

* Adopted unanimously.

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.

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 cases 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 satellite spacing.

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 [C.C.I.R., 1970-1974b]. 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 466-1,
- 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.

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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TILLOTSON, L. C. *et al.* [April, 1973] Efficient use of the radio spectrum and bandwidth expansion. *Proc. IEEE*, Vol. 61, 4.

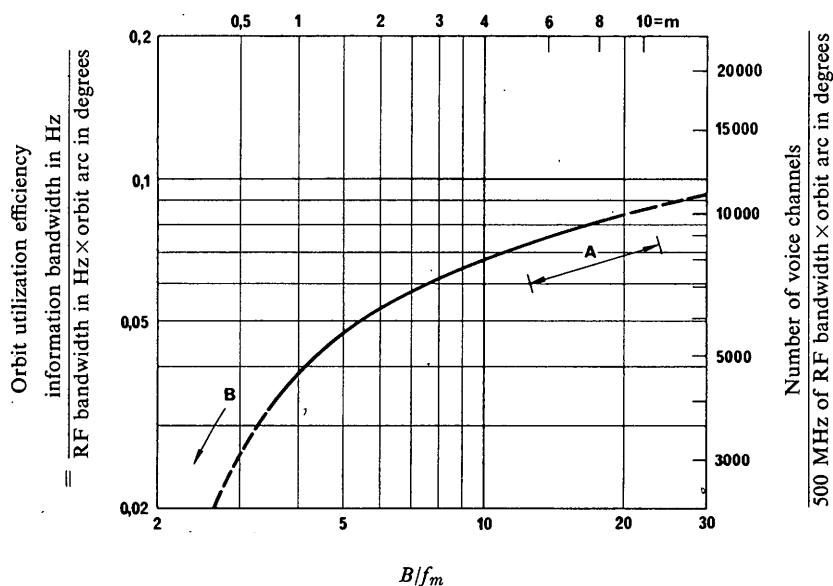


FIGURE 1

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

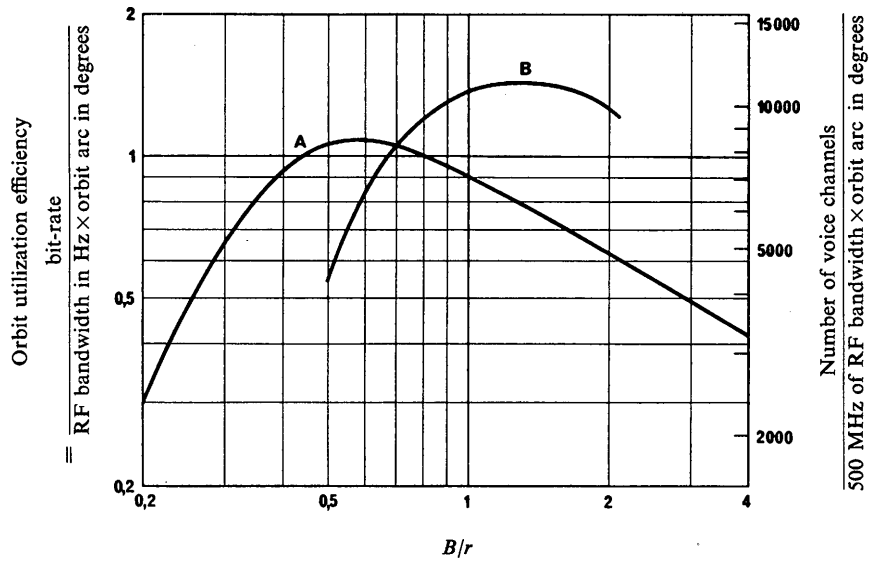


FIGURE 2

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

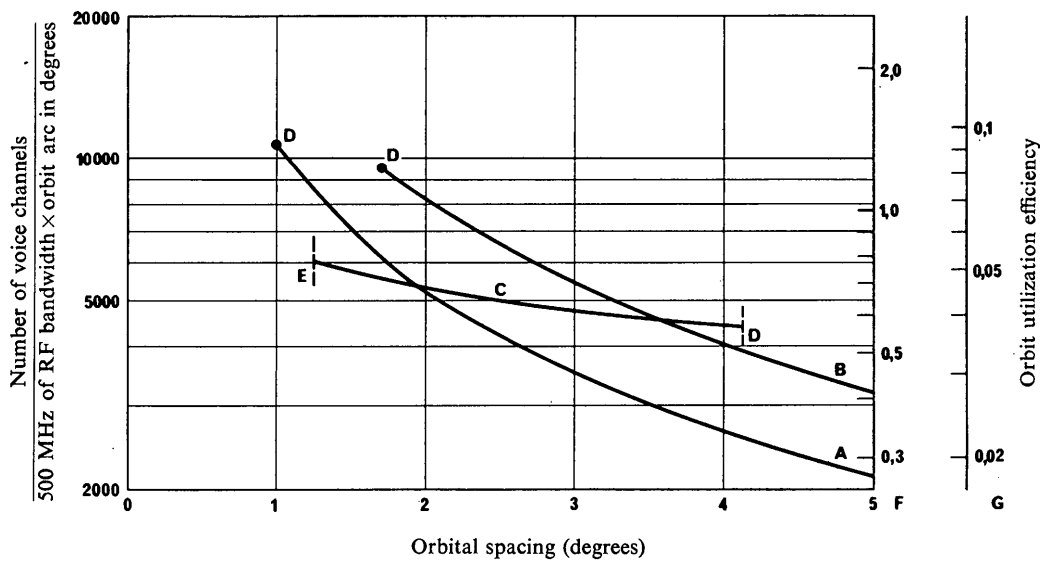


FIGURE 3

Orbit utilization efficiency versus orbital spacing
G/T = 40.7 dBK: perfect station-keeping

- A: 4-phase CPSK
- B: 8-phase CPSK
- C: FDM/FM
- D: Power-limited
- E: Threshold-limited

F: Scale for digital modulation
 G: Scale for frequency modulation

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 error-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) in equation 2, a quasi-continuous plot of E_b/N_0 versus B/r and E_0/N_0 versus B/r can be computed and these are shown on Figs. 4 and 5.

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:

$$\text{for analogue systems} \quad U \propto \frac{f_m}{\theta \times B} \quad (3)$$

$$\text{for digital systems} \quad V \propto \frac{r}{\theta \times B} \quad (4)$$

where θ is the required angular spacing between satellites.

* \propto means "proportional to".

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:

$$U = \frac{0.28^{\frac{1}{x}} (B/f_m)^{\frac{1}{x}-1} (B/f_m-2)^{\frac{2}{x}}}{\left[\frac{64\,000}{3} \times G_R/G_0 \times N_0/I_0 \right]^{\frac{1}{x}}} \quad \begin{array}{l} \text{Hz} \\ \text{Hz-degree} \end{array} \quad (5)$$

and for digital systems,

$$V = \frac{0.28^{\frac{1}{x}}}{B/r \left[G_R/G_0 \times N_0/I_0 \right]^{\frac{1}{x}} \left[f\left(\frac{B}{r}\right) \right]^{\frac{1}{x}}} \quad \begin{array}{l} \text{bit-rate} \\ \text{Hz-degree} \end{array} \quad (6)$$

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 $\theta = 1^\circ$.

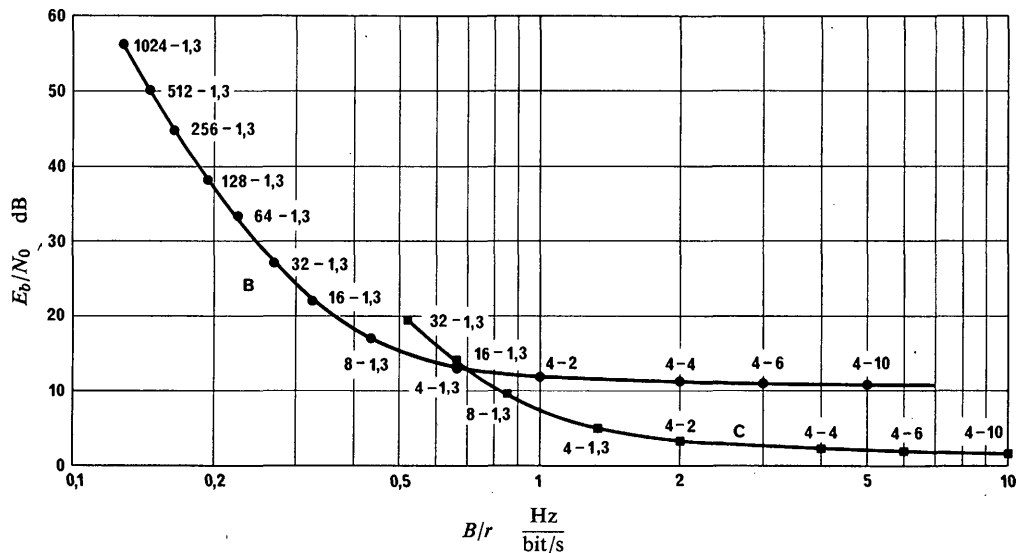


FIGURE 4

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)

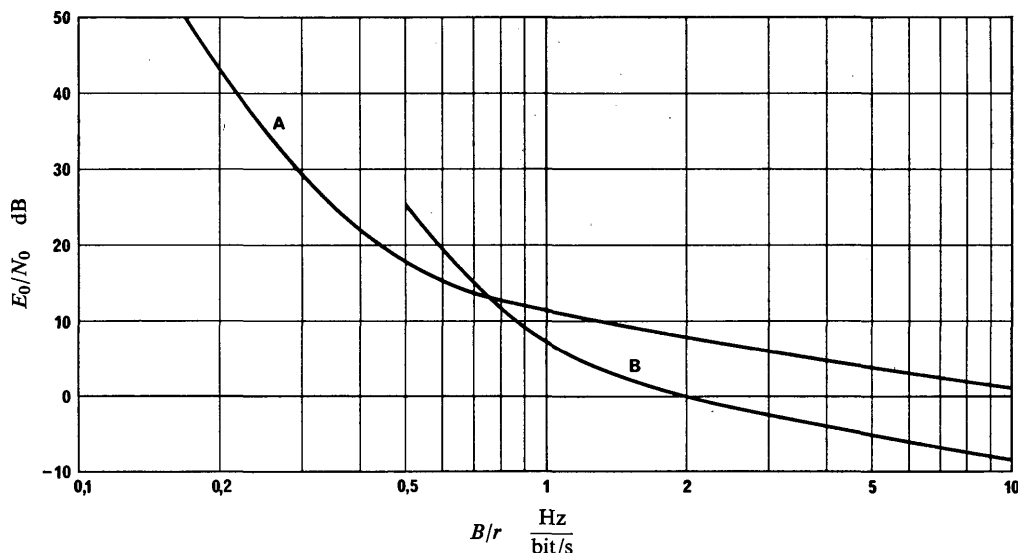


FIGURE 5

 *E_0/N_0 versus B/r for digital modulation*A: $f(B/r)$ Coherent phase detectionB: $f(B/r)$ Sequential decoding rate 1/2

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.

* Modulation index m = multi-channel peak deviation/top baseband frequency with peak to r.m.s. value of four.

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.

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

SECTION 4G: SHARING OF FREQUENCIES BETWEEN THE FIXED SATELLITE SERVICE
AND OTHER SATELLITE SERVICES

RECOMMENDATIONS AND REPORTS

Recommendations

There are no Recommendations in this section.

Reports

REPORT 560 *

SHARING CRITERIA FOR THE PROTECTION OF SPACE STATIONS
IN THE FIXED SATELLITE SERVICE RECEIVING IN THE BAND 14.0-14.4 GHz

(Study Programme 2M/4)

(1974)

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 14-14.3 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.

* Adopted unanimously.

TABLE I
*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 ₁₀ 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 14–14.3 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 the Annex 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 14–14.3 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 the Annex, 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:

$$-150 - 10 \log_{10} \frac{n}{4} \quad \text{dB (W/m}^2\text{) in any 1 MHz band}$$

$$-187 - 10 \log_{10} D \quad \text{dB (W/m}^2\text{) in any 1 MHz band.}$$

4. Protection of space station receivers of the fixed satellite service against interference from satellites in the radionavigation-satellite service in the band 14.3–14.4 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 coordination 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

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 ±3° of a geostationary satellite	$12 \times 10^3 \times \frac{6}{360} = 200$
Average number of radars within a 1 MHz band simultaneously pointing at a satellite	$200 \times \frac{1}{50} = 4$

REPORT 561 *

FREQUENCY BAND SHARING AT ABOUT 12 GHz BETWEEN GEOSTATIONARY SATELLITES OF THE FIXED SATELLITE AND BROADCASTING-SATELLITE SERVICES

(Study Programme 2K-1/4)

(1974)

1. Introduction

The frequency bands which have been allocated for the Earth-to-space paths for the fixed satellite service are available for up-paths to broadcasting satellites but there will be no corresponding down-paths in the space-to-Earth fixed satellite bands in Regions 1 and 3, where no space-to-Earth frequency bands are shared by these two services. The possibility arises, therefore, that this asymmetry will cause the Earth-to-space fixed satellite bands to become saturated in congested parts of the geostationary-satellite orbit when the space-to-Earth bands are not fully loaded, leading to inefficient spectrum utilization.

The World Administrative Radio Conference for Space Telecommunications (Geneva, 1971) allocated the band 11.7–12.2 GHz for space-to-Earth transmissions of the broadcasting-satellite service and of the fixed satellite service on an equal basis in Region 2. For reasons of operational convenience and wide-area coverage, it is anticipated that satellite networks implemented in this band will use the geostationary satellite orbit. It is of importance, therefore, to study ways in which the orbit and the frequency spectrum may be used efficiently by satellite networks providing these two types of service, because of the great differences in the network parameters that these systems are likely to use.

This Report reviews some initial studies of these problems for systems operating in frequency bands at about 12 GHz. To lessen interference problems, the bands allocated to the fixed satellite service in the neighbourhood of 30 GHz might be used for the broadcasting satellite connecting link. However, a study [C.C.I.R., 1970–1974a] has shown that the characteristics of the up-path have considerable influence on the performance of the link as a whole. In particular, a 30 GHz up-path would have a by no means negligible percentage of interruption by comparison with the down-path and it would be very difficult to obtain a reasonable overall percentage of interruption for the entire link. This Report will accordingly be confined to problems of sharing in the bands between 11 and 14 GHz.

2. Reduction of bandwidth required for up-links to 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. 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. Three possible ways of achieving this have been identified:

* Adopted unanimously. The attention of Study Groups 1, 10 and 11 is to be drawn to this Report.

- 2.1 It is readily feasible to provide much higher directivity for the antenna used at the transmitting earth station than for broadcast receiving antennae. Thus, given suitable satellite locations, the up-path frequency band can be re-used several times for each use of the down-path frequency band. An initial examination of this technique has been made [C.C.I.R., 1970-1974b] and the results are summarized in § 3 below.
- 2.2 Polarization discrimination is not likely to be feasible in the broadcasting-satellite down-path, but it is much more likely to be possible in the up-path, using orthogonal circular or linear polarizations. The aspects which should be taken into account are described in Report 555.
- 2.3 Wide-deviation FM is likely to be used for the broadcasting-satellite service in the foreseeable future. A different modulation technique might be used in the up-path, with remodulation in the satellite, in order to reduce the bandwidth required per channel, or to reduce the protection required against up-path interference.

Further study will be required in order to determine which of these techniques is to be preferred. Study Programme 2K-1/4 refers.

3. Up-path frequency re-use using the higher directivity of the transmitting earth-station antenna, relative to broadcast receiving antennae

The space segment of satellite-broadcasting systems serving a multi-national area of continental extent will probably consist of many satellites spaced at intervals of a few degrees over the geostationary-satellite orbit. 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 can be achieved 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.

For estimating the ratio of up-path to down-path frequency spectrum requirements, it is convenient to introduce the concept of orbital segments, a segment being defined as the minimum orbital arc required to use the total down-path bandwidth once. If all the down-path channels within a segment are broadcast from the same nominal orbital position, the size of segment is merely the spacing between adjacent orbital positions, and the bandwidths required for up-path and down-path are the same. However, if within each segment the down-path channels are transmitted from more than one orbital position, it is possible to re-use the same up-path frequency to each position, if the positions are sufficiently far apart. For a given number of frequency channels, the total up-path bandwidth required is, in theory, inversely proportional to the number of times each up-path frequency channel is used in each segment, given an equal division of transmissions between the several orbital positions used.

When the up-path frequency is re-used in this manner, the closer spacing between orbital positions using the same up-path frequency channel results in increased interference into the satellites. The interference on the down-path is not affected, provided that the pattern of channel positioning is repeated in each orbital segment. The overall increase in interference will be small for a small number of frequency re-uses and can be offset by a corresponding increase in segment size or alternatively by a small reduction in the up-path thermal noise contribution.

Preliminary studies of a satellite broadcasting scheme for 56 countries in a continental area [C.C.I.R., 1970-1974b] indicate 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. In this model, it was found necessary to increase the total orbital arc required by 3% to restore the up-path interference contribution to that which would have arisen if this threefold additional frequency re-use had not been employed.

Other studies of this approach [C.C.I.R., 1970-1974c] indicate, however, that there may be significant economic advantages in the use of a small number of orbit positions when planning a satellite broadcasting system. This arises from the possibility of grouping a number of satellite broadcasting transmitters in one spacecraft, so reducing launching costs. Furthermore, economies might arise from the use of common spare transmitters serving a group of transmitters in one spacecraft or in several spacecraft clustered in the same nominal orbital position. These economic considerations may conflict to some extent with the method of frequency re-use discussed above.

4. Shared use of the fixed satellite service bands 10.95-11.2 and 12.5-12.75 GHz for the down-paths of fixed-satellite networks and broadcasting satellite connecting up-paths

4.1 *Introduction*

In view of the new frequency allocations, the connecting path to broadcasting satellites might use the same frequency bands as the up-path of certain fixed-service satellites. Among the latter, those which are most likely to cause interference to broadcasting satellites or to suffer interference from them are satellites of the fixed satellite service with restricted land coverage serving the same areas, since they will occupy the same arc of the geostationary-satellite orbit. In view of the probable existence of a frequency and location plan for broadcasting satellites, it would be difficult to solve location conflicts which might arise between these two types of satellite. This difficulty would be aggravated by the fact that there is likely to be a large number of these regional satellites in the future.

Nevertheless, this difficulty could be appreciably reduced by using for these connecting paths a frequency band used for the fixed satellite service on the down-path. In this case, the probability of interference would be so low that there would no longer be any risk of conflict of location between the two types of satellite.

A study [C.C.I.R., 1970-1974d] has been made of the problem of interference when the same frequency band around 12 GHz is used for the down-path of a fixed-service network and the up-path for connection to a broadcasting satellite. Two interference modes arise:

- from the fixed satellite space station to the broadcasting-satellite space station, and
- to the fixed satellite earth station from the earth station transmitting to the broadcasting satellite.

4.2 *General hypotheses of the study*

Generally speaking, the assumptions made concerning interference were highly pessimistic and the interference levels encountered in practice would be far lower. The main hypotheses were as follows:

- the e.i.r.p. of a fixed-service geostationary satellite is taken as equal to the maximum value permissible under the Radio Regulations, which is well above the values at present envisaged;
- the maximum interference spectral power density from the fixed satellite space station is assumed to be present uniformly in all parts of the frequency band;

- the carrier-to-interference ratio in the 25 MHz television channel is assumed to be not worse than 30 dB;
- the e.i.r.p. of the earth station transmitting to the broadcasting satellite is taken as 76 dBW per 25 MHz channel (i.e. 18 dBW for a 10 m antenna). This power is assumed to be evenly distributed over 2 MHz.

4.3 *Interference caused to a broadcasting satellite by a fixed-service satellite*

4.3.1 *Band 10.95–11.2 GHz*

On the basis of these hypotheses, a minimum separation of 45 km would be obtained between satellites; taking a practical case, in fact, a minimum distance of 1600 m would be obtained. These values correspond to angular separations between satellites of 0.06° and 0.002° respectively. An angular separation of 0.1° between satellites is therefore quite adequate in all cases.

4.3.2 *Band 12.5–12.75 GHz*

In this band, on the basis of the hypotheses, a minimum separation of 55 km would be obtained; in a practical case, a minimum separation of 1600 m would be obtained. These values correspond to angular separations of 0.08° and 0.002° respectively. An angular separation of 0.1° between the satellites is thus quite adequate in this case also.

4.4 *Interference caused to a fixed-service earth station by the connecting earth station of the satellite broadcasting service*

If there is no site-shielding between stations, the minimum inter-station distance will be 90 km. If site-shielding is provided by an elevation of the horizon of 1° , this distance will be less than 40 km. If the stations are sited in such a way that each of them forms an angle of over 60° between the direction of the other station and its own main direction of radiation (which is fairly easily done) this results in a minimum inter-station distance of 20 km (this distance remains unchanged if there is the same degree of site-shielding as before).

5. **Broadcasting-satellite and fixed satellite services in the frequency band 11.7–12.2 GHz**

5.1 *Model description*

The sharing situation in the frequency band 11.7–12.2 GHz has been analyzed [C.C.I.R., 1970–1974e] by use of a model involving hypothetical systems in the broadcasting-satellite and fixed satellite services serving six, approximately equal-sized zones. These zones were chosen to cover parts of a large continental area extending into both northern and southern hemispheres. It is assumed that there is a fixed-service satellite and a broadcasting-service satellite serving each zone for a total of twelve, all using the band 11.7–12.2 GHz. There is one elliptical (shaped) beam per zone for the broadcasting satellite up-path and for the fixed satellite up- and down-paths. For the broadcasting-satellite down-path several beams per zone are postulated, to achieve full coverage. This is necessitated by the need to maintain a reasonable limit on RF power per satellite transponder.

Typical technical and operational assumptions for this model are indicated in Table I for each kind of traffic that these two types of satellites would likely carry. They are predicated on providing various services with performance standards in accordance with the relevant C.C.I.R. Recommendations.

In so far as possible, propagation data from the Report of the Special Joint Meeting, 1971, Annex 10-1 were used, tropical as well as temperate climate conditions being included.

The power transmitted from the broadcasting satellites has been determined according to the requirements of a typical small earth-station user.

The intent was to perform a conservative analysis and therefore, no improvement from polarization discrimination was assumed.

In the case where carriers of different bandwidths are mutually interfering, the number of interfering carriers of narrower bandwidth is chosen so as to fill up completely the bandwidth of the desired carrier. In addition, one of the interfering narrower-band carriers is co-channel to the desired carrier, which is the frequency plan resulting in worst-case interference. Co-channel operation is assumed for carriers of equal bandwidth.

The earth station antennae considered for this analysis have the ratio D/λ between 40 and 480. The C.C.I.R. pattern in Recommendation 465-1 was used even for the lower values.

The interference criteria used to establish orbital spacing are:

- *telephony* — a total performance objective of 10 000 pW0p with 1000 pW0p being allocated to interference from all other satellite entries (as per C.C.I.R. Recommendation 466-1);
- *television* — values of C/I at which “just perceptible” interference arises, as established by test for a carrier being interfered with by another single carrier. See Report 449-1 and the Report of the Special Joint Meeting, 1971, Part 1, § 3.4.1.3.

5.2 Analytical results

The analytical results in the form of spacing requirements are indicated in Table II.

5.2.1 Single satellite interference

The greatest spacing requirement from a fixed satellite standpoint is 11.3° for thin route telephony being interfered with by a direct broadcast carrier providing service to the same zone. The interference on a direct broadcast carrier from another direct broadcast carrier providing service to an adjacent zone is only slightly less critical at 9.8° spacing. The effect of these relatively large spacing requirements is to constrain the flexibility of satellite placement in orbit. The resulting sequencing/spacing criteria are listed for the above-mentioned pattern/protection ratio combination:

- broadcasting satellites for adjacent zones must be at least 9.8° apart;
- broadcasting satellites must be at least 11.3° from fixed satellites providing coverage to the same zone;
- broadcasting satellites must be at least 8.5° from fixed satellites providing coverage to an adjacent zone;
- fixed satellites for adjacent zones must be at least 2.4° apart.

It is apparent from Table II that the single-satellite spacing guidelines are strongly dependent upon the particular set of criteria and antenna patterns used.

5.2.2 Total system interference

The criteria given above apply only to satellites which are providing single channel coverage to the same or adjacent areas. The total analysis of the 12 satellites takes advantage of the “spot-beam” effect and the physical displacement of coverage zones, thus permitting close spacing of satellites which have little interference interaction.

No attempt was made here to achieve the minimum orbital arc consumption possible, which would entail determination of the mutual interference for every pair of carriers (411 pairs total) taking into account the specific geometry as well as the communication

performance parameters. The intent here was to show that the geostationary-satellite orbit can accommodate both satellite types with reasonable spacing. The concept of "clustering of like satellites" was employed since it usually results in relatively efficient spacing. Since the model being analyzed here has six zones, with three zones contiguous to one other zone, and the other three contiguous to two other zones, the above criteria govern the satellite spacing/sequencing. Therefore, maximum efficiency in the use of the orbit for this model will be achieved by interspersing the satellites which serve zones contiguous with one other zone with satellites which serve zones which are contiguous with two other zones.

5.3 Summary of results

- The results indicate that the assumed 12-satellite system model occupies only 34° of geostationary arc while meeting, or surpassing, desired performance objectives;
- it is clear that the results are sensitive to level of protection ratio for the broadcasting-satellite service and the nature of the assumed earth-station antenna pattern. These need to be more clearly specified;
- this study addressed only certain zonal arrangements and types of modulation. (Therefore, additional studies should be performed, particularly taking into account the use of digital modulation in the fixed satellite service, and other possible geographical models);
- the results are also sensitive to propagation information (and therefore further calculations should take into account the most recent propagation data available, particularly that applicable to tropical areas where there is heavy rainfall);
- this analysis implies that there exists a good deal of "orbital room" to accommodate more satellites than those assumed here, and hence that the band 11.7–12.2 GHz can be shared with reasonable efficiency by the fixed satellite and broadcasting-satellite services. This conclusion rests on two main sets of assumptions:
 - the specific link parameters, traffic mix, and performance objectives chosen, and
 - the analytic approximations used for the behaviour of signals subjected to interference.

Although the latter were based on the best available data, this is an area where much more information, theoretical and experimental, is needed. Nevertheless, despite some uncertainties, it seems fair to say that the geostationary-satellite orbit can accommodate both fixed and broadcasting satellites with reasonable average spacing.

6. Conclusions

The use of the same fixed satellite frequency bands for fixed service links and also for up-paths for connection to satellites in the broadcasting-satellite service raises certain problems. Nevertheless it may be concluded that there are various technical ways in which the bandwidth required for the latter purpose might be made considerably less than that needed for broadcasting-satellite down-paths. Furthermore, it is technically possible to use, on a shared basis, the bands 10.95–11.2 GHz and 12.5–12.75 GHz for the down-paths of networks in the fixed satellite service and the up-paths for connection to broadcasting satellites, subject to minor constraints. However, these matters need further study.

Where the fixed satellite and broadcasting-satellite services use both up-path and down-path frequency bands in common, it may be concluded that the geostationary-satellite orbit would be used most efficiently if satellites serving the two services were grouped in clusters of like satellites and the judicious placement of satellites with respect to the proximity of their coverage zones were effected. In this case the presence of the satellites of one service in one arc of the orbit would not greatly affect the networks served by satellites of the other service in the adjacent arc of the orbit while meeting or

surpassing desired performance objectives. However, the studies from which these conclusions are drawn have been addressed to specific cases, and there is a need for further work to be done, involving for example, different zonal situations, different types of modulation, and other propagation models, more particularly propagation models appropriate to the various typical tropical climates.

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JERUCHIM, M. C. and KANE, D. A. [31 December, 1970] Orbit/spectrum utilization study. Vol. IV, General Electric Co., Document 70-SD, 4293.

TABLE I
Link parameters for system model described in § 5

Parameter	Broadcasting-satellite service		Fixed satellite service							
	Community reception		Individual reception		Heavy-route telephony		Television distribution		Thin-route telephony	
	Up-path	Down-path	Up-path	Down-path	Up-path	Down-path	Up-path	Down-path	Up-path	Down-path
Transmitter band (GHz)	14.0-14.5	11.7-12.2	14.0-14.5	11.7-12.2	14.0-14.5	11.7-12.2	14.0-14.5	11.7-12.2	14.0-14.5	11.7-12.2
Transmitter RF power (W)	200	280	200	400	200	150	200	32	50	14
Satellite beam size (degrees)	3.5×7	3.5×7	3.5×7	1.5×2.6 (4 beams)	3.5×7	3.5×7	3.5×7	3.5×7	3.5×7	3.5×7
Satellite antenna gain (dB)	30.4	30.4	30.4	38.2	30.4	30.4	30.4	30.4	30.4	30.4
Ground antenna diameter (m)	10	2	10	1	10	10	10	10	5	5
Ground antenna gain (dB)	60.7	45.2	60.7	39.2	60.7	59.2	60.7	59.2	54.7	53.2
System noise temperature (K) (including antenna temperature).	2000	750	2000	1800	500	420	500	380	500	650
Ground antenna pointing and tracking error loss (dB)	0.5	1.6	0.5	3.0	0.5	0.5	0.5	0.5	1.0	1.0
Satellite pointing error (degrees)	0.5	0.5	0.5	0.8	0.5	0.5	0.5	0.5	0.5	0.5
Atmospheric attenuation (dB)	2	1.4	2	1.4	2	1.4	2	1.4	2	1.4
Rain margin (dB)	1.8	1.3	1.8	1.3	10	7	6	4	10	7
Miscellaneous losses (dB)	1	2	1	3	1	1	1	1	1.5	1.5
Modulation index	2.6		1.25		1.1 (r.m.s.)		3.5		4.7 (r.m.s.)	
Bandwidth (MHz).	28.8		18		36		36		2.2	

TABLE II

Required orbit separation for selected single-satellite interference criterion (degrees)

Desired carrier	Antenna pattern	Protection ratio criterion	Interfering carrier										
			Same area						Adjacent area				
			Broadcasting satellite		Fixed satellite			Broadcasting satellite		Fixed satellite			
			IR	CR	Television distribution	Thin-route telephony	Heavy route telephony ⁽¹⁾	IR	CR	Television distribution	Thin-route telephony	Heavy-route telephony	
Broadcasting-satellite service	Individual reception (IR)	C.C.I.R.	Report 449-1	12.9	6.2	3.2	4.2	3.8	9.8	4.7	2.4	3.2	2.8
		C.C.I.R.	Special Joint Meeting	22.4	10.8	5.3	7.2	6.4	17.5	8.2	4.1	5.5	4.9
	Community reception (CR)	C.C.I.R.	Report 449-1	10.2	4.7	2.2	2.7	2.2	7.7	3.7	1.8	2.1	1.8
		C.C.I.R.	Special Joint Meeting	17.5	8.2	3.9	4.7	3.9	13.5	6.2	3.0	3.6	3.0
Fixed satellite service	Television distribution	C.C.I.R.	Report 449-1	4.9	2.3	1.2	1.3	1.0	3.7	1.8	0.9	1.0	0.7
		C.C.I.R.	Special Joint Meeting	8.7	3.9	2.1	2.2	1.7	6.6	3.0	1.6	1.7	1.3
	Thin-route telephony	C.C.I.R.	—	11.3	5.2	2.9	2.0	1.9	8.5	4.0	2.2	1.5	1.5
	Heavy-route telephony	C.C.I.R.	—	6.4	3.1	1.8	2.6	3.2	5.0	2.3	1.4	2.0	2.4

(1) A fourth type of traffic, namely digital data could be considered. Some calculations [Jeruchim and Kane, 1970] indicate that at least for 4-phase PSK the spacing requirement for analogue signals is more stringent.

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 C.C.I.R.,

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?
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STUDY PROGRAMME 1A-1/4

REFERENCE RADIATION DIAGRAM OF ANTENNAE AT EARTH STATIONS
IN THE FIXED SATELLITE SERVICE

(1972 – 1974)

The C.C.I.R.,

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 fixed 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.

STUDY PROGRAMME 1B/4

RADIATION CHARACTERISTICS OF SATELLITE ANTENNAE IN THE
FIXED SATELLITE SERVICE

(1974)

The C.C.I.R.,

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 atmospheric effects in the transmission path;
6. determination of techniques for evaluation of these antenna characteristics.

STUDY PROGRAMME 1C/4

CHARACTERISTICS OF ANTENNAE AT EARTH STATIONS IN THE
FIXED SATELLITE SERVICE

(1974)

The C.C.I.R.,

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;

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.

QUESTION 2-2/4

**TECHNICAL CHARACTERISTICS OF SYSTEMS IN THE
FIXED SATELLITE SERVICE**

(1963 – 1970 – 1974)

The C.C.I.R.,

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 optimum from the 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;
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?

STUDY PROGRAMME 2A-2/4

FEASIBILITY OF FREQUENCY SHARING BETWEEN SYSTEMS IN THE
FIXED SATELLITE SERVICE AND TERRESTRIAL SERVICES

(1965 – 1966 – 1970 – 1974)

The C.C.I.R.,

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, the spectrum should be shared with terrestrial services to the extent practicable, in the interest of spectrum conservation;
- (c) that the feasibility of sharing spectrum space with radio-relay systems should be investigated;

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.
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STUDY PROGRAMME 2C-1/4

SYSTEMS IN THE FIXED SATELLITE SERVICE

Feasibility of frequency sharing among networks in the fixed satellite service

(1963 – 1970 – 1974)

The C.C.I.R.,

CONSIDERING

- (a) that the use of systems in the fixed satellite service will require extensive occupancy of the radio-frequency spectrum;
- (b) that the feasibility of frequency sharing among radiocommunication satellites, operating in the same system or operating in different systems, should be investigated;

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the criteria which affect interference among radiocommunication satellite networks in a given system and between satellite systems in the fixed satellite service, taking into account all relevant transmission paths, for:
 - 1.1 systems using geostationary satellites;
 - 1.2 systems using non-geostationary satellites;
 - 1.3 interference between geostationary and non-geostationary satellites;
 2. 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 in the fixed satellite service;
 3. the criteria which affect the minimum elevation angle which should be employed at the earth stations, from the standpoint of frequency sharing among networks in the fixed satellite service;
 4. the optimum range of powers to be employed by satellites and by earth-station transmitters, to facilitate frequency sharing among networks in the fixed satellite service;
 5. the effects of baseband and modulation characteristics on frequency sharing among networks in the fixed satellite service;
 6. the extent to which the selection of preferred frequencies would facilitate frequency sharing among networks in the fixed satellite service.
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STUDY PROGRAMME 2D-1/4

FIXED SATELLITE SERVICE

Preferred modulation characteristics and energy-dispersal

(1961 – 1963 – 1970 – 1974)

The C.C.I.R.,

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 fixed 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 382-2, 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 C.C.I.R. 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.

STUDY PROGRAMME 2E-1/4

**PREFERRED MULTIPLE-ACCESS CHARACTERISTICS IN THE
FIXED SATELLITE SERVICE**

(1965 – 1966 – 1970 – 1974)

The C.C.I.R.,

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.
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STUDY PROGRAMME 2H-2/4
USE OF FREQUENCY BANDS ABOVE 10 GHz IN THE
FIXED SATELLITE SERVICE

(1968 – 1970 – 1974)

The C.C.I.R.,

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.

STUDY PROGRAMME 2J-1/4

SYSTEMS IN THE FIXED SATELLITE SERVICE

Technical factors influencing the efficiency of use of the geostationary-satellite orbit by radiocommunication satellite networks sharing the same frequency bands **

(1968 – 1970 – 1974)

The C.C.I.R.,

CONSIDERING

- (a) that, for radiocommunication satellite networks, the geostationary-satellite orbit is particularly valuable;

* "Adaptive", in this sense, means changing the information rate or radiated power over a transmission link to compensate for changes in path attenuation.

** Other space services will also be using the geostationary-satellite orbit, operating in their appropriate frequency bands.

- (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 Spa2-15 of the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, calls upon the C.C.I.R. to give priority to studies on these subjects;

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. those technical characteristics of systems in the fixed satellite service which affect the utilization of the geostationary-satellite orbit, and the interrelationship between them;
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 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 account of the various applications and the different frequency allocations in the three I.T.U. Regions.

Note. — The following are some of the factors which should be taken into account in carrying out these studies:

- the permissible levels of interference noise in different systems in the fixed satellite service;
- the apportionment of thermal, interference and intermodulation noise;
- the radiation patterns of the earth station and satellite antennae;
- the difference in the values of e.i.r.p. used on the one hand by different earth stations and on the other by different radiocommunication satellites;

- the minimum acceptable wanted-to-unwanted carrier ratios resulting from the various baseband processing and modulation techniques;
- factors affecting the multiple use of the same frequencies within a single radiocommunication satellite;
- errors in satellite position and attitude;
- polarization discrimination;
- the technical means by which the service arc of a satellite can be maximized.

STUDY PROGRAMME 2K-1/4

**CHARACTERISTICS OF AN EARTH-TO-SPACE PATH OF THE FIXED
SATELLITE SERVICE USED FOR THE CONNECTION OF A SATELLITE
IN THE BROADCASTING SERVICE**

(1972 – 1974)

The C.C.I.R.,

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 and utilization principles to be recommended for these paths, taking into account the special requirements of the satellite broadcasting 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. — The attention of Study Groups 1, 10 and 11 should be drawn to this Study Programme and the results of any such studies should also be presented to these Study Groups.

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 C.C.I.R.,

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.

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 C.C.I.R.,

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;

* The same subject is dealt with by Study Group 8 under Study Programme 17D/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. — The attention of Study Group 8 should be drawn to this Study Programme.

QUESTION 7-1/4

BASEBAND TRANSMISSION VARIABILITY, DELAY, ECHOES AND SWITCHING DISCONTINUITIES IN SYSTEMS IN THE FIXED SATELLITE SERVICE

(1962 – 1963 – 1970 – 1974)

The C.C.I.R.,

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 C.C.I.T.T. (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;

STUDY PROGRAMME 2N/4

**INTERFACE CHARACTERISTICS FOR INTERNATIONAL DIGITAL
TRANSMISSION LINKS IN THE FIXED-SATELLITE SERVICE**

(1976)

The C.C.I.R.,

CONSIDERING

- (a) that the C.C.I.T.T. suggests a demarcation line between the study of the C.C.I.T.T. Special Study Group D and the C.C.I.R. 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 C.C.I.T.T., in the study of the international digital links;
- (c) that the C.C.I.T.T. 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;

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.

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 C.C.I.T.T. and CMTT, as appropriate?

QUESTION 13-1/4

**CONTRIBUTIONS TO THE NOISE TEMPERATURE OF AN
EARTH-STATION RECEIVING ANTENNA**

(1965 – 1970 – 1974)

The C.C.I.R.,

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?

QUESTION 14-2/4

PROPAGATION FACTORS AFFECTING SHARING OF THE RADIO-FREQUENCY SPECTRUM BETWEEN EARTH STATIONS AND TERRESTRIAL RADIO-RELAY SYSTEMS AT FREQUENCIES ABOVE 1 GHz

(1966 – 1970 – 1974)

The C.C.I.R.,

CONSIDERING

- (a) that the calculation of interference probability between earth stations and radio-relay systems must take account of all propagation mechanisms and effects and of the characteristics of the intervening terrain;
- (b) that much information regarding propagation between two points on the earth surface has already been provided but that this information is as yet incomplete;
- (c) that the determination of coordination distance on a given azimuth from an earth station must also take account of all propagation mechanisms and effects but without reference to precise information regarding the terrain except in the vicinity of the earth station;
- (d) that coordination distances should be determined with a minimum of initial information and while they must be sufficiently large to ensure that terrestrial stations outside the coordination area will experience or cause only a negligible amount of interference, they should not be so large as to involve unnecessary consultations between Administrations;

UNANIMOUSLY DECIDES that the following questions should be studied:

1. that studies should continue with regard to propagation over known terrestrial paths, to provide additional data regarding:
 - 1.1 a method or methods to predict the transmission loss between two points on the surface of the Earth, taking into account:
 - all known propagation mechanisms and modes, and their possible combination;
 - the influence of general or specific terrain characteristics of the surface of the Earth;
 - the influence of natural or man-made obstacles which make up the radio horizon at either terminal along the paths of predominant propagation mechanisms as a function of obstacle geometry, distance and elevation angle, including negative elevation angles;

- the influence of the terrain, of the propagation medium and of the pointing geometry of directive antennae on their gain along the paths of predominant propagation mechanisms;
 - the influence of the characteristics of the troposphere and their variations with time and location, including atmospheric absorption, refractive index and its variations with altitude, precipitation and other pertinent climatological effects;
 - the influence of variations in the characteristics of the surface of the Earth and of the troposphere along the path (“mixed paths”);
 - the influence of polarization;
- 1.2 the manner in which the predicted transmission loss varies as a function of the frequency; *
 - 1.3 the manner in which the predicted transmission loss depends on the percentage of the time for which it is not exceeded, for 20%, 1%, 0.1%, 0.01% and 0.001% of the time;
 - 1.4 the accuracy of prediction of the transmission loss;
2. that studies should be carried out leading to information regarding:
 - 2.1 a simple method to determine the distance at which it is likely that a specified transmission loss is exceeded (“the coordination distance”) taking into account:
 - all pertinent propagation mechanisms and modes;
 - the influence of general terrain characteristics of the surface of the Earth;
 - the influence of natural or man-made obstacles which comprise the radio horizon of the earth-station location along a given azimuth as a function of the horizon elevation angle, including negative elevation angles;
 - the influence of the pointing geometry of a directive earth-station antenna, assuming the most unfavourable pointing direction of radio-relay antennae likely to be found in practice;
 - the influence of the pertinent characteristics of the troposphere in terms of a limited number of simply defined radio-climatic zones;
 - the influence of the existence of one or more terrain and radio-climatic zones within the coordination distance (“mixed paths”);
 - 2.2 the manner in which the distance defined in § 2.1 above varies as a function of frequency;
 - 2.3 the manner in which the distance defined in § 2.1 above varies for the various percentages of the time, 20%, 1%, 0.1%, 0.01% and 0.001%.

Note 1. — The studies to be undertaken under this Question are detailed in Study Programmes which derive from Question 5-2/5 of Study Group 5. Contributions relative to Question 14-2/4 should be transmitted to Study Group 5.

Note 2. — The development of methods for the determination of the coordination distance and for the calculation of the probability of interference between earth and terrestrial stations, employing the propagation data provided by Study Group 5, is a matter for joint study by Study Groups 4 and 9.

* In particular, in the case of rain scatter for frequencies above 8 GHz, and in the case of ducting for frequencies above 12 GHz.

QUESTION 20-1/4

OPERATION AND MAINTENANCE OF EARTH STATIONS

(1970 – 1974)

The C.C.I.R.,

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?

QUESTION 22/4 *

**USE OF SYSTEMS IN THE FIXED SATELLITE SERVICE
IN THE EVENT OF NATURAL DISASTERS, EPIDEMICS, FAMINES
AND SIMILAR EMERGENCIES**

(1972)

The C.C.I.R.,

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, 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;

* See also Questions 22/3, 22/8 and 20/9.

- (c) that the World Administrative Radio Conference for Space Telecommunications, Geneva, 1971, has adopted Recommendation No. Spa2-13;
- (d) that use of space radiocommunication systems is one of the means by which rapid and reliable telecommunications could be provided for 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?

QUESTION 23/4

LOW CAPACITY EARTH STATIONS AND ASSOCIATED SATELLITE SYSTEMS

(1974)

The C.C.I.R.,

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 C.C.I.R.,

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?
-

QUESTION 25/4*

**SPURIOUS EMISSIONS RADIATED FROM AND RECEIVED BY EARTH STATIONS
AND SPACE STATIONS OF THE FIXED-SATELLITE SERVICE**

(1976)

The C.C.I.R.,

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;

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?

* This Question is to be brought to the attention of Study Groups 1, 2, 7, 8, 9, 10 and 11.

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 C.C.I.R.,

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 fixed-satellite frequency allocations;
- (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;
- (f) that studies on some of these topics are already in progress, for example under Study Programmes 2K-1/4 and 2M/4, and that Recommendation DD from the WARC on Satellite Broadcasting at 12 GHz also refers;

DECIDES that the following studies should be carried out:

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 fixed-satellite frequency bands for feeder connections of specific satellite services or groups of services;
3. what 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 take into account in considering frequency allocations for feeder connections?

* This Question is to be brought to the attention of Study Groups 2, 7, 8, 10 and 11.

DECISION 2
(RESOLUTION 56)

FREQUENCY SHARING BETWEEN RADIOCOMMUNICATION SATELLITES

Technical considerations affecting the efficient use of the geostationary-satellite orbit

(Study Programme 2J-1/4)

(1970 – 1974)

The C.C.I.R.,

CONSIDERING

- (a) that studies on the technical factors affecting the efficient use of the geostationary-satellite orbit need to be carried on 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;

UNANIMOUSLY 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-1/4);
 - 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 times of 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;
- 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, United States of America, France, 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 I.F.R.B.*;
- 3. that the coordination 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 I.T.U.

* *Note by the Secretariat.* — In addition, participation by the People's Republic of China was announced by a letter addressed to the Director of the C.C.I.R. during the course of the XIIIth Plenary Assembly.

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