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INTERNATIONAL TELECOMMUNICATION UNION

CCIR

INTERNATIONAL
RADIO CONSULTATIVE
COMMITTEE

RECOMMENDATIONS AND REPORTS OF THE CCIR, 1982

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

XVth PLENARY ASSEMBLY
GENEVA, 1982

VOLUME V

PROPAGATION IN NON-IONIZED MEDIA



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ISBN 92-61-01431-3

**PLAN OF VOLUMES I TO XIV
XVTH PLENARY ASSEMBLY OF THE CCIR**

(Geneva, 1982)

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

All references within the texts to CCIR Recommendations, Reports, Resolutions, Opinions, Decisions, Questions and Study Programmes refer to the 1982 edition, unless otherwise noted; i.e., only the basic number is shown.

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

Volumes I to XIV, XVth Plenary Assembly, contain all the valid texts of the CCIR and succeed those of the XIVth Plenary Assembly, Kyoto, 1978.

1. Recommendations, Reports, Resolutions, Opinions, Decisions

1.1 Numbering of these texts

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

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

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

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(I) Published separately.

1.3.1 Note concerning Reports

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

1.4 Resolutions

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1.6 Decisions

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6	VI	33	XI-1	51	X/XI-2
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21	VI	43, 44	X/XI-2	56	I
27	I	45	III		

1.6.1 Note concerning Decisions

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

2. Questions and Study Programmes

2.1 Text numbering

2.1.1 Questions

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

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

2.1.2 *Study Programmes*

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

Examples:

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

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

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

2.2 *Arrangement of Questions and Study Programmes*

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

VOLUME V

PROPAGATION IN NON-IONIZED MEDIA

(Study Group 5)

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Decision 37**	Technical and operational studies relating to the division of the world into regions for the purposes of allocating frequency bands	

* See page 143 of Volume I of the XIVth Plenary Assembly, Kyoto, 1978.

** This Decision is not mentioned in the Volume of the XIVth Plenary Assembly, Kyoto, 1978, and only appears in the Conclusions of the Interim Meeting of Study Group 5, Geneva, 1980, page 364.

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Note. — Questions, Study Programmes, Resolutions, Opinions and Decisions which already appear in numerical order in the table of contents, are not reproduced in this index.

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CONTAINING INFORMATION OF INTEREST TO PROPAGATION
IN NON-IONIZED MEDIA**

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Study Programme 5A/2	Criteria for evaluation of interference to radioastronomy	II
Report 696	Feasibility of frequency sharing between radioastronomy and other services	II
Recommendation 479	Protection of frequencies for radioastronomical measurements in the shielded zone of the Moon	II
Study Programme 7B/2	Shielding effects due to the Moon	II

Text	Title	Volume
Report 205	Factors affecting the selection of frequencies for telecommunications with space stations in the fixed-satellite service	IV
Report 552	Use of frequency bands above 10 GHz in the fixed-satellite service	IV
Report 385	Feasibility of frequency sharing between systems in the fixed-satellite service and terrestrial radio services. <i>Criteria for the selection of sites for earth stations in the fixed-satellite service</i>	IV
Report 869	Low-capacity earth stations and associated satellite systems in the fixed-satellite service	IV
Report 710	Interference allocations in digital systems operating at frequencies greater than 10 GHz in the fixed-satellite service	IV
Report 876	Frequency sharing between systems in the fixed-satellite service and the fixed service in frequency bands above 40 GHz	IV/IX
Report 393	Intersections of radio-relay antenna beams with orbits used by space stations in the fixed-satellite service	IV/IX
Report 791	Inter-satellite service sharing with the fixed and mobile services	IV/IX
Report 382	Determination of coordination area	IV/IX
Recommendation 372	Use of data on radio noise	VI
Report 258	Man-made radio noise	VI
Report 322	Characteristics and applications of atmospheric radio noise data (published separately)	VI
Report 342	Radio noise within and above the ionosphere	VI
Report 254	Measurement of atmospheric radio noise from lightning	VI
Question 29/6	Radio noise	VI
Question 60/8	Broadcasting and aeronautical radionavigation services in the LF bands. <i>Interference between Regions</i>	VIII
Report 779	Interference in digital radio-relay systems with coherent PSK modulation	IX
Report 784	Effects of propagation on the design and operation of line-of-sight radio-relay systems	IX
Report 285	Propagation effects on the design and operation of trans-horizon radio-relay systems	IX
Recommendation 557	Availability objective for a hypothetical reference circuit and a hypothetical reference digital path	IX
Report 782	Radio-frequency channel arrangements for high-capacity digital systems in the 10.7 to 11.7 GHz frequency band	IX
Report 607	Radio-frequency channel arrangements for radio-relay systems in the ranges 10.5 to 10.68 GHz and 11.7 to 15.35 GHz	IX
Report 783	Radio-relay systems in frequency bands above about 40 GHz	IX
Report 376	Diversity techniques for radio-relay systems	IX

Text	Title	Volume
Report 614	Reference radiation patterns for radio-relay system antennas	IX
Question 25/9	Effects of propagation on the design and operation of radio-relay systems	IX
Question 29/9	Possible limits for reducing transmitter power and repeater distance of radio-relay systems operating in the band 2 to 8 GHz	IX
Decision 55	Effects of propagation on the design and operation of line-of-sight radio-relay systems	IX

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PROPAGATION IN NON-IONIZED MEDIA

STUDY GROUP 5

Terms of reference:

To study with the object of improving radiocommunication the propagation of radio waves (and the study of associated radio noise):

- at the surface of the Earth,
- through the non-ionized regions of the Earth's atmosphere,
- and in space where the effect of ionization is negligible.

1978-1980 *Chairman:* J. A. SAXTON (United Kingdom) (deceased)

Vice-Chairman: A. KALININ (U.S.S.R.)

1980-1986 *Chairman:* A. KALININ (U.S.S.R.)

Vice-Chairman: H. T. DOUGHERTY (USA)

INTRODUCTION BY THE CHAIRMAN, STUDY GROUP 5

The period between the XIVth and XVth CCIR Plenary Assemblies was a busy one for Study Group 5. At its Interim and Final Meetings more than 200 contributions, containing the results of experimental and theoretical research conducted in a large number of countries, were presented. The geographical scope of its work was increased and now covers a wider variety of climatic and topographical conditions.

Concerning the structure of Volume V, Report 565 relating to satellite broadcasting has been transferred to Section 5F in order to assemble texts relating to space services in the same Section.

On the basis of the data contained in the contributions to the Interim and Final Meetings of Study Group 5, it was possible to produce substantially updated versions of the Study Group's texts and also to prepare the following new Recommendations and Reports:

Recommendation 581: The definition of "worst month"

Report 880: Propagation in tunnels and mines

Report 883: Attenuation of visible and infra-red radiation

Report 879: Methods for estimating effective electrical characteristics of the surface of the Earth

Report 885: Propagation data required for evaluating interference between stations in space and those on the surface of the Earth

Report 882: Scattering by precipitation

Report 881: Effects of small-scale spatial or temporal variations of refraction on radio-wave propagation

Report 878: Special features of the concept of transmission loss in the ground-wave propagation case

Report 884: Propagation data for maritime and land mobile satellite systems above 100 MHz

The new Reports contain extremely useful information on various aspects of propagation in the non-ionized regions of the atmosphere. Report 879 will be of great assistance to developing countries in classifying their territory according to the effective electrical characteristics of the Earth's surface.

Substantial changes and additions have been made to Report 338 "Propagation data required for line-of-sight radio-relay systems", Report 564 "Propagation data required for space telecommunication systems" and Report 565 "Propagation data for broadcasting from satellites". These Reports set out provisional methods for statistical calculations of rain attenuation on land and oblique paths, based on a unified approach to the calculation of the spatial non-uniformity of rain.

Significant changes were made to Report 238 "Propagation data required for trans-horizon radio-relay systems". This Report now contains only data necessary for calculating link reliability, while data relating to interference have been transferred to Report 569.

Report 569 "The evaluation of propagation factors in interference problems between stations on the surface of the Earth at frequencies above about 0.5 GHz" and Report 724 "Propagation data required for the evaluation of coordination distance in the frequency range 1 to 40 GHz" were updated in the light of new data on the statistics of interfering signal levels. However, because of the limited nature of these data, it was felt that it was still too early to propose a change to the corresponding sections of Appendix 28 of the Radio Regulations in accordance with Resolution No. 60 of the WARC-79.

Basic changes were made to Report 563 "Radiometeorological data". This Report now gives more precise information on the world's rainfall intensity regions.

Report 723 "Worst-month statistics" has been improved and progress has been made in resolving the problems it sets forth. However, Report 723 and Recommendation 581 need to be further refined to take account of the possible wishes of Study Groups 4, 9 and also 8, 10 and 11.

Report 229 "Electrical characteristics of the surface of the Earth" has been supplemented with fresh information on the influence of vertical soil structure and seasonal changes in the effective electrical characteristics of the Earth's surface. Information on the electrical characteristics of ice and the influence of irregularities in the Earth's surface on the reflection coefficient have also been added.

Fresh data on depolarization phenomena arising in multipath propagation and occurring as a result of precipitation are included in Report 722.

In Recommendation 528 "Propagation curves for the aeronautical services using the VHF, UHF, and SHF bands", the curves showing basic transmission loss as a function of path distance and antenna height have been replaced by new curves which take into account time variations of signal levels.

Two new Resolutions have been approved. Resolution 72 sets out the procedure for preparing a world atlas of ground conductivities. Resolution 73 requests the CCIR Secretariat to prepare a handbook of propagation curves for frequencies above 10 MHz on the basis of the GRWAVE computer program.

Under new Decision 50, IWP 5/5 has been set up to study *inter alia* all methods for calculating signal characteristics for the terrestrial broadcasting and mobile services. These matters have been excluded from the terms of reference of IWP 5/2, which will now examine only questions relating to the fixed terrestrial and space services, and problems of interference.

Editorial improvements have been made to the texts of almost all the Recommendations and Reports. The texts of a large number of Questions and Study Programmes have been amplified to take account of matters of interest to other Study Groups.

By agreement with Study Group 1, an updated Recommendation 341 "The concept of transmission loss for radio links" is now a Study Group 5 text.

Solution of problems arising from the WARC-79

The Interim and Final Meetings of Study Group 5 paid considerable attention to the solution of the problems assigned to the CCIR by the WARC-79.

A joint IWP 5/4 was set up by Decision 37 at the Interim Meeting of Study Group 5 and all CCIR Study Groups and administrations were asked to participate with a view to the implementation of Resolution No. 66 of the WARC-79 concerning the study of the technical and operational bases for the possible revision of the division of the world into Regions for the purposes of allocating frequency bands.

IWP 5/4 met in May 1981 and prepared a preliminary report for submission to the XVth Plenary Assembly. At its Final Meeting, Study Group 5 approved those parts of this report which fell within its terms of reference. The report of IWP 5/4 was also sent for consideration to other CCIR Study Groups for direct submission of their comments to the XVth Plenary Assembly. IWP 5/4 having thus completed its task, Decision 37 was cancelled at the Final Meeting of Study Group 5.

The updating of the Recommendations and Reports of Study Group 5 at its Interim and Final Meetings contributed towards a solution of the problems formulated in Resolution Nos. 5, 31, 34, 60, 61, 505, 509, 510 and 701 and Recommendation Nos. 3, 60, 68, 100, 101, 300, 301, 505, 705, 708 and 711 of the WARC-79. Further progress towards the implementation of these Resolutions and Recommendations will be made as a result of broader and more detailed studies carried out by administrations in connection with the relevant Questions and Study Programmes of Study Group 5.

The Final Meeting of Study Group 5 discussed a draft Resolution dealing with the intensification of work on propagation in tropical areas in accordance with Resolution No. 68 of the WARC-79. This would be very important for the developing countries most of which are situated in these areas. Since the text dealt not only with technical but also with organizational and financial problems, Study Group 5 refrained from formally approving the Resolution, and referred it to the XVth Plenary Assembly. The Plenary Assembly modified this text to include ionospheric propagation (Study Group 6) within the field of application, and approved it as Resolution 79. This Resolution is to be found in Vol. XIII of the CCIR.

Main problems for study in the next period

The main problems for study in the next period are as follows:

- (a) The establishment of a single model for the spatial non-uniformity of rain cells in the horizontal and vertical directions in connection with the prediction of radio wave attenuation, depolarization and scatter.
- (b) More detailed studies of general methods for calculation of radio wave attenuation in rain on terrestrial paths and on Earth-to-space paths, taking into account the spatial non-uniformity of rain.
- (c) The development of a general method for calculating the statistical distributions of fading depth, duration and rates in multipath propagation on the basis of the data given in Report 338. Methods for calculating the statistical characteristics of sub-refraction fading must also be included in this Report.
- (d) Continued studies into the selective nature of multipath fading on terrestrial and slant paths in connection with digital communication systems. Development of an appropriate statistical model and definition of the parameters of this model as a function of path and frequency characteristics.
- (e) Further studies on signal stability improvement by means of frequency and space diversity reception.
- (f) Further studies of depolarization phenomena arising in multipath propagation and resulting from the effects of rain on terrestrial and slant paths.
- (g) Continuation of studies of anomalous propagation in various climatic regions over a wider range of frequencies and distances, including investigations into tropospheric duct propagation. Special attention will have to be paid to statistics of the maximum horizontal lengths of ducts which determine the limit ranges of interfering signal propagation. Studies will also have to be made of the conditions governing duct formation and the escape of energy from ducts as a function of vertical duct structure, antenna height and the characteristics of the terrain.
- (h) Improvements of methods for calculating rain scatter taking into account the spatial non-uniformity of rain cells and the attenuation of radio waves within the scattering volume. Determination of the lower frequency limit at which this scattering becomes negligible.
- (i) Expanding and clarifying the statistics of the radiometeorological parameters given in Report 563, and also statistical clarification of the concept of the worst month in Report 723 taking into account the requirements of other CCIR Study Groups.
- (k) Development of more precise propagation curves for terrestrial broadcasting and mobile services particularly for cases in which only limited experimental data are available. It is also important to ascertain the limits governing the applicability of existing methods for calculating the effect of rough ground in areas with very uneven terrain, and if possible to find other more appropriate methods than the use of the Δh concept.

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- (l) Obtaining additional statistical data on propagation for the mobile services in towns, due attention being paid to the requirements of digital communications systems. Elucidating how these data vary with the nature and density of buildings, vegetation, etc.
 - (m) Obtaining more precise propagation data for the maritime mobile-satellite service including the influence of sea surface conditions, particularly for small angles of elevation.
 - (n) Obtaining more precise data on the world regions from the point of view of the electrical characteristics of the Earth's surface. Obtaining further information on radio wave reflection in rough terrain.
 - (o) Preparation of a manual containing curves showing field strengths (or basic transmission losses) as a function of distance at frequencies above 10 MHz for different antenna heights.
-

SECTION 5A: TEXTS OF GENERAL INTEREST

Recommendations and Reports

INTRODUCTION TO TEXTS OF STUDY GROUP 5

PROPAGATION IN NON-IONIZED MEDIA

It is the responsibility of Study Group 5 to study the propagation of radio waves (including radio noise):

- at the surface of the Earth,
- through the non-ionized regions of the Earth's atmosphere,
- in outer space wherever the effect of ionization is negligible,

with the object of improving communications. Terrain effects are due either to the topography or to the electrical characteristics of the Earth's surface, and these effects occur throughout the radio-frequency spectrum. The most important part of the non-ionized atmosphere is the troposphere, and its influence on propagation is effectively confined to frequencies greater than about 30 MHz. Propagation in outer space is mainly an extension of the free-space concepts widely used in general calculations. These factors therefore define the primary areas of activity of the Study Group.

The fundamental problem confronting a radiocommunications engineer in setting up a service is that he must achieve a satisfactory signal-to-noise ratio (in digital systems – a very low error rate). That is, he must ensure a signal adequate to satisfy performance requirements of the service in question, given the circumstances in which it is to operate. To solve this problem, he requires a knowledge of the fluctuations in the desired signal on the one hand, and in the noise signals on the other. Now the noise level, viewed as a whole, is partly controllable and partly uncontrollable. Noise in this context consists of:

- noise arising in the terminal equipment or inherent in the system due to multipath propagation (e.g. inter-modulation noise in FM-FDM links);
- man-made noise, that is to say man-made radio noise as distinct from other sources of emissions;
- noise of natural origin, including extra-terrestrial noise;
- signals of other radio services that are unwanted at the receiver in question, or in other words, interference.

Note. – It will be seen that all radio energy unwanted at the receiver is considered as noise *in this context*.

Therefore the first essential is for the engineer to have some realistic idea of the total, varying, noise level – and its characteristics – that he is likely to encounter. Based on the specified requirements of a particular system, it is then possible for him to define the minimum signal required to give reliable operation under given circumstances. This normally follows from the system requirements concerning transmission losses not exceeded for a specified percentage of the time, typically 99.9% or 99.99% of a year or worst month. The total interference from whatever source or sources therefore must not significantly affect system performance for more than the complementary time percentage, in the foregoing cases 0.1% or 0.01% of the time respectively. This means that, since wanted signals and all forms of noise (other than that inherent in the system itself) are dependent on the way in which radio waves are propagated, for the service path it is essential to know the transmission loss not exceeded during say 99.9% of the time, and for all relevant noise paths it would consequently be essential to know the transmission losses not exceeded for 0.1% of the time. It is more difficult to determine the latter than the former. In view, firstly, of the severe and increasing congestion of the radio-frequency spectrum, secondly, of the necessity for sharing some frequency bands between different services and thirdly, of the need for repeating the use of the same frequency within a given service, the use of excessive radiated power to maintain a given service in the presence of noise is self-defeating and should never be considered.

1. Types of service

Services may be broadly classified into two categories:

- point-to-point services, and
- point-to-area services, for example, sound broadcast, television and the mobile services.

The above two categories of services may in general again be subdivided as follows:

- those in which the propagation paths are exclusively terrestrial, and
- those in which the propagation paths are Earth-space or space-space.

The terrestrial point-to-point services are planned with due regard to the topographical peculiarities of the propagation path between the points in question. In the case of terrestrial point-to-area services propagation can be considered to take place over a multiplicity of individual paths, but up to now the problem of determining service performance has mainly been considered on a basis of statistical coverage because of the practical impossibility of making surveys of all the individual paths in question. However, the recent development of suitable computer techniques together with improved estimation of propagation characteristics over typical paths has enabled a more rigorous approach to be made to the point-to-area problem.

Except for those services which involve propagation phenomena affected by the ionosphere, all services are dependent to some degree on the propagation data produced by Study Group 5, and include radar, navigational aids, radioastronomy and space science telemetry in addition to the communication services mentioned above. Consequently there are Study Group 5 Reports which are quite general in nature (e.g. in radiometeorology and ground-wave propagation) and not restricted to a particular category of service. The main characteristics of propagation phenomena are reviewed in the following section.

2. Propagation characteristics

2.1 Terrain effects

When radio waves are propagated over or through the Earth, the propagation characteristics are determined by:

- the electrical properties of the Earth;
- the physical configuration of the surface of the Earth, including vegetation and man-made structures of arbitrary dimensions.

Except for transmission through the Earth, which is of limited importance, and perhaps some aspects of mixed-path transmission, the electrical characteristics of the Earth are primarily of importance at frequencies less than about 100 MHz over land and 1 GHz over sea. The circumstances in which these characteristics are important may be found in Report 715 and Report 229. At frequencies above about 30 MHz it is the physical configuration that matters most. The relevant effect on overall transmission loss is determined by the frequency concerned, the electrical characteristics in question and/or the topography of the terrain. It should be noted that in the case of tropospheric propagation near the surface of the Earth the effects of irregular terrain are important at all times.

2.2 Tropospheric effects

Waves propagated through the non-ionized regions of the atmosphere are affected by the gaseous constituents of the atmosphere and also by all forms of cloud and precipitation. The relative importance of these factors depends on climate and on frequency.

The gaseous constituents of the atmosphere influence propagation of radio waves both by the absorption of energy and by the variations in refractive index, which cause reflection, refraction and scattering of the waves. Absorption takes place principally due to the presence of oxygen, water vapour and liquid water and is not significant at frequencies lower than about 3 GHz. However, while phenomena associated with variations in refractive index are known to occur at frequencies lower than 30 MHz, such phenomena are primarily significant in system planning at frequencies above about 30 MHz.

Clouds and precipitation influence propagation in two basic ways:

- by the absorption of part of the energy passing through them;
- by scattering and changing the polarization of radio waves.

Scattering clearly contributes to the attenuation of the forward beam, but is also important because it deflects energy into other directions, including directly back toward the transmitter. Once again, these effects are of importance at frequencies greater than about 3 GHz.

Changes in polarization occur when the scattering particles are non-spherical in shape. In the case of scattering by water particles there is significant associated attenuation, while in the case of ice particles the attenuation is generally insignificant.

The variability in propagation characteristics due to atmospheric effects is of paramount importance in determining the interference likely to be experienced in radio systems, especially in those modes of propagation associated with transmission well beyond the normal horizon.

2.3 *Multipath*

This covers all cases in which the effective received signal is made up of several components which arrive at the receiving antenna over different transmission paths. These components have differing phase relationships and perhaps differing amplitudes, and their relationships with one another vary continuously with time. This phenomenon results from a multiplicity of paths in the troposphere, reflections from objects such as aircraft, specular reflections due to water surfaces such as lakes and rivers, swamps and estuaries, and from horizontal interfaces between different layers in the atmosphere. Such multipath (which is the cause of all fast fading observed on radio links) can seriously degrade the quality of a service, especially with regard to bandwidth, and is not uncommon even in cases of line-of-sight propagation.

2.4 *Noise*

The main concern of Study Group 5 with respect to noise relates to noise at frequencies for which the non-ionized atmosphere and the Earth itself affect propagation. This includes man-made noise at such frequencies, noise due to the atmosphere and its constituents, galactic noise and noise radiated from the Earth and obstacles thereon.

3. **Classification of texts**

To assist the practical application of the propagation data, the texts have been classified as follows (see the Table of Contents of this Volume):

Section 5A: Texts of general interest

Section 5B: Effects of the ground (including ground-wave propagation)

Section 5C: Effects of the atmosphere (radiometeorology)

Section 5D: Aspects relative to the terrestrial broadcasting and mobile services

Section 5E: Aspects relative to the terrestrial fixed service

Section 5F: Aspects relative to space telecommunication systems (including space research)

Section 5G: Propagation factors in interference, space and terrestrial systems.

The Table of Contents has been so arranged as to give detailed indications concerning the information to be found in each text in the above sections, and careful reading of the Table of Contents is therefore essential for the efficient use of this Volume.

It is believed that this arrangement of texts is the most convenient one for practical applications. However, it is important to recognize the inter-relationship between many propagation characteristics. In many cases, the effects of more than one propagation mode are superimposed and a clear understanding of the individual phenomena and their probability of occurrence is essential in evaluating the overall effect on a particular system.

RECOMMENDATION 525-1

CALCULATION OF FREE-SPACE ATTENUATION

(1978-1982)

The CCIR,

CONSIDERING

that free-space propagation is a fundamental reference for radio-engineering,

UNANIMOUSLY RECOMMENDS

that the methods in Annex I be used for the calculation of attenuation in free-space.

ANNEX I

1. Introduction

As free-space propagation is often used as a reference in other CCIR texts, this Annex lists certain relevant formulae, together with nomograms for rough graphical calculations which may be useful in many cases.

2. Basic formulae for telecommunication links

Free-space propagation may be calculated in two different ways, each of which is adapted to a particular type of service.

2.1 Point-to-area links

If there is a transmitter serving several randomly-distributed receivers (broadcasting, mobile service), the field is calculated at a point located at some appropriate distance from the transmitter, and in a given direction, by the expression:

$$E = \frac{\sqrt{30 p}}{d} \quad (1)$$

in which:

E : is the r.m.s. field strength in volts per metre (Note 1)

p : is the equivalent isotropically radiated power (e.i.r.p.) of the transmitter in the direction of the point in question (Note 2), in watts

d : is the distance from the transmitter to the point in question, in metres.

Expression (1) is often replaced by (2) which uses practical units:

$$E_{mV/m} = 173 \frac{\sqrt{p_{kW}}}{d_{km}} \quad (2)$$

These two relations are shown in Fig. 1.

For antennas operating in free-space conditions the cymomotive force may be obtained by multiplying together E and d in expression (1). Its dimension is volts.

Note 1. — If the wave is elliptically polarized and not linear, and if the electric field components along two orthogonal axes are expressed by E_x and E_y , the left-hand term of equation (1) should be replaced by $\sqrt{E_x^2 + E_y^2}$. E_x and E_y can be deduced only if the axial ratio is known. E should be replaced by $E\sqrt{2}$ in the case of circular polarization.

Note 2. — In the case of antennas located at ground level and operating on relatively low frequencies with vertical polarization, radiation is generally considered only in the upper half-space. This should be taken into account in determining the e.i.r.p. (see Recommendation 368).

2.2 Point-to-point links

With a point-to-point link it is preferable to calculate the free-space attenuation between isotropic antennas, also known as the basic free-space transmission loss (symbols: L_{bf} or A_0), as follows:

$$L_{bf} = 20 \log \left(\frac{4\pi d}{\lambda} \right) \quad \text{dB} \quad (3)$$

in which:

L_{bf} : the free-space basic transmission loss in dB,

d : the distance,

λ : the wavelength, and

d and λ are expressed in the same unit.

Expression (3) can also be written using the frequency instead of the wavelength.

$$L_{bf} = 32.5 + 20 \log f_{\text{MHz}} + 20 \log d_{\text{km}} \quad \text{dB} \quad (4)$$

Expressions (3) and (4) are shown in Fig. 2.

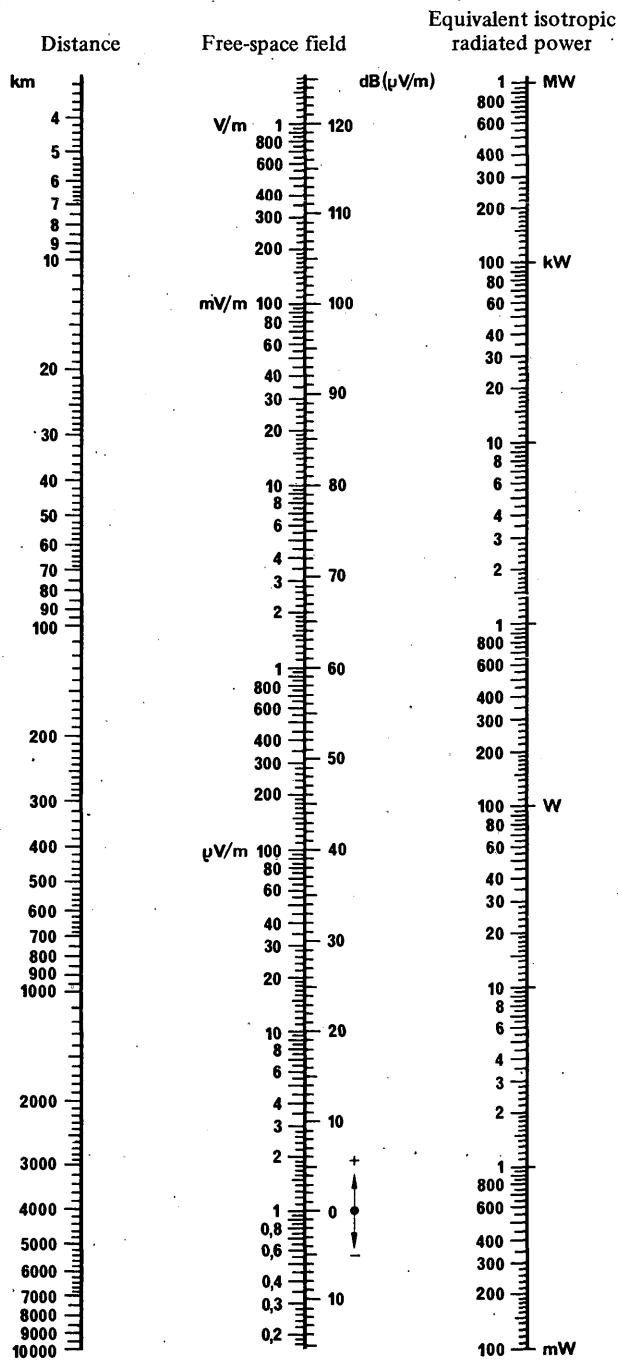


FIGURE 1 – Electro-magnetic field in free space

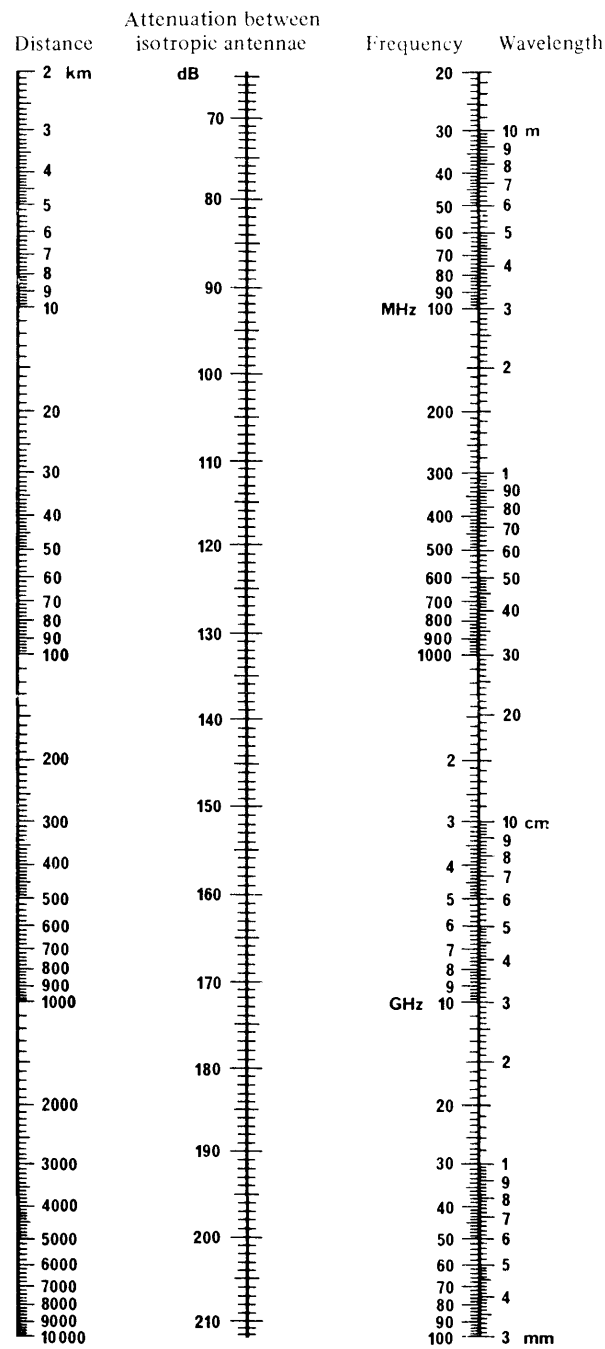


FIGURE 2 — Free-space attenuation between isotropic antennae

2.3 Relations between the characteristics of a plane wave

There are also relations between the characteristics of a plane wave (or a wave which can be treated as a plane wave) at a point:

$$S = \frac{E^2}{120\pi} = \frac{4\pi p_r}{\lambda^2} \quad (5)$$

in which:

S : is the power flux-density in watts per square metre,

E : is the r.m.s. field strength in volts per metre,

p_r : is the power in watts available from an isotropic antenna located at this point,

λ : is the wavelength in metres.

Expression (5) is shown in Fig. 3.

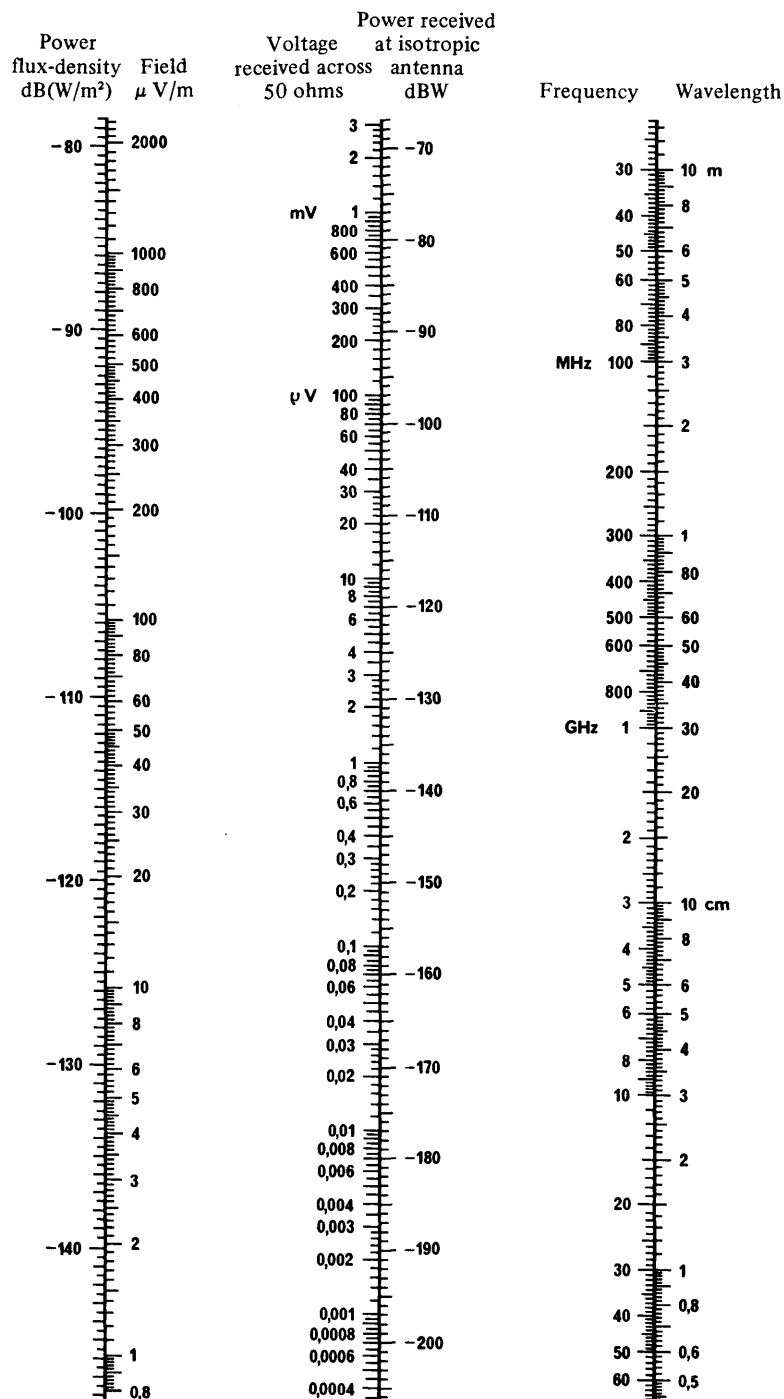


FIGURE 3 – Characteristics of a plane wave

3. The free-space basic transmission loss for a radar system (symbols: L_{br} or A_{0r})

Radar systems represent a special case because the signal is subjected to a loss while propagating both from the transmitter to the target and from the target to the receiver. For radars using a common antenna for both transmitter and receiver, a radar free-space basic transmission loss, L_{br} , can be written as follows:

$$L_{br} = 103.4 + 20 \log f + 40 \log d - 10 \log \sigma \quad \text{dB} \quad (6)$$

in which:

- σ : the radar target cross-section in m^2 ,
- d : the distance from the radar to the target in km, and
- f : the frequency of the system in MHz.

The radar target cross-section of an object is the ratio of the total isotropically equivalent scattered power to the incident power density.

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RECOMMENDATION 341-1

THE CONCEPT OF TRANSMISSION LOSS FOR RADIO LINKS *

(1959-1982)

The CCIR,

CONSIDERING

- (a) that in a radio link between a transmitter and a receiver, the ratio between the power supplied by the transmitter and the power available at the receiver input depends on several factors such as the losses in the antennas or in the transmission feed lines, the attenuation due to the propagation mechanisms, the losses due to faulty adjustment of the impedances or polarization, etc.;
- (b) that it is desirable to standardize the terminology and notations employed to characterize transmission loss and its components;
- (c) that Recommendation 525 provides the free-space reference conditions for propagation,

UNANIMOUSLY RECOMMENDS

that, to describe the characteristics of a radio link involving a transmitter, a receiver, their antennas, the associated circuits and the propagation medium, the following terms, definitions and notations should be employed:

1. Total loss (of a radio link) ** (symbols: L_l or A_l)

The ratio, usually expressed in decibels, between the power supplied by the transmitter of a radio link and the power supplied to the corresponding receiver in real installation, propagation and operational conditions.

Note. — It is necessary to specify in each case the points at which the power supplied by the transmitter and the power supplied to the receiver are determined, for example:

- before or after the radio frequency filters or multiplexers that may be employed at the sending or the receiving end,
- at the input or at the output of the transmitting and receiving antennas feed lines.

* Throughout this Recommendation, capital letters are used to denote the ratios, expressed in decibels, of the corresponding quantities designated with lower-case type, e.g. $P_l = 10 \log p_l$. P_l is the input power to the transmitting antenna, expressed in decibels relative to 1 W when p_l is the input power in watts.

** A graphical depiction of this and subsequent definitions is shown in Fig. 1.

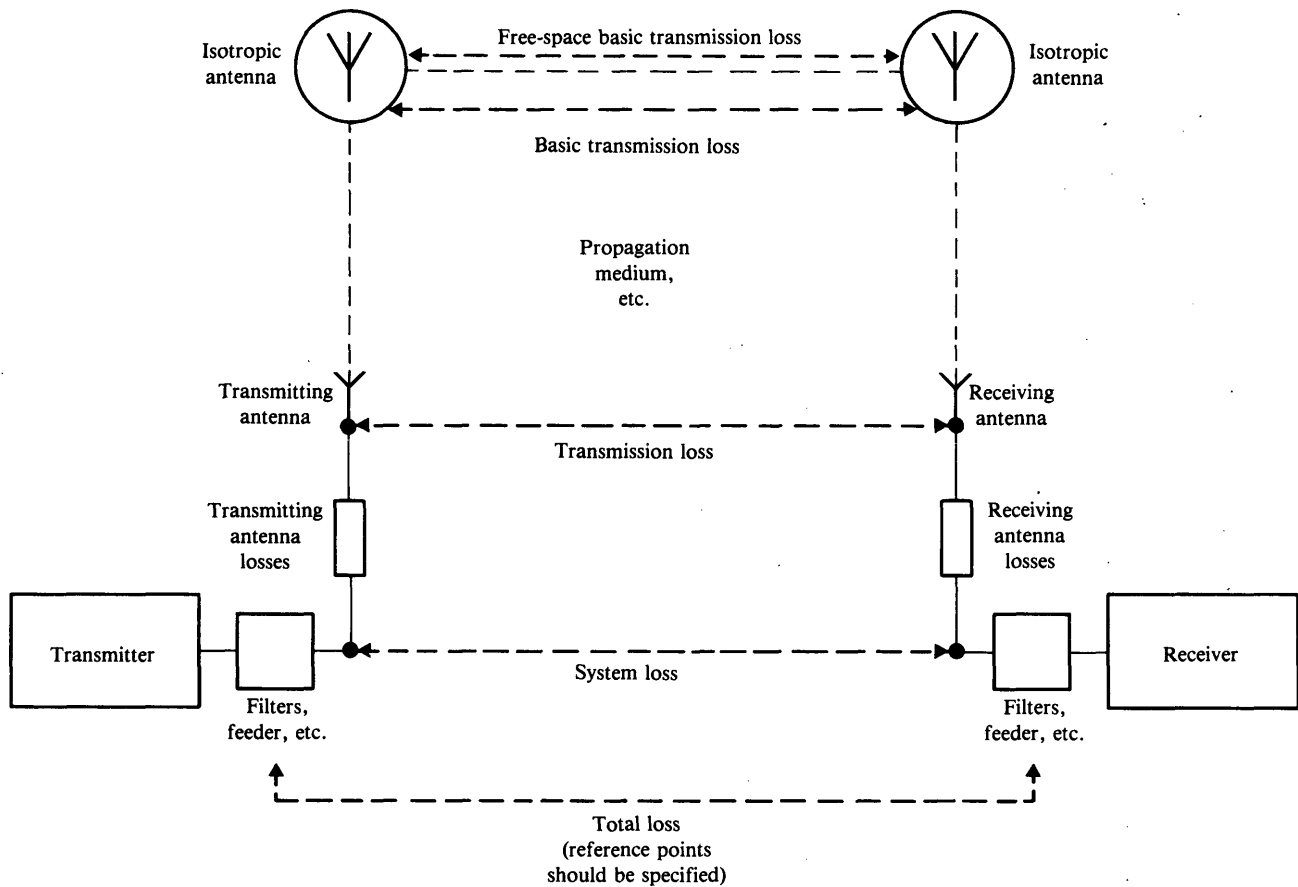


FIGURE 1 – Graphical depiction of terms used in the transmission loss concept

2. System loss (symbols: L_s or A_s)

The ratio, usually expressed in decibels, of the radio frequency power input to the terminals of the transmitting antenna, p_t , and the resultant radio frequency signal power available at the terminals of the receiving antenna, p_a .

Note 1. – The available power is the power which would be delivered to the load if the impedances were conjugately matched.

Note 2. – The system loss may be expressed by:

$$L_s = 10 \log (p_t/p_a) = P_t - P_a \quad \text{dB} \quad (1)$$

Note 3. – The system loss, as defined above, excludes any transmitting or receiving antenna transmission line losses. On the other hand, the system loss includes all of the losses in the transmitting and receiving antenna circuits, including not only the transmission loss due to radiation from the transmitting antenna and re-radiation from the receiving antenna, but also any ground losses, dielectric losses, antenna loading coil losses, terminating resistor losses in antennas, etc.

3. Transmission loss (of a radio link) (symbols: L or A)

The ratio, usually expressed in decibels, for a radio link between the power radiated by the transmitting antenna and the power that would be available at the receiving antenna output if there were no loss in the radio frequency circuits, it being assumed that the antenna radiation diagrams are retained.

Note. – The transmission loss may be expressed by:

$$L = L_s - L_{tc} - L_{rc} \quad \text{dB} \quad (2)$$

where L_{tc} and L_{rc} are the losses, expressed in decibels, in the transmitting and receiving antennas circuits respectively, excluding the dissipation associated with the antennas radiation, i.e., the definitions of L_{tc} and L_{rc} are $10 \log (r'/r)$, where r' is the resistive component of the antenna circuit and r is the radiation resistance.

4. Basic transmission loss (of a radio link) (symbols: L_b or A_i)

The transmission loss that would occur if the antennas were replaced by isotropic antennas with the same polarization as the real antennas, the propagation path being retained, but the effects of obstacles close to the antennas being disregarded.

Note 1. — The basic transmission loss is equal to the ratio of the equivalent isotropically radiated power of the transmitter system to the power, available from an isotropic receiving antenna.

Note 2. — Any local features, such as the ground or nearby structures (e.g. the vehicle itself in the case of mobile terminals) which affect the power gain and directivity of the antenna, but which do not affect the overall propagation path, are assumed to be removed.

The effect of the local ground is included in computing the antenna gain, but not in L_b . For instance, in the case of ionospheric propagation using an antenna near the ground, which has a strong influence on the effective gain for the sky-wave path, the ground is removed for the calculation of L_b , so as to maintain the gain in the desired direction; but in the case of a tropospheric link involving diffraction over a distant obstacle, that obstacle is not removed in estimating L_b .

5. Free-space basic transmission loss (symbols: L_{bf} or A_0)

The transmission loss that would occur if the antennas were replaced by isotropic antennas located in a perfectly dielectric, homogeneous, isotropic and unlimited environment, the distance between the antennas being retained.

Note. — If the distance d between the antennas is much greater than the wavelength λ , the free-space attenuation in decibels will be:

$$L_{bf} = 20 \log \left(\frac{4\pi d}{\lambda} \right) \quad \text{dB} \quad (3)$$

6. Ray path transmission loss (symbols: L_t or A_t)

The transmission loss for a particular ray propagation path, taking account of the transmitting and receiving antenna gains in the ray path directions.

Note. — The ray path transmission loss may be expressed by:

$$L_t = L_b - G_t - G_r \quad \text{dB} \quad (4)$$

where G_t and G_r are the plane-wave directive gains (see Annex I) of the transmitting and receiving antennas for the directions of propagation and polarization considered.

7. Loss relative to free space (symbols: L_m or A_m)

The difference between the basic transmission loss and the free-space basic transmission loss, expressed in decibels.

Note 1. — The loss relative to free space may be expressed by:

$$L_m = L_b - L_{bf} \quad \text{dB} \quad (5)$$

Note 2. — Loss relative to free space (L_m) may be divided into losses of different types, such as:

- *absorption loss* (ionospheric, atmospheric gases or precipitation);
- *effective reflection or scattering loss*, including the results of any focusing or defocusing due to curvature of a reflecting layer, as in the ionospheric case; or loss due to the limited area of the reflecting surface;
- *polarization coupling loss*; this can arise from any polarization mismatch between the antennas for the particular ray path considered;
- *aperture-to-medium coupling loss* or antenna gain degradation, which may be due to the phase front being non-planar at a receiving antenna which may be due to the presence of substantial scatter phenomena on the path;
- *effect of wave interference between the direct ray and rays reflected* from the ground, other obstacles or atmospheric layers at locations distant from the antennas, when such rays are important with the antennas being used in the system.

ANNEX I

1. Directivity

When converting transmission loss, or, in specific cases, ray path transmission loss to basic transmission loss the plane wave directivities * for the transmitting and receiving antennas at the particular direction and polarization must be taken into account. In cases where the performance of the antenna is influenced by the presence of local ground or other obstacles (which do not affect the path) the directivity is the value obtained with the antenna *in situ*.

In the particular case of ground wave propagation with antennas located on or near the ground, although the directivity of the receiving antenna G_r is determined by the above definition, the aperture for signal capture, and hence the available power, is reduced below its free-space value. Thus the value to be used for G_r must be reduced (see Report 878).

2. Reference standard antennas

In the study of propagation over radio links in different frequency bands, a number of reference antennas are used and referred to in CCIR texts. According to Recommendation 311 this reference should be clearly defined in each case with respect to an isotropic antenna.

Nevertheless a number of reference antennas are defined and a distinction may be made between:

- the isotropic or absolute gain ** (G_i) when the standard antenna is an isotropic antenna isolated in space;
- the gain ** in relation to a half-wave dipole (G_d) when the standard antenna is a half-wave dipole isolated in space, the equatorial plane of which contains the given direction;
- the gain ** in relation to a short vertical antenna (G_v) when the standard antenna is a linear conductor much shorter than the quarter wavelength normally found on the surface of a perfectly conducting plane containing the direction concerned.

Table I gives the directivity G_r for some typical reference antennas. The corresponding values of the cymomotive force are also shown for a radiated power of 1 kW.

TABLE I - Directivity for typical reference antennas and its relation to cymomotive force

Reference antenna	g_r	$G_r^{(1)}$ (dB)	Cymomotive force for a radiated power of 1 kW (V)
Isotropic in free space	1	0	173
Hertzian dipole in free space	1.5	1.75	212
Half-wave dipole in free space	1.65	2.15	222
Hertzian dipole, or a short vertical monopole on a perfectly conducting ground ⁽²⁾	3	4.8	300
Quarter wave monopole on a perfectly conducting ground	3.3	5.2	314

(1) $G_r = 10 \log g_r$

The values of G_r (g_r) equal the values of G_r (g_r) for antennas in free space. See Report 878 for values of G_r for antennas on a perfectly conducting ground.

(2) In the case of the hertzian dipole, it is assumed that the antenna is near a perfectly conducting ground.

* Directivity in a given direction is defined as the ratio of the intensity of radiation (the power per unit solid angle (steradian)), in that direction, to the radiation intensity averaged over all directions.

** The gain in these cases is the power gain which corresponds to the maximum directivity for lossless antennas. The power gain is defined as:

The ratio, generally expressed in decibels, between the power required at the input of a standard antenna without losses and the power supplied to the input of the antenna concerned to ensure that both antennas produce in a given direction the same field strength or the same power flux-density at the same distance. In the absence of information to the contrary, it is the gain of the antenna in the direction of maximum radiation. If necessary, the gain for a specified polarization may be considered.

RECOMMENDATION 311-4

PRESENTATION OF DATA IN STUDIES
OF TROPOSPHERIC-WAVE PROPAGATION

(1953-1956-1959-1970-1974-1978-1982)

The CCIR,

CONSIDERING

that to facilitate the comparison of results, it is desirable that administrations and operating agencies should present propagation data in a uniform manner,

UNANIMOUSLY RECOMMENDS

1. that the field strengths or transmission losses exceeded for 0.001%, 0.01%, 0.1%, 1%, 5%, 10%, 50%, 90%, 95%, 99%, 99.9%, 99.99% and 99.999% of the overall time should, whenever possible, be determined for all locations at which measurements are made;
2. that for broadcasting and mobile services, the median values of field strength or transmission loss exceeded at 10%, 50% and 90% of the locations should be determined;
3. that it is desirable to amplify these overall statistics by a more detailed and precise analysis; for this purpose, the methods proposed in Annex I of the present Recommendation might be taken as a basis;
4. that, since log-normal distributions are most frequently encountered in propagation data *, the statistical results of field-strength or transmission loss measurements should be displayed on probability paper. The field strength should be plotted along the ordinate and expressed in dB(μ V/m), the values of field strength increasing, moving up the ordinate. The percentage of total valid recording time, or percentage of locations should be plotted along the abscissa;
5. that all measured values should be referred to a standard which is clearly defined in each case with respect to an isotropic source;
6. that, for sound and television broadcasting, wherever possible, all measurements should be referred to a receiving antenna at a standard height of 10 m above the ground and this antenna should not be highly directional in the vertical plane.

Note. — Methods of field-strength measurements particularly suitable for broadcasting and mobile services are described in Reports 227 and 228.

ANNEX I

It should be noted that the recommendations given above refer particularly to the propagation of waves over long distances (especially in connection with interference problems) and also to propagation characteristics within the operational distances of point-to-point links or within the service areas of broadcasting stations or stations in the mobile service. While the first interest lies in ascertaining those values of field strength exceeded for various percentages of the overall time at varying distances, for a more detailed analysis it might, however, be useful to analyse measurements within unit periods of 1 hour. This latter procedure would permit studies to be made of diurnal variations, while similarly seasonal variations could conveniently be studied by grouping the values obtained at specified hours of the day for a whole month and examining the change of field-strength distributions from month to month. Report 723 presents a procedure for estimating worst-month statistics. Presentation of the results in this form would, moreover, permit later correlation of radio measurements with meteorological data.

For the study of propagation over fixed line-of-sight links in the VHF (metric), UHF (decimetric) or SHF (centimetric) bands, a more precise correlation between received field-strength and prevailing atmospheric conditions might be required. For this and other reasons it is considered that results should be capable of being presented separately for each hour of the day of each month during which tests are being conducted. At the same time, overall distribution curves for periods of one month will be required to permit a study of seasonal variations; overall distribution curves for even longer periods will also, no doubt, be required by the planning engineer. It is generally convenient to refer results to the free space value for the distance and other conditions concerned.

* Except situations of rapid fading which may require more detailed studies, depending on the type of service, e.g. point-to-point transmissions carrying multiplexed voice or data communication channels.

Although it will usually be necessary to preserve, for reference, the original recordings of the field-strength variations, it is essential that some much simpler and more conveniently accessible means of displaying the essential data be employed. One method is to plot the maximum, median and minimum field strengths for each hour on linear graph paper, the spread of results within the hour being shown by a vertical line. In addition, by determining the hourly median value or the value over some other percentage of the time, it is possible to obtain, for any given hour of the day, the statistical distribution of these values for a month (or any other desired period of time).

REPORT 227-3 *

**GENERAL METHODS OF MEASURING THE FIELD STRENGTH
AND RELATED PARAMETERS**

(Question 7/5)

(1959-1963-1974-1978-1982)

1. Introduction

This Report is concerned with general methods of measuring radio field strength and related quantities such as power-flux density, power available at the terminals or output port of a receiving antenna, and power radiated from a transmitting antenna. General formulae for calculating the relationships between these quantities are given in Recommendation 525.

2. Purposes of measurements

Measurements of these quantities are generally made for one or more of several purposes:

- 2.1 To determine the adequacy of the radio signal strength for a given service.
- 2.2 To determine the interfering effects of an intentional radio emission (electromagnetic compatibility).
- 2.3 To check the strength and interfering effects of unintentional emissions of any wave shape from equipment which produces electromagnetic energy, and to assess the effectiveness of devices for suppressing such emissions.

3. Measurement of radio wave characteristics

Measurements should be made to determine the amplitude, the polarization, and sometimes the phase of the radio wave. Amplitude measurements are necessary in order to determine the absolute value of the received energy, or the attenuation loss of the wave energy in propagating from the transmitting antenna to the receiving antenna. Polarization needs to be determined in order to specify the optimum orientation of the receiving antenna relative to the surface of the Earth. For example, when the electric vector of the radio wave is parallel to the surface of the Earth (horizontal polarization) a dipole antenna to have optimum orientation must be placed in the horizontal position. Measurements of phase or relative phase of the radio wave becomes important for objectives such as distance measurements at lower frequencies and diversity receiving systems at higher frequencies (see § 6.1 for antennas).

3.1 Units of measurement

The standard unit of field-strength measurement is volts per metre, (V/m), or decimal multiples or submultiples thereof. This unit refers of course to the electric-field component of the electromagnetic field. In empty space or at points remote from discontinuities of the propagation medium, the magnetic field strength can be calculated if the electric field strength is known, but this cannot be done in the vicinity of conducting or reflecting objects. At frequencies above 1 GHz and at lower frequencies occasionally, it is possible to make the measurements under quasi-free-space conditions that allow this calculation to be made with reasonable accuracy. Also, under such conditions, the power flux-density can be calculated. Conversely, it is then possible to measure the power flux-density (W/m^2) or the magnetic field strength (A/m) and to calculate the other two quantities.

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

3.2 *Transmission loss*

The concept of transmission loss is sometimes used to express the results of field-strength measurements when the emphasis is on the wave-propagation aspects of the communication system [Norton, 1941, 1965]. For a fixed or point-to-point system, the transmission loss (usually expressed in decibels) is the ratio of the power input to the transmitting antenna to the power output of the receiving antenna with CW transmission, or alternatively, the ratio of the instantaneous values at appropriately separated times so that the ratio is taken for corresponding points on the signal waveform. Formulae for transmission loss are given in Recommendation 341.

4. **Polarization**

It is important to make a field-strength measurement using a receiving-antenna polarization that matches that of the communications system to which the measurements pertain, if the measurement does pertain to the performance of a particular system. Some wave-propagation phenomena can cause a change in the polarization characteristics of a received signal relative to the polarization that was transmitted, and it may sometimes be desirable or necessary to measure two orthogonal components e.g., horizontal and vertical, of the received wave. Changes in polarization can result from Faraday rotation in the ionosphere (significant at frequencies below about 1 GHz), from reflection by solid objects (hills, buildings), from earth reflection (because the reflection coefficient of earth and water is in general polarization-sensitive), and from atmospheric scattering by refractive-index irregularities (significant at frequencies above 100 MHz).

When these effects occur, the ratio of field strength for the two orthogonal polarizations, as well as their root-mean-square value, may vary with both the time and the position of the measurement. Therefore it is essential in such cases to obtain measurements over a sufficient range of times and positions to permit obtaining a satisfactory average and other appropriate statistics, readily achievable with current data processing equipment.

Since circularly-polarized signals normally change rotational sense when reflected, and because a circularly-polarized receiving antenna is receptive only to circularly-polarized signals of the same rotational sense, reflected signals are strongly attenuated where both transmitting and receiving antennas are circularly polarized in the same rotational sense. Care must be exercised to take this factor into account when making measurements involving reflected circularly-polarized emissions.

5. **Typical measurements**

For continuous wave signals, the type of measurement made (average, peak, etc.), is relatively unimportant. However, with complex waveforms, the indicated value of the field strength or available power will be influenced by the characteristics of the measuring instrument, i.e. its detector characteristics, bandwidth, dynamic range, integration time, etc. Thus, the equipment must be capable of making the measurement that is suitable for the evaluation of the type of waveform that is present. With a coherent signal of known waveform, one parameter is usually sufficient; but with an incoherent signal such as atmospheric noise, two or more parameters are often necessary for an adequate description.

If the bandwidth of the measuring instrument is smaller than the bandwidth of the signal being measured, the result will be erroneous unless correction is made. For example, if the "signal" is wide-spectrum noise of uniform spectral density (quasi-white noise), the electric intensity measurement will be proportional to the square root of the instrument bandwidth and power measurement will be linearly proportional to the bandwidth. The results should then be reported in terms of $V/(m \cdot Hz^{1/2})$, or $W/(m^2 \cdot Hz)$. See also § 6.6.

5.1 *Measurement of average value*

The average value of a signal is given by the receiver, when the circuit following a linear envelope detector is designed to average the detector output voltage over a time interval long enough for rapid variations to be imperceptible. The average value is generally preferred for many modulated emissions, including amplitude- and frequency-modulated telephony (A3E and F3E). It is also used for on-off keyed telegraphy (A1A, A1B or A2A, A2B), where the key-down position can be maintained during measurement. It may also be used to measure the peak value on signals having a high duty factor for pulses at the peak value, such as television visual emissions with positive synchronizing signals. The peak value will, of course, be derived from the average value by the addition of a predetermined correction factor. It is also used as one of the parameters in evaluating atmospheric noise and other interference phenomena.

5.2 Measurement of peak value

The peak value of a signal is given by the receiver, when the detector circuit is designed to give an output corresponding to the maximum instantaneous voltage of the signal.

Peak measurements are particularly suitable for low duty-cycle signals, including impulsive interference, but are often subject to greater fluctuations than the quasi-peak or average values. If the bandwidth of the signal to be measured is greater than that of the field-strength set, then peak value of the emission, as measured by the detector, is affected. While measurements made at one bandwidth can be corrected to another bandwidth for certain simple types of emission, this is not the typical situation and bandwidth standardization for the sets is necessary if comparisons are to be made. Under such conditions, the bandwidth of the field-strength set should be stated. Similar bandwidth considerations may apply as in quasi-peak measurements, and reference should be made to Table I in § 5.3 for standard bandwidths.

5.3 Quasi-peak measurement

The quasi-peak value is that measured when the detector output is weighted by adjustment of its charge and discharge time constants T_c and T_d and the mechanical time constant of the indicating meter T_m . Because of its convenience, the quasi-peak value is generally used for types of emission which are keyed or pulsed, or for which the average value varies with modulation level. It is generally appropriate for impulsive interference measurements and, if the charge and discharge time constants are suitably chosen, quasi-peak measurements can provide a direct indication of the audible effect produced by interfering signals of any shape on modulated transmissions such as telephony.

As regards bandwidth, similar considerations to those of peak measurements apply, and care must be used in selecting both the bandwidth and the charge and discharge time constants to suit the type of emission being measured and to prevent overloading the set. Only a few sets of standard constants have been recognized by qualified organizations, and these are listed in Table I.

TABLE I

Frequency range (MHz)	Bandwidth at 6 dB down (kHz)	Charge time constant T_c (s)	Discharge time constant T_d (s)	Mechanical time constant T_m (s)
0.015–0.15	Variable (0.08–0.8) ⁽²⁾	0.001 ⁽²⁾	0.600 ⁽²⁾	0.160 ⁽¹⁾
0.15–30	9 ⁽¹⁾	0.001 ⁽²⁾	0.160 ⁽³⁾	
25–300	Variable (1–12) ⁽²⁾	0.001 ⁽²⁾	0.600 ⁽²⁾	0.1 ⁽¹⁾
	120 ⁽¹⁾		0.550 ⁽¹⁾	
	150 ⁽²⁾		0.600 ⁽²⁾	

⁽¹⁾ CISPR [CISPR].

⁽²⁾ ASA [ASA a].

⁽³⁾ Used by both the above organizations.

5.4 R.m.s. voltage

The r.m.s. voltage [URSI] is measured by means of a thermo-couple or electronic squaring circuit in conjunction with a suitable averaging circuit. It provides a direct measurement of the average power received in the bandwidth of the measuring instrument. For emissions with a uniform frequency spectrum, the r.m.s. voltage is proportional to the square root of the bandwidth (the average power is proportional to the bandwidth). The r.m.s. value is suitable for the measurement of many types of broadband phenomena, but is particularly useful in the measurement of atmospheric noise. Since the squared values have a wider range of fluctuation than the original phenomenon, a wider dynamic range and longer time constant are required. With atmospherics, a time constant of 500 s has been found satisfactory.

5.5 Average logarithm

The average logarithm is obtained by inserting a logarithmic amplifier between the detector and the averaging circuit. This type of measurement, in conjunction with measurements of the average and r.m.s. values, provides information on the character or interference potential of noise. For atmospheric noise, these three parameters provide a means of determining the complete amplitude-probability distribution [Crichlow and Spaulding, 1958; URSI].

5.6 Statistical measurement

It is frequently of interest to determine the statistical variations of field strength with time, by considering the variation of the instantaneous values, or the variations of the average value of any of the above parameters. The latter can be measured by means of time totalizers with several pre-set thresholds, so that the total time above each threshold is indicated on counters. These counters are read at the end of any desired period of time.

When the variations of the instantaneous values are of interest, counting circuits are used that will respond to the instantaneous IF or detector output. By means of suitable gating and threshold circuits, the amplitude-probability distribution of these values can be obtained. The complete amplitude-probability distribution has been found useful in evaluating the interference, particularly that of atmospheric noise, to the reception of various types of signal [Watt *et al.*, 1959].

5.7 Measurements relative to emission types

Table II is a summary of suggested measurements for various emissions, as classified in the Radio Regulations.

When the radiated power is wholly or largely independent of the degree of modulation, it should suffice, for most field-strength measurements, to specify the unmodulated carrier power. However, when the radiated power is largely dependent on the degree of modulation, it appears desirable, for high precision field-strength measurements, for the two terminals to cooperate, either by recording the transmitter output power with an instrument having characteristics similar to those of the field-strength recorder, or by the transmission of special signals.

TABLE II

Type of emission	Parameter measured (see § 8)
NON, A2A, A2B, A3E, A3C, A9W NON, F1B, F2B, F3E, F3C, F3F, F8W ⁽¹⁾ A1A, A1B (key down) C3F (negative sync.) ⁽²⁾	Average
A1A, A1B, R3E, B8E, R9X C3F (positive sync.) PON and other pulsed emissions	Quasi-peak Quasi-peak or peak

⁽¹⁾ Care must be exercised that the bandwidth of the field-strength meter is adequate to pass the FM emissions.

⁽²⁾ It is usual to define the field strength of a negative sync. television signal as the peak-white value. This can be derived from the average value, if the waveform being radiated at the time the measurement is made is known.

6. Equipment considerations relative to signal characteristics

The nature of field-strength measuring equipment varies greatly depending on:

- the power or field-strength level of the field being measured;
- the signal waveform — e.g., CW, pulse, wideband noise, or complex modulation;
- the frequency region.

Simpler equipment is naturally adequate at high field-strength levels, with the CW waveform, and at low frequencies. The most complex equipment, conversely, is needed for measurement of low-intensity fields, complex waveforms (especially if the field strength fluctuates temporarily and spatially), and at microwave or millimetre-wave frequencies.

6.1 *Antennas used for measurement*

The measurement of field strength may be made with any kind of receiving antenna, but it is common practice to use either a loop or a short dipole antenna at frequencies below about 30 MHz. (The "dipole" may be in the form of a monopole, which operates in conjunction with a ground plane.) "Short" here means relative to a half wavelength. At frequencies above 30 MHz, but below about 300 MHz, half-wave dipoles (sometimes with addition of supplementary elements) are used. At still higher frequencies, waveguide horns and various optical types of antennas (parabolic reflectors and lenses) are used. In principle, any antenna can be used if its pattern characteristics and power gain are known.

In applications that involve a communication system,* it is often advantageous to utilize the receiving antenna of the actual system under test. The result of measuring the available power at the terminals or output port of that antenna will often provide a more directly useful result than would be provided by use of a simple standard antenna. This is especially true when the received field varies spatially in so complex a manner that it makes it difficult to calculate the actual system performance by means of field-strength measurements made with another antenna, especially one of much simpler form, such as a loop, a dipole, or a small horn.

The virtue of the small simple antenna types lies in their relevant receiving properties which can be calculated quite accurately from theoretical expressions; these properties may be expressed as effective length (of a short dipole), effective area, power gain, and pattern function. If the actual system antenna is used for the measurements, its equivalent properties at the operating frequency should be determined and reported, utilizing standard definitions and equations, along with the measured signal power data [IEEE, 1973; Jasik, 1961].

6.2 *High field strengths*

The field strength to be measured can range from levels of the order of a microvolt per metre or less to levels of several volts per metre in the service area of the transmitter. For the higher levels, the measuring equipment at low and intermediate frequencies (below about 30 MHz) can consist simply of a short-dipole antenna with a simple RF voltmeter except in the near field where the polarization is undefined. At frequencies in the microwave or higher regions where dipole lengths may be too short for connection to simple meters, it is more feasible to employ a horn antenna and to measure the power delivered to a matched load. RF wattmeters suitable for this purpose are commercially available.

6.3 *Very low field strengths*

At low power levels such as those encountered at great distance from the radiating source, it is generally necessary to employ amplifying equipment which is essentially a "radio receiver" such as would be used in a communication system, except that the equipment must have performance characteristics that are stable and calibrated, with provision for metering the output level.

6.4 *Pulse waveforms*

When the field to be measured has a pulse waveform, the measurement process can consist of comparing the amplitude of received pulses, as viewed on an oscilloscope display, with slightly time-displaced pulses from a standard (calibrated) signal generator. The pulses from the signal generator are coupled into the receiver input transmission line via a directional coupler whose effect on the signal to be measured is negligible. The output attenuator of the signal generator is adjusted until the two pulses are of visually equal amplitude, and the power level of the signal being measured can then be calculated by allowing for the coupling factor of the directional coupler and the setting of the attenuator. By this method, the calibration of a signal generator replaces the need for a calibrated receiver and output meter. It is necessary in this method to make sure that the signal generator pulse has the same waveform (and hence the same bandwidth) as the pulse being measured, and that the receiver amplification does not vary in the time interval separating the two pulses. The latter requirement can be readily checked by varying the time positioning of the signal generator pulse relative to the pulse being measured.

* The term "communication system" is used here and elsewhere in this Report to mean any application of radio wave propagation that results in transmission of information between remote points, including radar.

6.5 *Complex waveforms*

When the signal modulation is complex, as in television or voice communication, the bandwidth of the measuring equipment must be sufficient to pass all of the significant sidebands of the signal. If the modulation is of such a nature that it can be considered to be time-stationary in the stochastic sense, a significant measurement can be obtained by averaging the measured signal level over a sufficient period of time. The required averaging time can be determined by comparing the results of successive averages for acceptable agreement. If the transmitting source is cooperative, the measurement can be made with the modulation off, so that a CW signal is transmitted, or with some known "standard" modulation. If such control is not possible, it may be desirable to measure not only the average level but also additional parameters such as the variance and possibly the full statistical distribution. For such purposes, a data system is desirable such that successive sample measurements over a period of time are recorded digitally on a magnetic tape in a computer-compatible format. The data thus recorded can then be processed by standard techniques to obtain the desired statistical information.

6.6 *Broad band noise*

If the signal to be measured is noise-like, the bandwidth may exceed that of the measuring equipment. In that case, the signal power density is reported in terms of spectral as well as spatial terms — e.g. $W/(m^2 \cdot Hz)$. If the noise is white or quasi-white, a measurement at the frequency of interest will suffice. In cases where the spectral characteristic of the noise is of interest, measurement over a range of frequencies within the total noise spectrum should be made, with a receiver bandwidth that is small relative to the spectral variation, but yet large enough to permit measurement of the noise level. As in the case of complex waveforms, it may be desirable or necessary to obtain a sequence of time samples at appropriate intervals and over a sufficient time span to permit determination of the statistical parameters. As noted previously, digital recording on magnetic tape to permit computer analysis is highly desirable (see Report 413 (Kyoto, 1978) and Report 670).

6.7 *Correction for noise in measuring equipment*

When extremely low-level signals are being measured, so that very high amplification is necessary, there will be unavoidably present additional receiver output from internal noise and from external radiating sources other than the source of interest. It is then necessary to make the measurement in such a way that correction can be made for the effects of these unwanted noise sources. This can be done in different ways, depending partly on the nature of the signal being measured.

If the signal being measured is noise of the same statistical and spectral characteristics as the normal receiver noise (thermal noise of Gaussian distribution and uniform spectral density within the receiver passband), then the incremental output of the receiver, when the noise signal under measurement is present, is a direct measure of its power level. In other words, if P_0 is the receiver noise power reading with the desired signal off (or with a highly directional receiving antenna pointed away from the source of the noise being measured), and if P_1 is the reading when the signal is "on", then of course the power due to the signal alone is $P_s = P_1 - P_0$.

The surface of the Earth both emits and reflects thermal radiation. At microwave frequencies this reflection may be largely specular (as in the case of water surfaces) or diffuse (vegetation). The source of the reflected thermal radiation may be the Sun, the atmosphere or the background cosmic noise. The spaceborne radiometer (or receiving antenna) receives this radiation through the atmosphere which may attenuate the radiation as well as emit radiation itself, particularly if there are clouds or rain. Consideration of the effects of radio emission associated with absorption by atmospheric gases and precipitation are discussed in Report 720.

If the signal being measured is a sine wave (CW), the same simple arithmetic can be used if P_1 and P_2 are measured before detection* (demodulation, rectification) of the signal, but otherwise this simple formula cannot be used, as a general rule. Pre-detection measurement of power can be made with a sensitive bolometer and a matched load impedance at the receiver intermediate frequency (IF), if sufficient power amplification is available at IF. But if the observing and measuring is done after a linear detector, the measurement and correction can be made using a d.c. voltmeter by properly taking into account the nonlinear characteristic of the detector. The procedure is described in [Blake, 1972].

* The term "detection" unfortunately has more than one meaning, especially in radar. The meaning here is indicated parenthetically. In particular, a linear detector is one that transforms the modulated RF signal into the modulation signal, the "envelope" of the RF cycles. It consists of a linear rectifier followed by a low-pass filter.

If the signal being measured is a pulse, and if the previously described method of comparison to a similar pulse from a calibrated signal generator is used, no correction is necessary because the comparison is being made between two exactly equal signals immersed in exactly equal noise power, assuming stationary quality of the noise to be that which is ordinarily permissible.

7. Calibration of equipment

Calibration of field-strength measuring equipment can be either direct or indirect [IEEE, 1968]. Direct calibration means that the entire measuring system — antenna and measuring device — is immersed in an electromagnetic field of known strength. This method is most appropriate when the antenna is of a complex type such that its characteristics cannot be calculated with confidence, and when the receiving environment is such that the field intensity is not affected significantly by nearby reflecting objects and/or the atmosphere. In particular it is appropriate at microwave or higher frequencies with highly directional antennas that do not “see” nearby objects or the surface of the Earth.

8. Effects of environment on the measurement

Field strength or related quantities measured in the vicinity of the earth's surface will in general be significantly affected by reflections from the surface and from nearby objects such as buildings, trees, power lines, etc. The resulting multipath effect causes the measured field strength to be different — sometimes greater and sometimes less, in a node and null pattern — from the value that would be observed in free space at the same distance from the transmitter. Refraction and rain absorption in the atmosphere can also modify the field strength. Molecular absorption attributable to atmospheric water vapour and oxygen may be experienced during wave propagation through the atmosphere at centimetre or millimetre wavelengths. Absorption lines are centred at frequencies of 22.2 GHz (isolated-H₂O), 60 GHz (band-O₂), 118.8 GHz (isolated-O₂), 183 GHz (isolated-H₂O), and 324 GHz (isolated-H₂O) (see Report 719).

The refractive phenomenon known as ducting can be especially significant under certain atmospheric conditions at frequencies in the VHF region and above (with increasing likelihood as the frequency increases) [Bean and Dutton, 1966]. When the vertical gradient in a layer of the atmosphere is less than -157 N-units/km the radius of curvature of ray paths is less than the radius of the earth. However, the thickness of the atmospheric layer which makes this possible is never more than a few hundred metres and may be as little as a few metres. This part of the atmosphere is called an atmospheric ducting layer. This layer, together with a portion of the layer's underlying standard refractive or sub-refractive atmosphere, constitutes an atmospheric duct. Energy is no longer propagated in accordance with the inverse distance square law, and may be subjected to much less attenuation than that calculated for free space under the same conditions.

8.1 In general, the measurements should be made in a multipath environment similar to that which would be encountered in normal use of the communications system. If the multipath environment is of the unpredictable type, the measurements should be made at a sufficient number of adequately separated locations to permit statistical averaging.

8.2 In the special case of measurements made to determine radiated power of a transmitter or directivity (gain) of an antenna, the measurements should be made in an area as free as possible from multipath effects of the unpredictable type, so that the measurements can be related to the radiated power by use of the appropriate inverse distance formula.

8.3 The effect of overhead wires or cables is detrimental at all frequencies, and if possible the receiving antenna used for measurements should be located at a distance from such overhead objects. In areas of good conductivity this distance should be at least several times the height of the object, and even further in areas of poor conductivity. When a loop or other antenna having a sharp directivity null is being used, the presence of reflection or reradiation from such objects can sometimes be detected from observations of the direction of arrival of signals, or from the fact that the nulls are poorly defined. In measurements whose objective is to investigate nulls in a radiation pattern, caution is necessary because a long power line or communication line may conduct signals into the area that would otherwise be a null area.

8.4 Underground cables can also create disturbing effects at low frequencies, but these effects are not usually observed above a few megahertz. At frequencies below 2 MHz, such cables can be troublesome especially in areas of poor ground conductivity. Fortunately, the observed field caused by such cables is usually the induction field rather than the radiation field, and it therefore decreases very rapidly with increasing distance. Measurements can be made to determine the rate of decrease and thus to estimate the distance required to reduce the effect from the cable to a negligible quantity.

8.5 Even when no wire, cable, or building exists, the presence of the conducting ground itself (soil or water) will cause a variation of field strength with altitude. If a receiving antenna is raised in height from ground level, ordinarily the field strength will increase at first, until a maximum is reached, and thereafter it will vary cyclically with increasing height. A similar situation occurs if the receiving antenna is at a fixed height and the transmitting antenna is raised, beginning at ground level. The detailed law of variation will depend on the frequency, wave polarization, electrical properties of the ground or water, and whether the separation of the transmitting and receiving antennas places the latter in the interference region or the diffraction region. Additional anomalous variation with altitude, and departure from the inverse-distance law, can occur as the result of atmospheric refraction and absorption. The refractive phenomenon known as ducting can be especially significant under certain atmospheric conditions at frequencies in the VHF region and above [Bean and Dutton, 1966].

8.6 Care must be taken with some types of equipment to avoid a disturbing effect caused by the proximity of the operator to the receiving antenna used for the field measurement. This effect is unimportant when the antenna is highly unidirectional if the operator remains out of the "main beam".

8.7 Measurement of fields in forests or dense vegetation presents a number of special problems because of the non-uniform density of the media. Radio waves propagating over many different paths will result in nulls and crests of field strength at unpredictable locations within and near forested environments. Changes in antenna patterns typically will be observed. Care must be taken to measure changes in the antenna impedance after changes in the antenna location or antenna polarization or following a rainfall, because such changes will result in variations in the measured field. Horizontally polarized waves are attenuated less than vertically polarized waves at frequencies less than about 1000 MHz. In general, higher frequencies are attenuated more than lower frequencies when propagating through trees or vegetation. Effects of forested environments are reduced during the winter months in climates where trees and vegetation change with the seasons [Tamir, 1977] (see Report 236).

9. Accuracy of measurements

The accuracy of a field-strength measurement is usually dependent on two separate factors:

- the accuracy of calibration of the actual measurement apparatus (which may consist, for example, of an amplifying "receiver" and demodulator), with an output indicator or digital print-out;
- the accuracy of knowledge of the receiving antenna characteristics.

However, if the complete measuring system (antenna, receiving device, and output meter) is calibrated as a unit by immersing it in a field of known strength, the accuracy then depends only on the accuracy with which this calibrating field is known. The accuracy of that knowledge, in turn, may be affected by the local environment (e.g., proximity of reflecting objects) and, for distant sources, by the absorption and refraction of the atmosphere.

The characteristics of simple antennas, such as short dipoles or monopoles, small loops, resonant dipoles, and waveguide horns, are ordinarily calculable with good accuracy. More complicated antennas must generally have their characteristics determined by measurement. Appropriate calculation formulae and measurement techniques are described in readily available literature [Jasik, 1961; IEEE, 1965]. Simple antennas are more useful at relatively low frequencies (below about 30 MHz) while more complicated types are more often needed at higher frequencies, where the "capture cross section" of simple antennas is inadequate.

The accuracy that can practically be attained in field-strength measurement is generally dependent on:

- the voltage or power level of the field;
- the frequency of the measurement.

The accuracy depends also on whether the field-strength meter calibration was performed by comparison with a national (primary) standard, by comparison with a secondary standard, or by service or production-level standards [IEEE, 1968]. Generally, the attainable accuracy is in the range of 0.3 dB to 3.5 dB, the highest accuracy being obtained with high field strengths at very low frequencies and the lowest with low field strengths at microwave frequencies. The accuracy is limited at low field strengths by the presence of noise, and at high field strengths by the accuracy of attenuators required to prevent exceeding the range of the measurement apparatus.

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SECTION 5B: EFFECTS OF THE GROUND (INCLUDING GROUND-WAVE PROPAGATION)

Recommendations and Reports

RECOMMENDATION 368-4 *

GROUND-WAVE PROPAGATION CURVES FOR FREQUENCIES
BETWEEN 10 kHz AND 30 MHz

(Question 3/5)

(1951-1959-1963-1970-1974-1978-1982)

The CCIR,

CONSIDERING

that, in view of the complexity of the calculation, it is useful to have a set of ground-wave curves for a range of standard frequency values and ground characteristics,

UNANIMOUSLY RECOMMENDS

1. that the curves of Annex I, applied in the conditions specified below, should be used for the determination of ground-wave field strength at frequencies between 10 kHz and 30 MHz;
 2. that, as a general rule, these curves should be used to determine field strength only when it is known that ionospheric reflections will be negligible in amplitude. Ionospheric propagation is treated in Volume VI;
 3. that these curves not be used in those applications for which the receiving antenna is located well above the surface of the Earth;
- Note.* — That is, when $\epsilon_r \ll 60\lambda\sigma$ the curves may be used up to a height $h = 1.2 \sigma^{1/2} \lambda^{3/2}$.
4. that these curves, plotted for homogeneous paths under the conditions established in Annex I, may also be used to determine the field strength over mixed paths as indicated in Annex II.

ANNEX I

CONDITIONS OF VALIDITY (HOMOGENEOUS PATHS)

The propagation curves in this Recommendation are calculated for the following assumptions:

- they refer to smooth homogenous spherical Earth;
- in the troposphere, the refractive index decreases exponentially with height, as described in Recommendation 369;
- both the transmitting and the receiving antennas are at ground level;
- the radiating element is a short vertical monopole. (The equivalent dipole moment is $5\lambda/2\pi$, see Report 714.) Assuming such a vertical antenna to be on the surface of a perfectly conducting plane Earth and excited so as to radiate 1 kW, the field strength at a distance of 1 km would be 300 mV/m; this corresponds to a electromotive force of 300 V (see Recommendation 525);
- the curves are drawn for distances measured around the curved surface of the Earth;
- the curves give the value of the vertical field-strength component of the radiation field, i.e. that which can be effectively measured in the far-field region of the antenna.

Note 1. — The inverse-distance curve A shown in the figures, to which the curves are asymptotic at short distances, passes through the field value of 300 mV/m at a distance of 1 km. To refer the curves to other reference antennas, see Table I of Recommendation 341.

Note 2. — The GRWAVE program and the methods described in Report 714 have been used for these calculations.

Note 3. — These curves can also be used for the rapid evaluation of the induced e.m.f. For details, see [Rašajski and Petrović, 1981].

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* This Recommendation is brought to the attention of Study Groups 8 and 10.

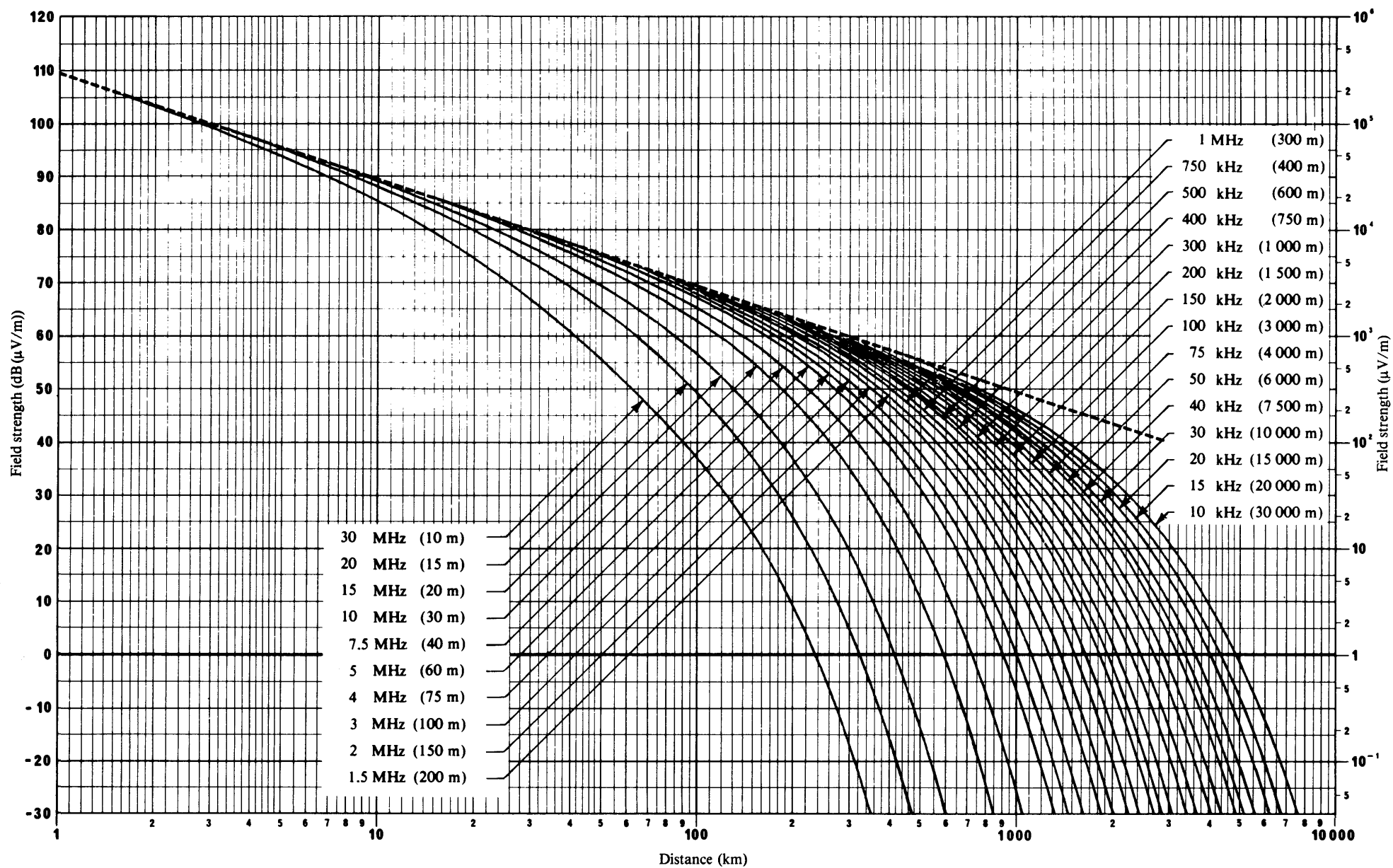


FIGURE 1 – Ground-wave propagation curves; Sea water, average salinity, 20°C, $\sigma = 5$ S/m, $\epsilon = 70$

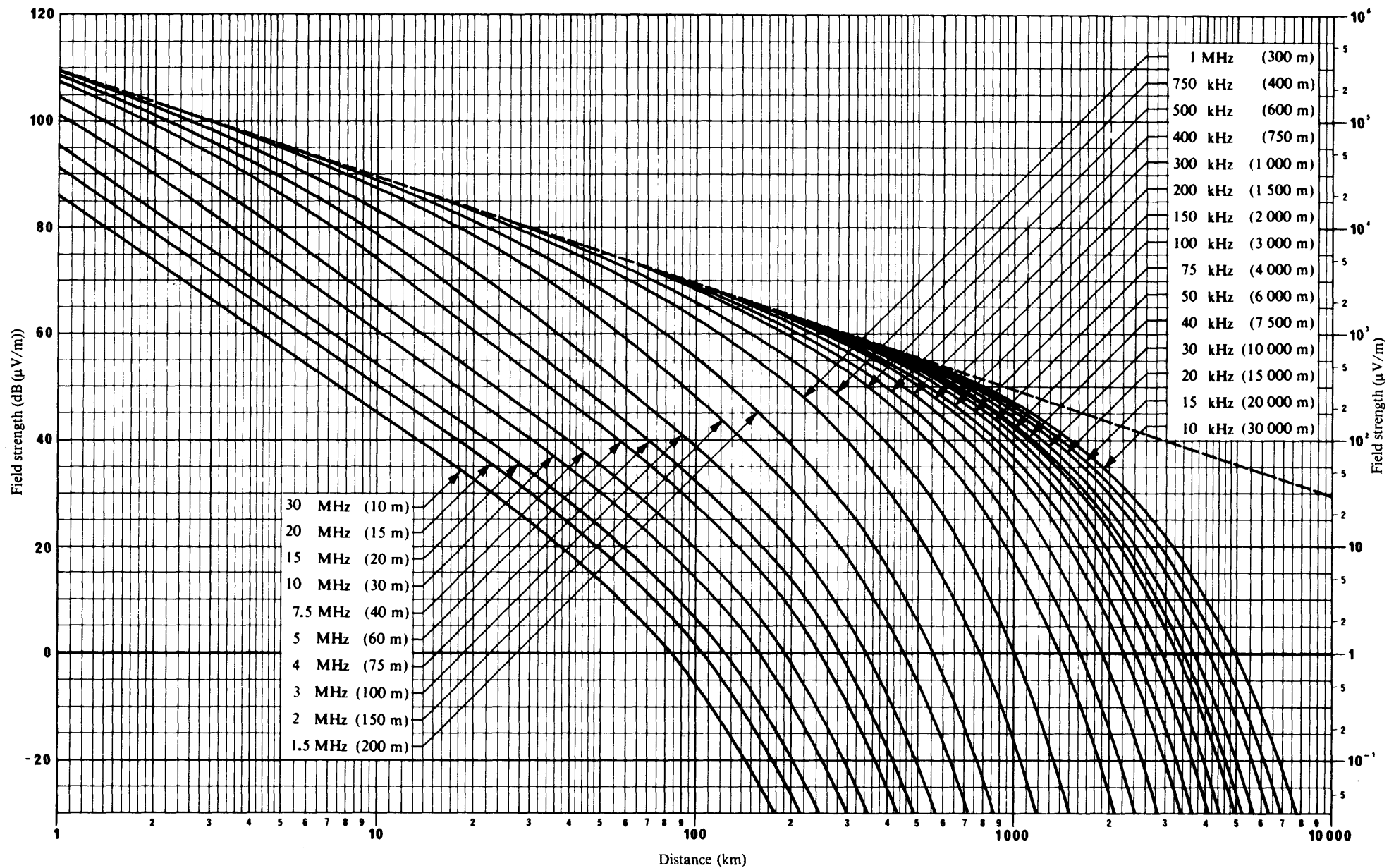


FIGURE 2 - Ground-wave propagation curves; Land, $\sigma = 3 \times 10^{-2} \text{ S/m}$, $\epsilon = 30$

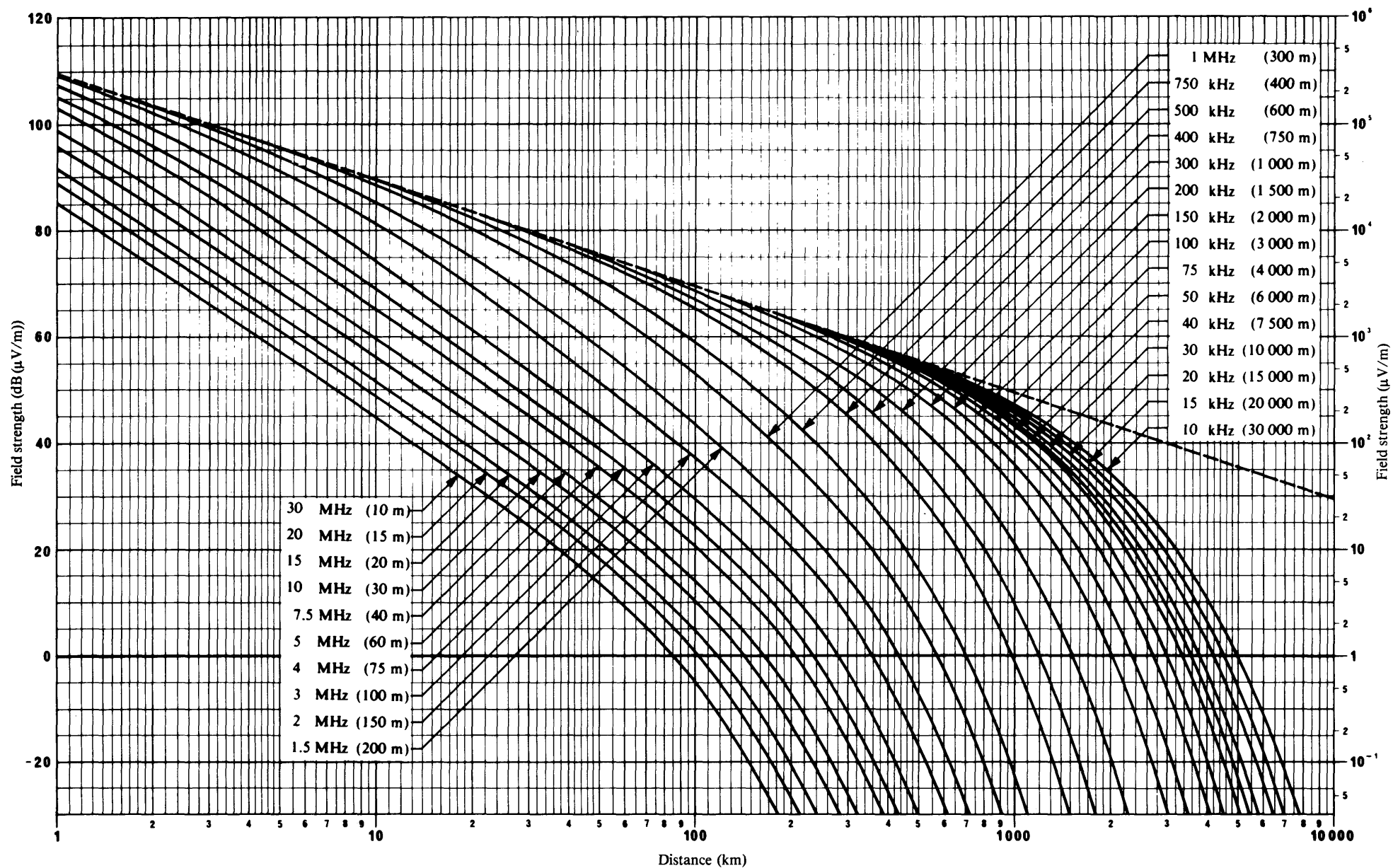


FIGURE 3 - Ground-wave propagation curves; Wet ground $\sigma = 10^{-2}$ S/m, $\epsilon = 30$

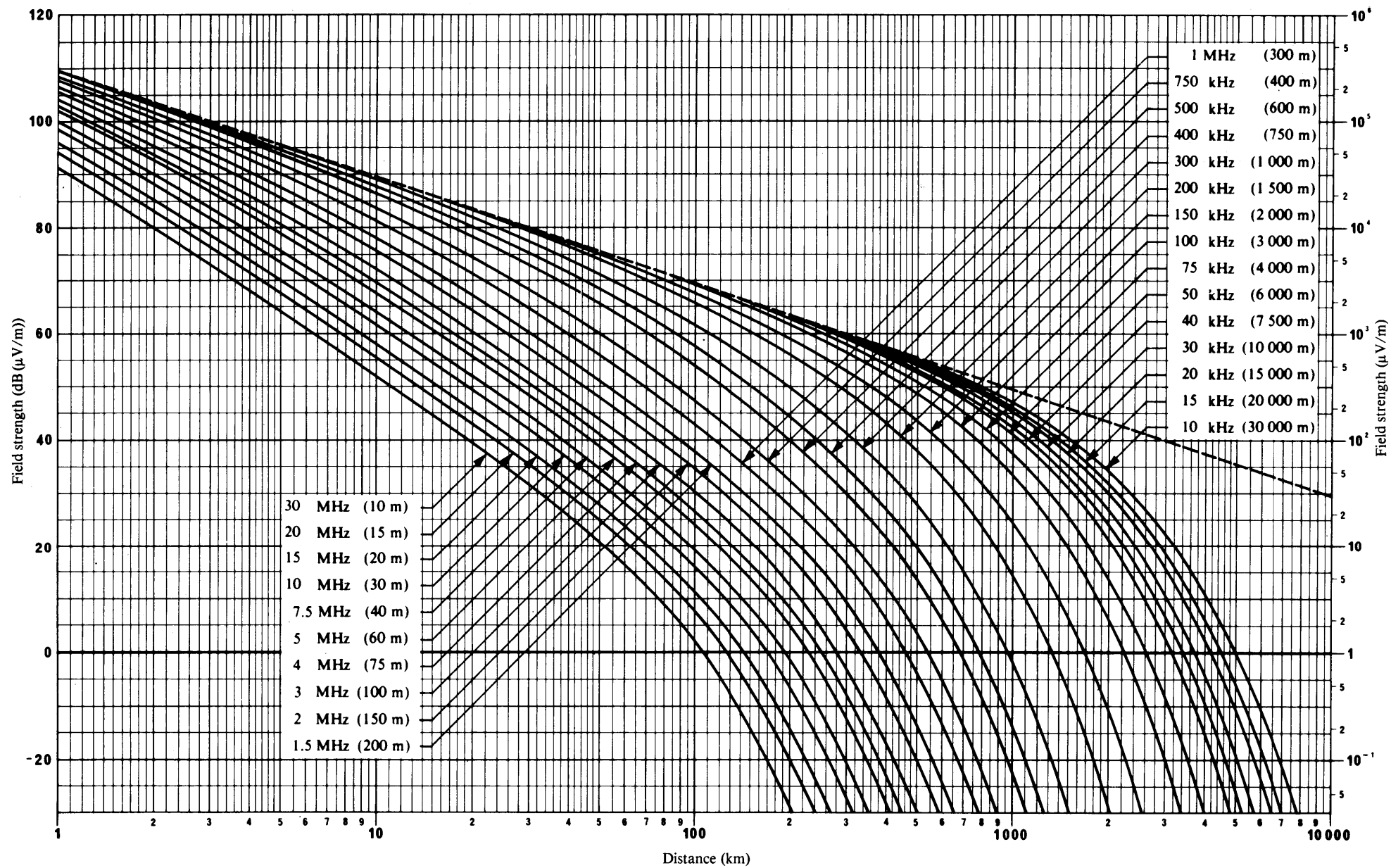


FIGURE 4a - Ground-wave propagation curves; Fresh water, $\sigma = 3 \times 10^{-3} \text{ S/m}$, $\epsilon = 80$

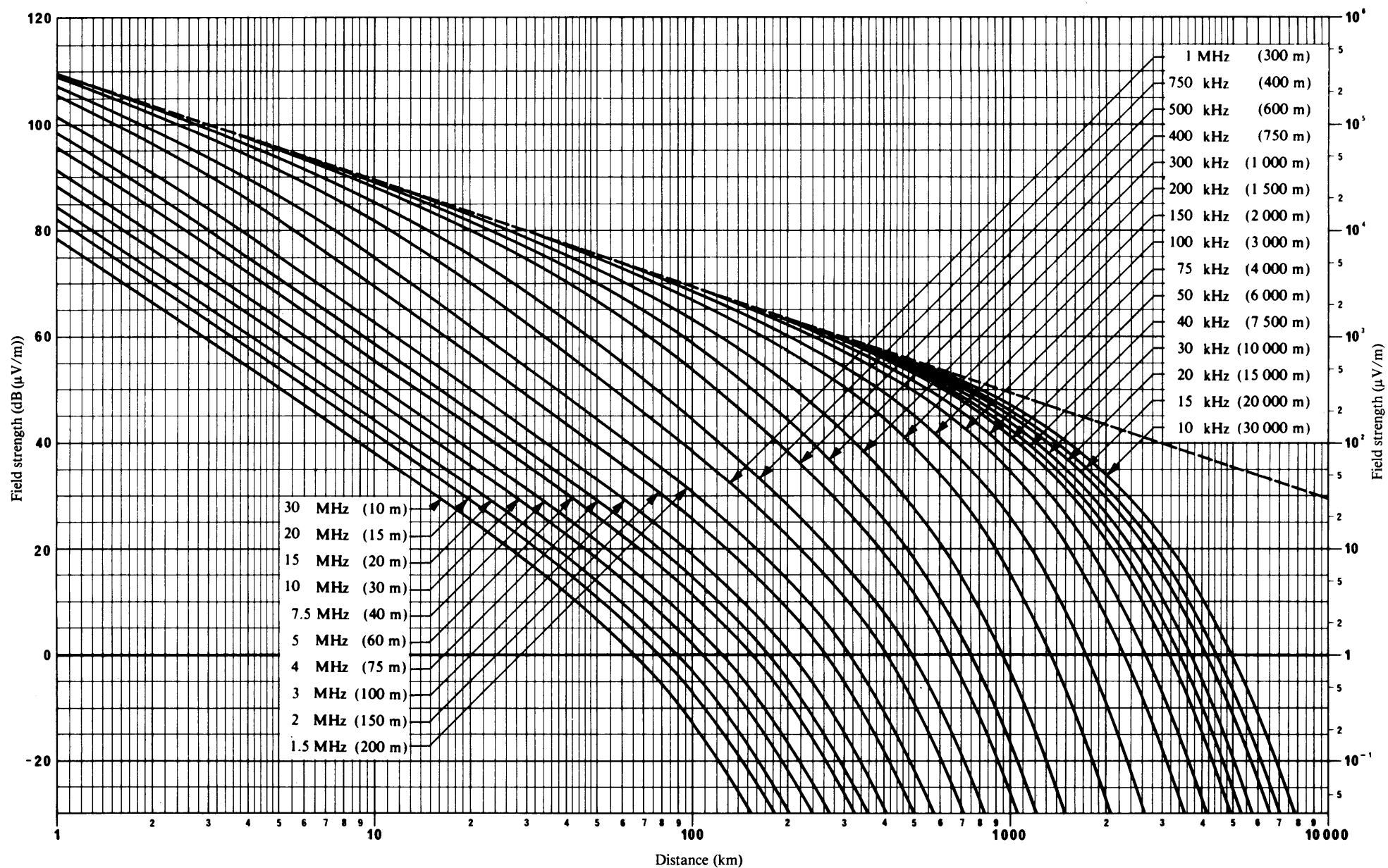


FIGURE 4b – Ground-wave propagation curves; Land, $\sigma = 3 \times 10^{-3} \text{ S/m}$, $\epsilon = 15$

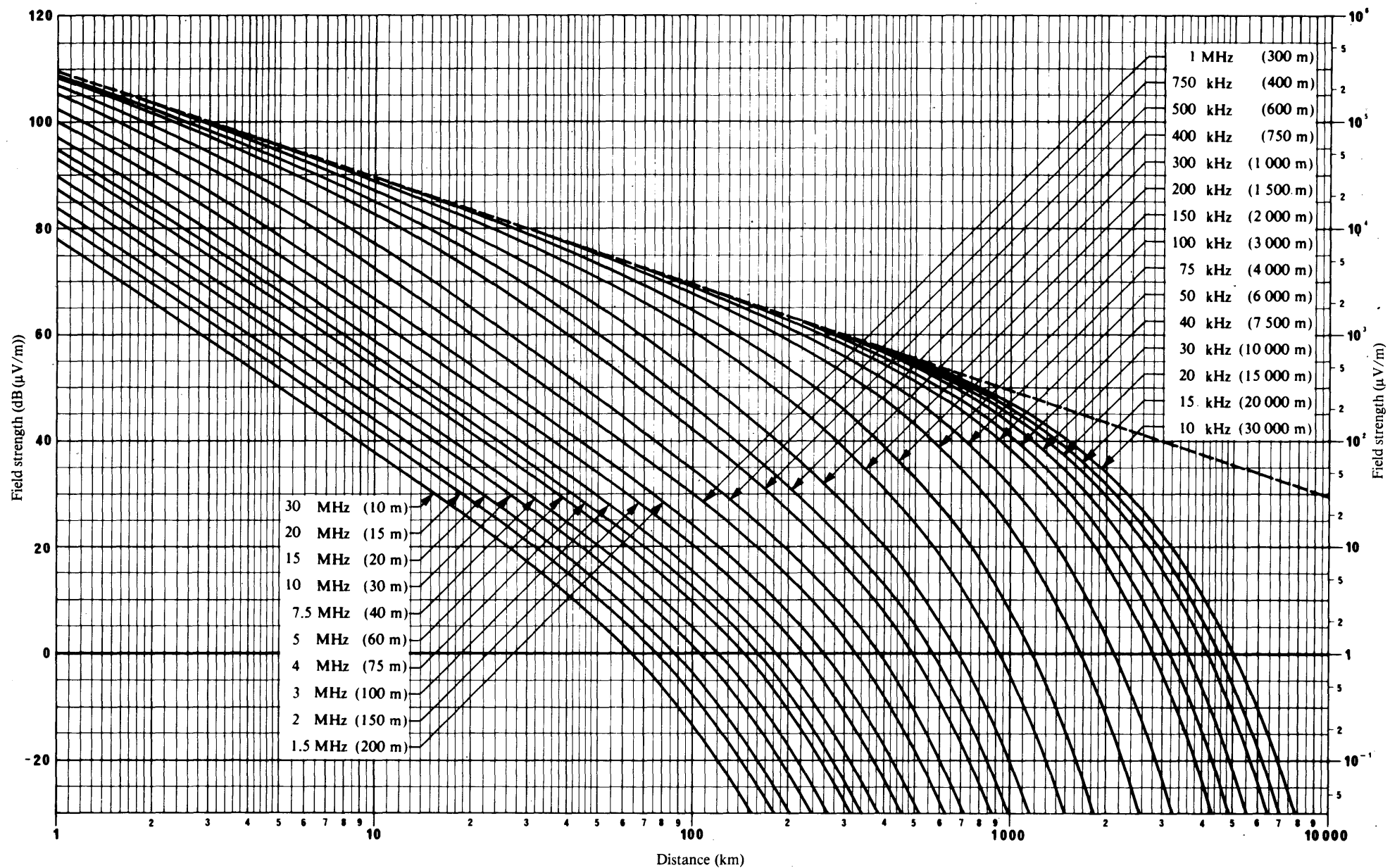


FIGURE 5 – Ground-wave propagation curves; Medium dry ground, $\sigma = 10^{-3} \text{ S/m}$, $\epsilon = 15$

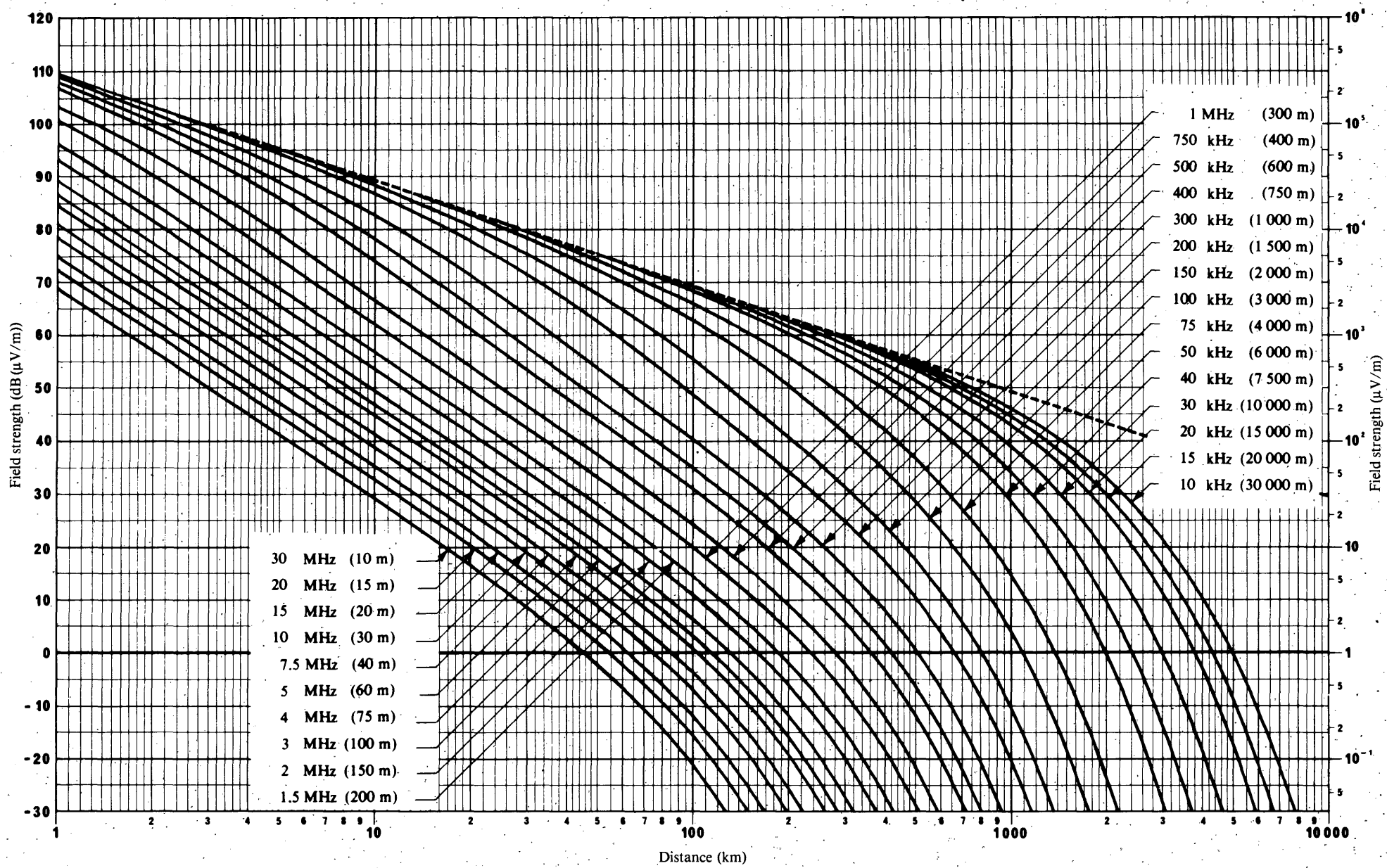


FIGURE 6 - Ground-wave propagation curves; Dry ground, $\sigma = 3 \times 10^{-4} \text{ S/m}$, $\epsilon = 3$

----- Inverse distance curve

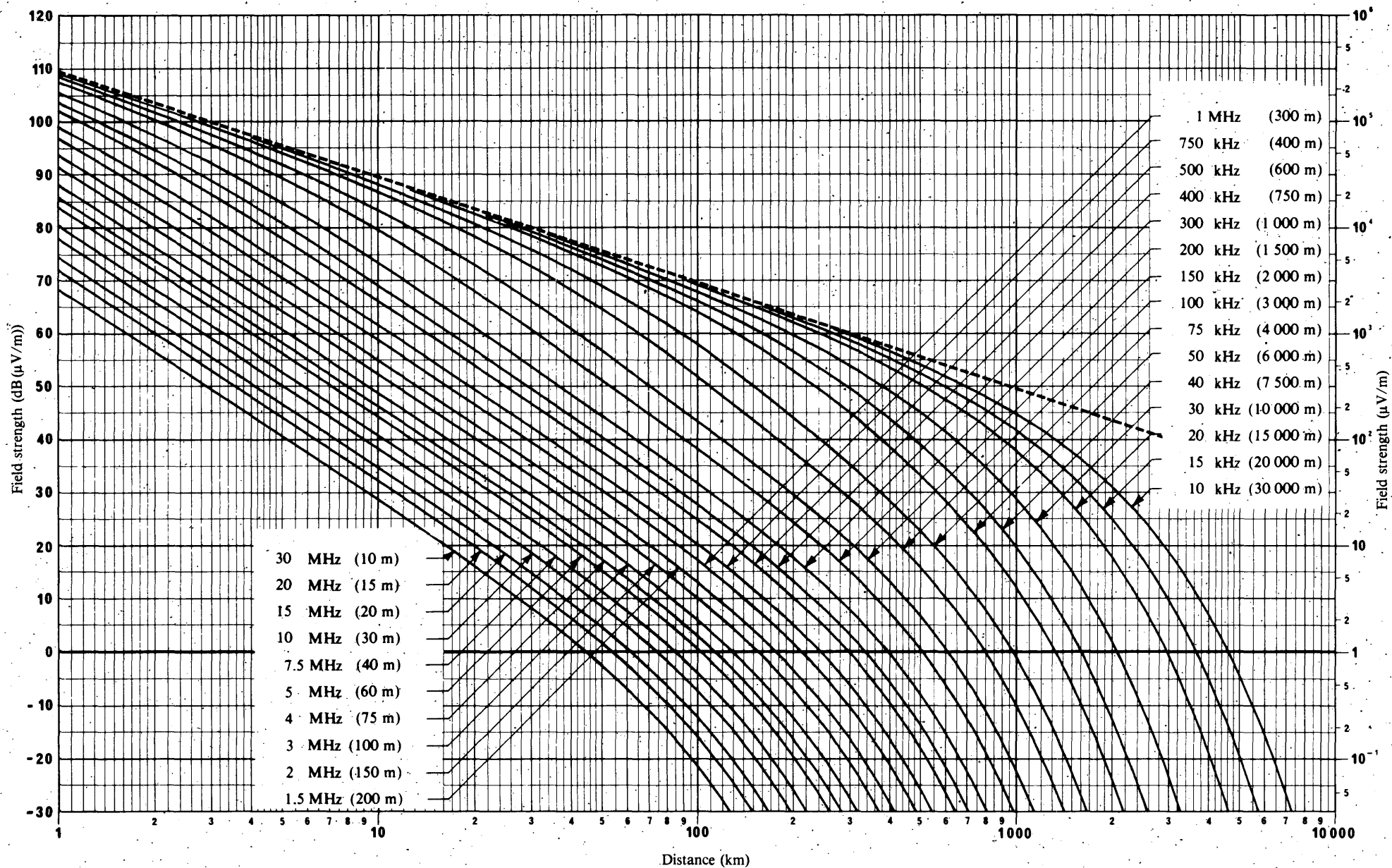


FIGURE 7 – Ground-wave propagation curves; Very dry ground, $\sigma = 10^{-4} \text{ S/m}$, $\epsilon = 3$

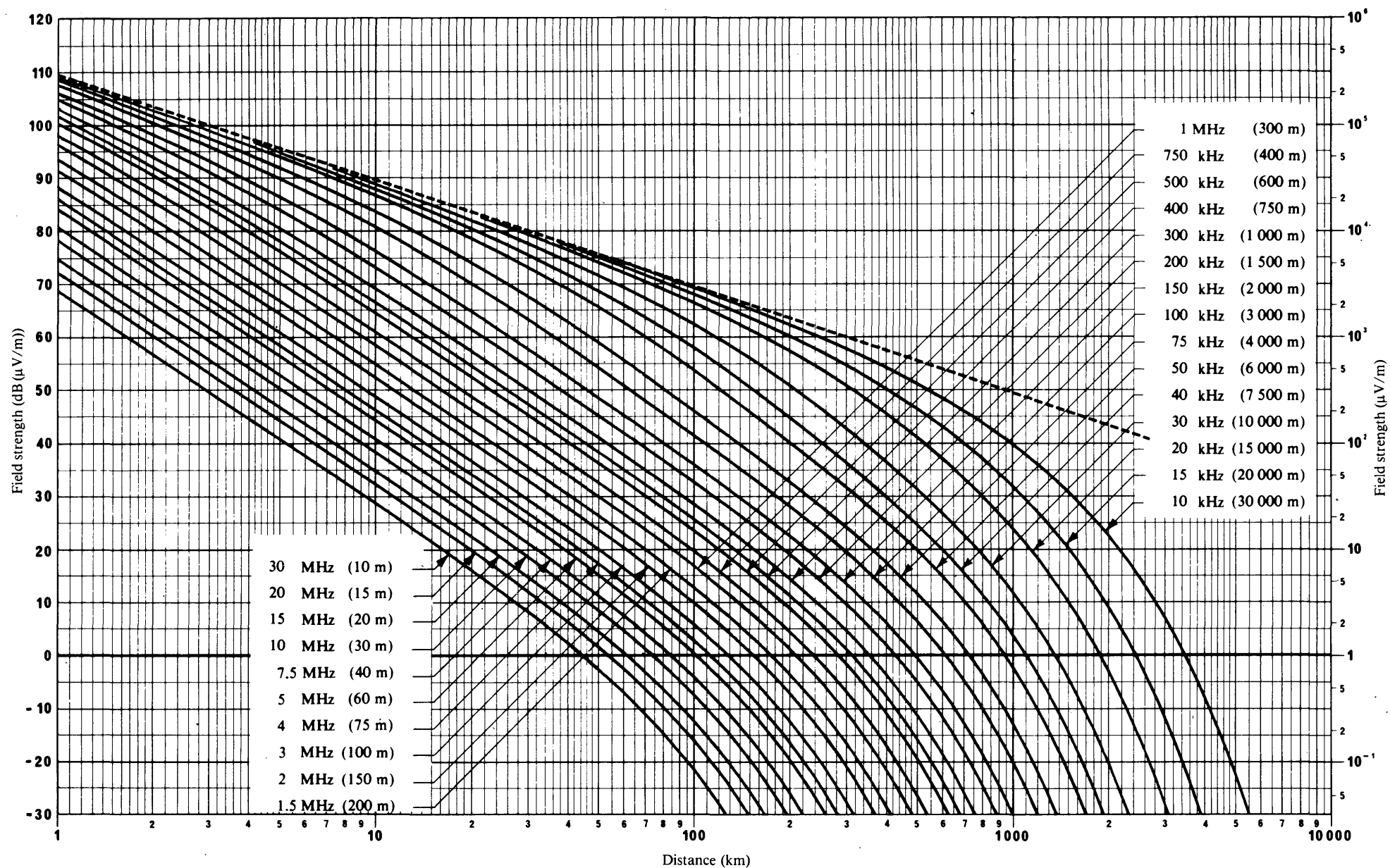


FIGURE 8 - Ground-wave propagation curves; Fresh water ice, -1°C , $\sigma = 3 \times 10^{-5} \text{ S/m}$, $\epsilon = 3$

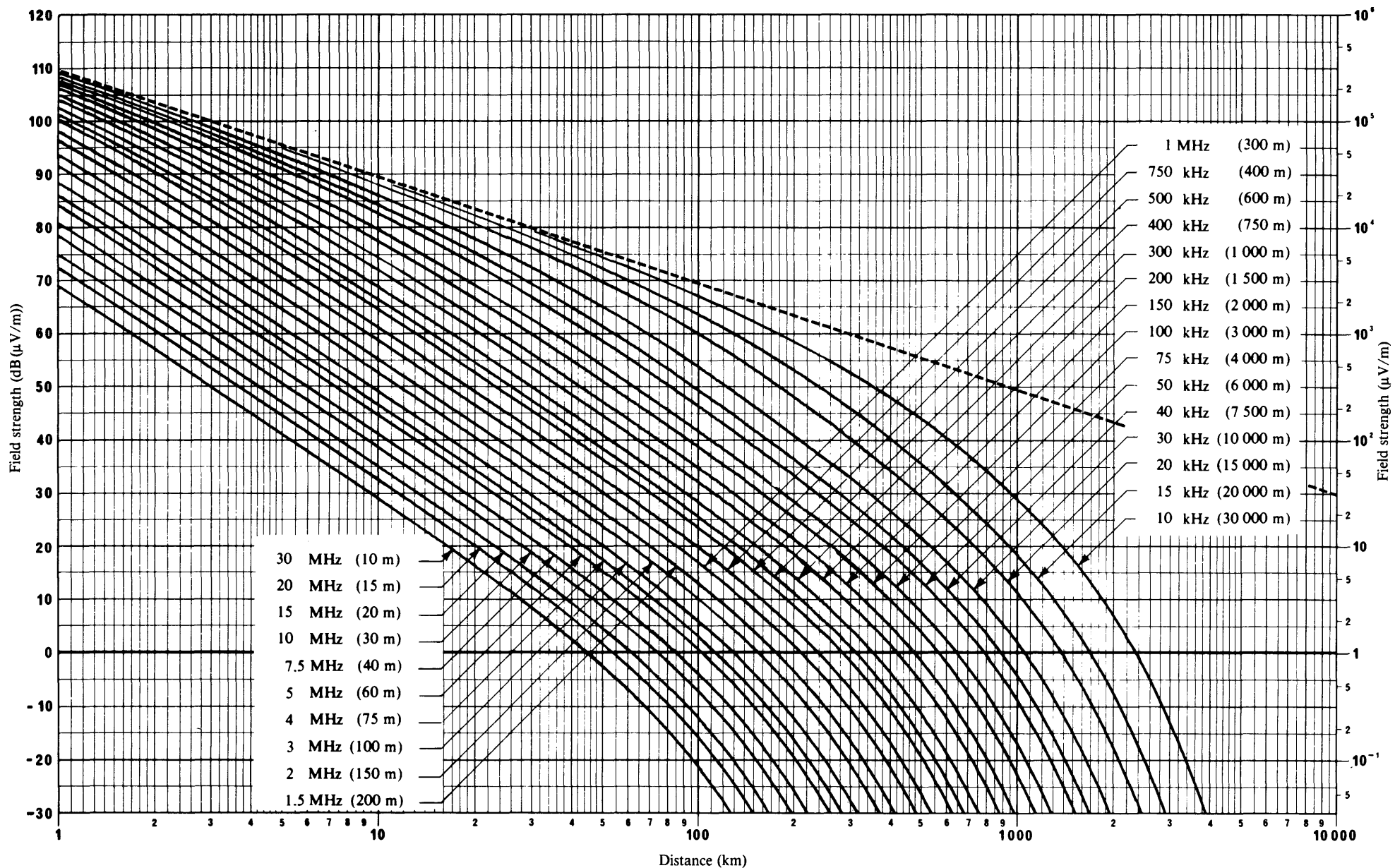


FIGURE 9 – Ground-wave propagation curves; Fresh water ice, -10°C , $\sigma = 10^{-5}\text{ S/m}$, $\epsilon = 3$

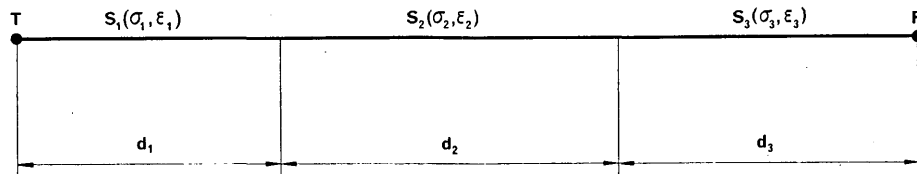
--- Inverse distance curve

ANNEX II

APPLICATION TO MIXED PATHS

1. The curves of Annex I may be used for the determination of propagation over mixed paths (non-homogeneous smooth earth) as follows:

Such paths may be made up of sections S_1, S_2, S_3 , etc., of lengths d_1, d_2, d_3 , etc., having conductivity and permittivity $\sigma_1, \epsilon_1; \sigma_2, \epsilon_2; \sigma_3, \epsilon_3$, etc., as shown below for three sections:



There are various semi-empirical methods of determining the propagation over such paths, of which that due to Millington [1949] is the most accurate and has been made to satisfy the reciprocity condition. The method assumes that the curves are available for the different types of terrain in the sections S_1, S_2, S_3 , etc., assumed to be individually homogeneous, all drawn for the same source T defined, for instance, by a given inverse-distance curve. The values may then finally be scaled up for any other source.

For a given frequency, the curve appropriate to the section S_1 is then chosen and the field $E_1(d_1)$ in dB(μ V/m) at the distance d_1 is then noted. The curve for the section S_2 is then used to find the fields $E_2(d_1)$ and $E_2(d_1 + d_2)$ and, similarly, with the curve for the section S_3 , the fields $E_3(d_1 + d_2)$ and $E_3(d_1 + d_2 + d_3)$ are found, and so on.

A received field strength E_R is then defined by:

$$E_R = E_1(d_1) - E_2(d_1) + E_2(d_1 + d_2) - E_3(d_1 + d_2) + E_3(d_1 + d_2 + d_3) \quad (1)$$

The procedure is then reversed, and calling R the transmitter and T the receiver, a field E_T is obtained, given by

$$E_T = E_3(d_3) - E_2(d_3) + E_2(d_3 + d_2) - E_1(d_3 + d_2) + E_1(d_3 + d_2 + d_1) \quad (2)$$

The required field is given by $1/2[E_R + E_T]$, the extension to more sections being obvious.

The method can in principle be extended to phase changes if the corresponding curves for phase as a function of distance over a homogeneous earth are available. Such information would be necessary for application to navigational systems. The Millington method is generally easy to use, particularly with the aid of a computer.

2. For planning purposes where the coverage of a certain transmitter is needed, a *graphical procedure*, based on the same method, is convenient for a rough and quick estimation of the distance at which the field strength has a certain value.

A short description of the graphical method is given here.

Figure 10 applies to a path having two different sections characterized by the values σ_1, ϵ_1 and σ_2, ϵ_2 , and extending for distances d_1 and d_2 respectively. It is supposed that the modulus of the complex permittivity* (dielectric constant) $|\epsilon'(\sigma_1, \epsilon_1)|$ is greater than $|\epsilon'(\sigma_2, \epsilon_2)|$. For the distances $d > d_1$ the field-strength curve obtained by the Millington method (§ 1) lies between the curves corresponding to the two different electrical properties $E(\sigma_1, \epsilon_1)$ and $E(\sigma_2, \epsilon_2)$. At the distance $d = 2d_1$, where d_1 is the distance from the transmitter to the border separating the two sections, the Millington curve goes through the mid-point between the curves $E(\sigma_1, \epsilon_1)$ and $E(\sigma_2, \epsilon_2)$ provided that the field strength is labelled linearly in decibels. In addition, the same curve approaches an asymptote, which differs by m dB from the curve $E(\sigma_2, \epsilon_2)$ as indicated in Fig. 10, where m is half the difference in decibels between the two curves $E(\sigma_1, \epsilon_1)$ and $E(\sigma_2, \epsilon_2)$ at $d = d_1$. The point at $d = 2d_1$ and the asymptote make it easy to draw the resulting field-strength curve.

* See Report 229.

Figure 11 shows the Millington curve for a two-section path with electrical constants changing from σ_2, ϵ_2 to σ_1, ϵ_1 where the modulus of the complex permittivity $|\epsilon'(\sigma_1, \epsilon_1)| > |\epsilon'(\sigma_2, \epsilon_2)|$. The above-mentioned procedure can be applied here bearing in mind that the asymptote is now parallel to the curve of the $E(\sigma_1, \epsilon_1)$.

For paths consisting of more than two sections, each change can be considered separately in the same way as the first change. The resulting curve has to be a continuous curve, and the portions of curves are displaced parallel to the extrapolated curve at the end of the previous section.

Figure 12 indicates how the approximate graphical method can be used to find the distance (for example, for purposes of determining coverage) where the field strength is 1 mV/m for a transmitted power of 100 kW over a path having several sections with different values of conductivity. By means of ground-wave propagation curves for the three different values of conductivity, where the field strength is given in dB(μ V/m) for a transmitted power of 1 kW, the graphical procedure is repeated for the various sections. By way of illustration, the values 1 mV/m and 100 kW correspond to 40 dB(μ V/m) and 1 kW, which gives a distance of 170 km in the example.

For use of the graphical method it would be convenient to have ground-wave propagation curves for some different sets of electrical constants at each frequency concerned. Examples of such curves are given in Figs. 13 and 14 for 200 and 700 kHz. Further sets of curves can easily be prepared for a number of frequencies by means of the curves of Annex I. In some cases it is convenient to use a linear scale for the distances.

The accuracy of the graphical method is dependent on the difference in slope of the field-strength curves, and is therefore to an extent dependent on the frequency. For the LF band, the difference between the method described in § 1 and this approximate method is normally negligible, but for the highest part of the MF band the differences in most cases will not exceed 3 dB. Figure 15 is a comparison, carried out by the use of a computer, between the Millington method and this approximate method.

A full description of the graphical method is given in Stokke [1975].

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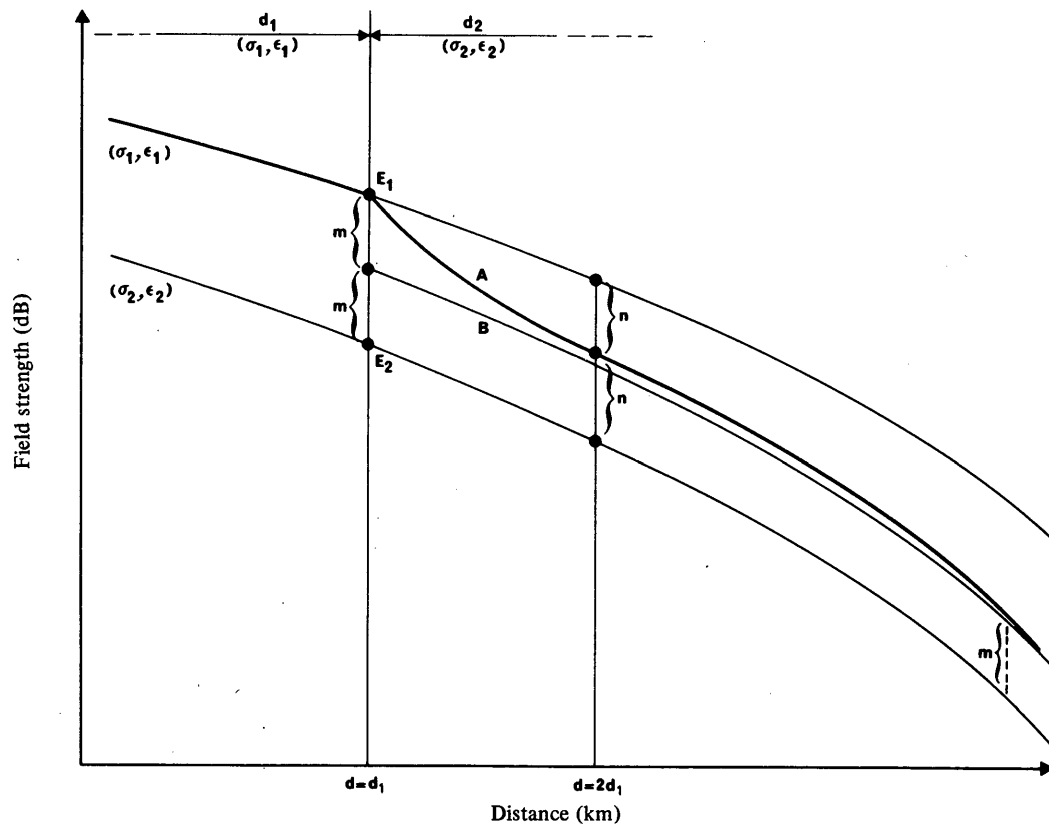


FIGURE 10 – Comparison of results

A: Millington field-strength curve
B: Asymptote

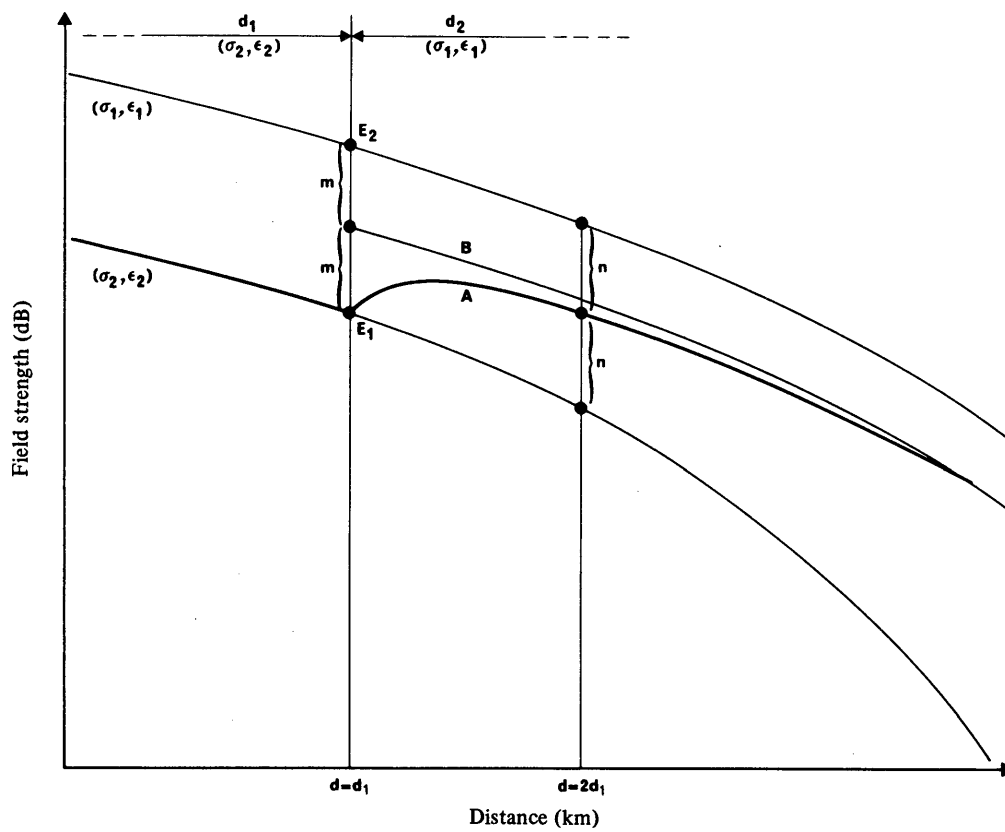


FIGURE 11 – Comparison of results

A: Millington field-strength curve
B: Asymptote

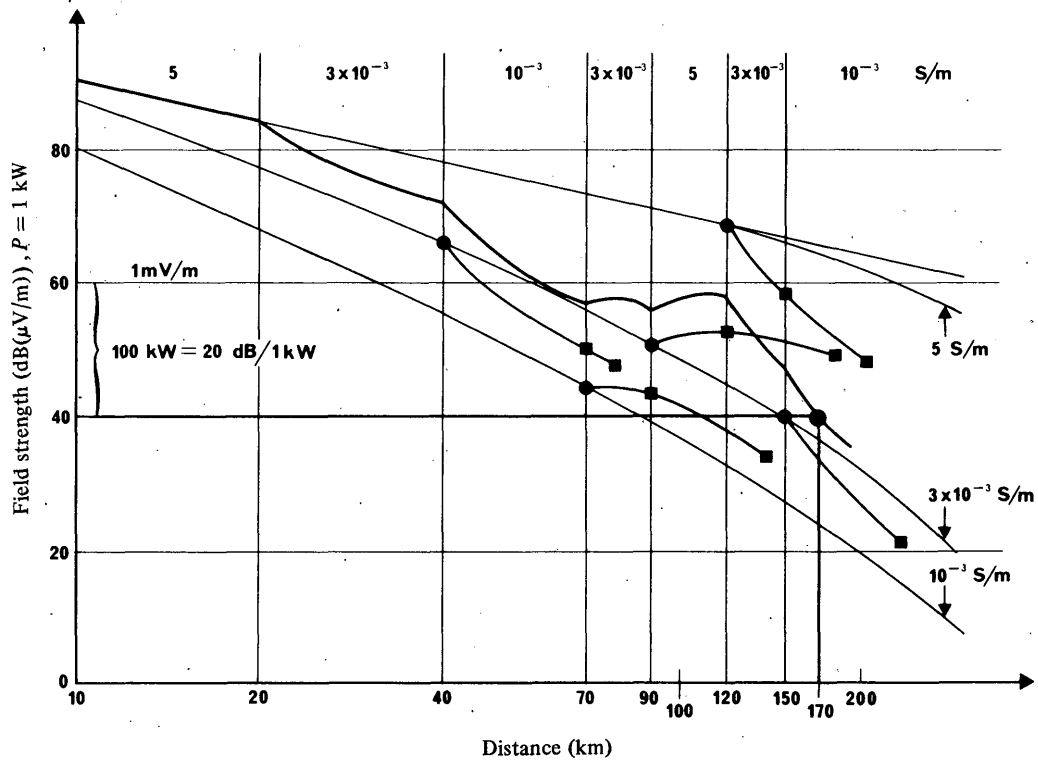
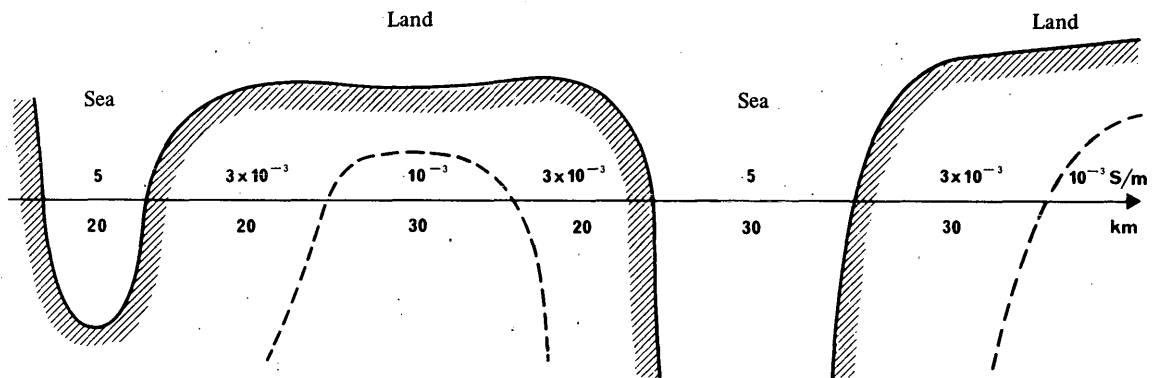
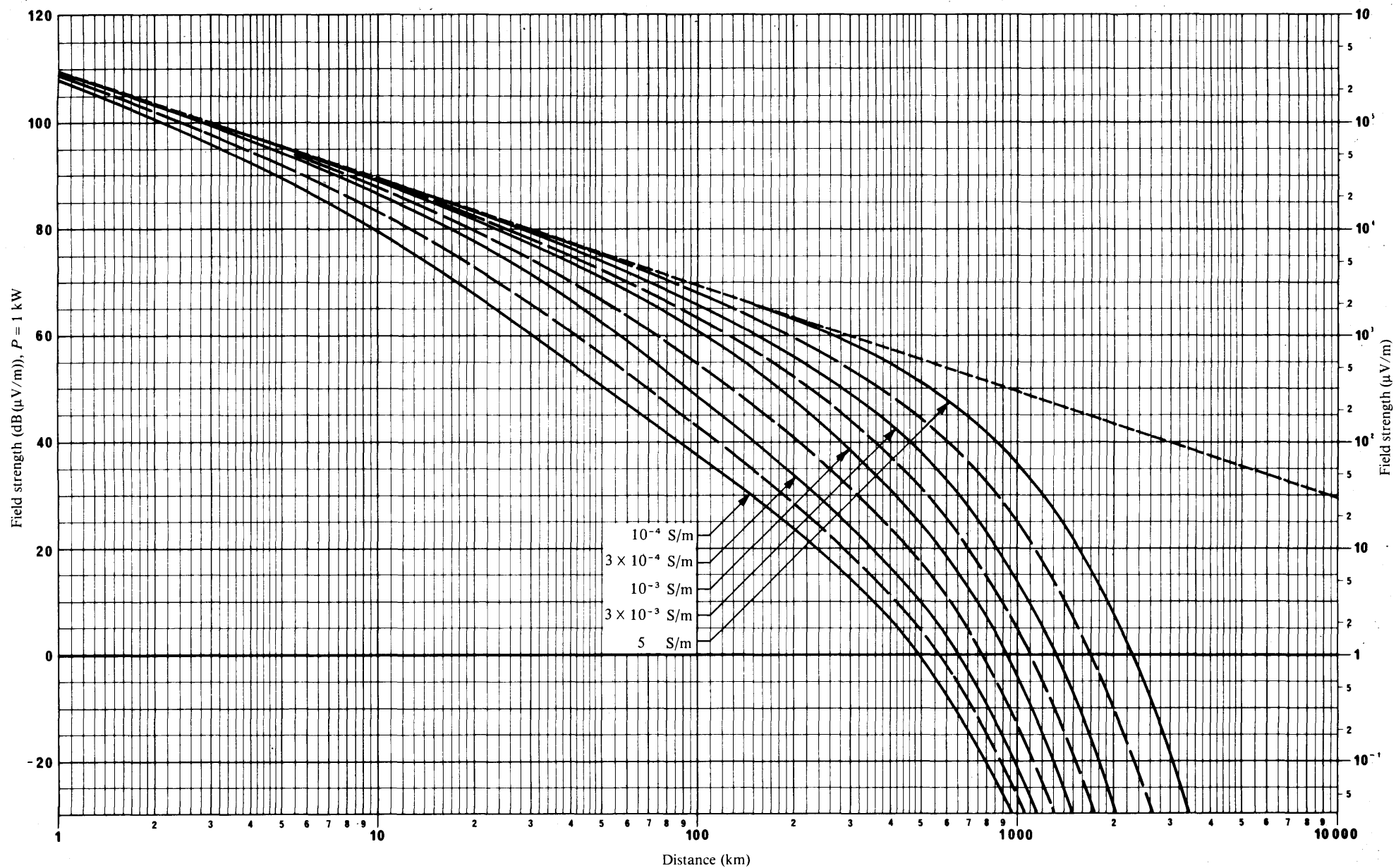


FIGURE 12 – Mixed-path field-strength curve
Frequency : 700 kHz

FIGURE 13 - Ground-wave propagation: different values of σ

Frequency: 200 kHz

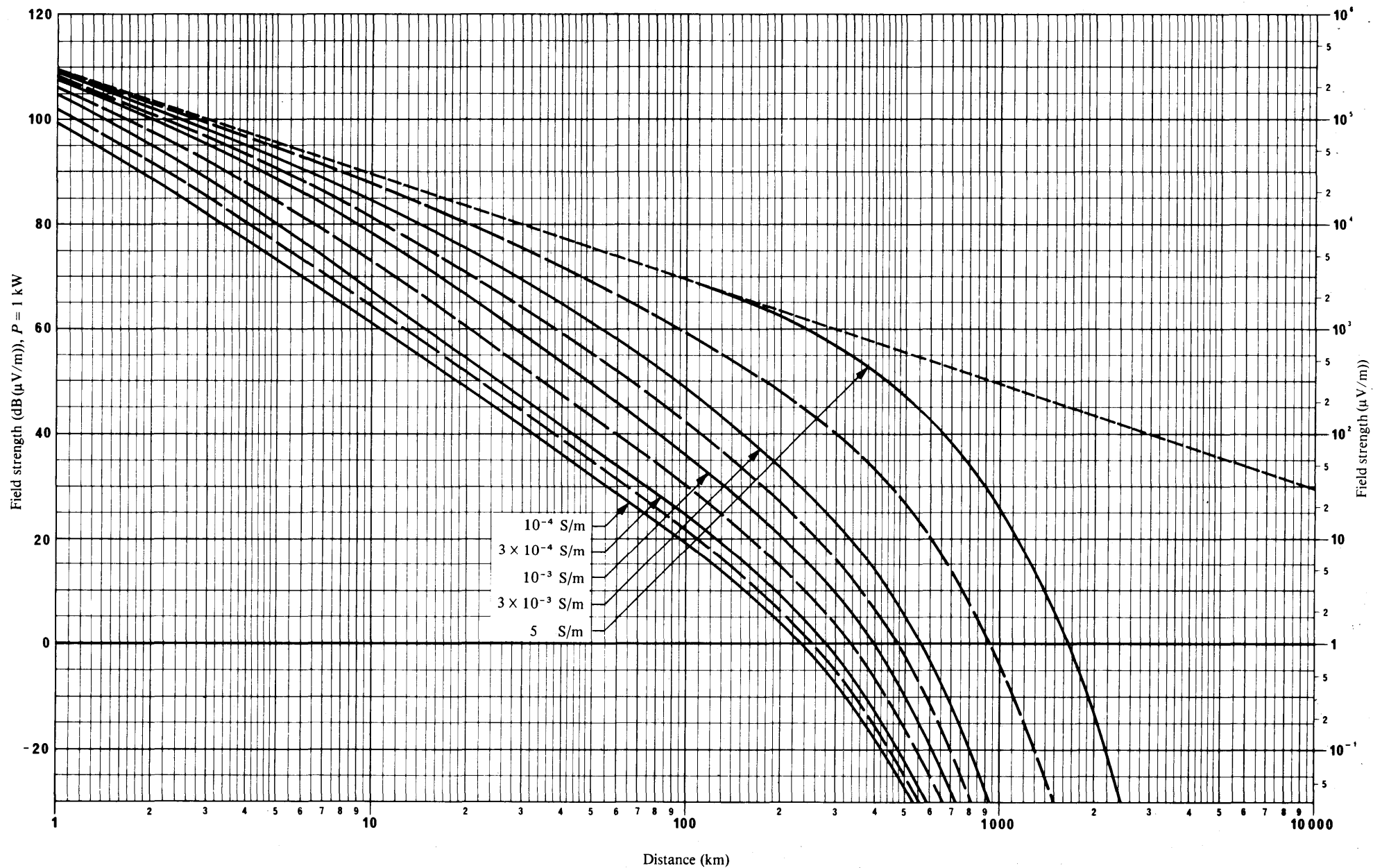


FIGURE 14 – Ground-wave propagation: different values of σ

Frequency: 700 kHz

— — — — — Mixed path curves where $d_1 = d_2$
 - - - - - Inverse distance curve

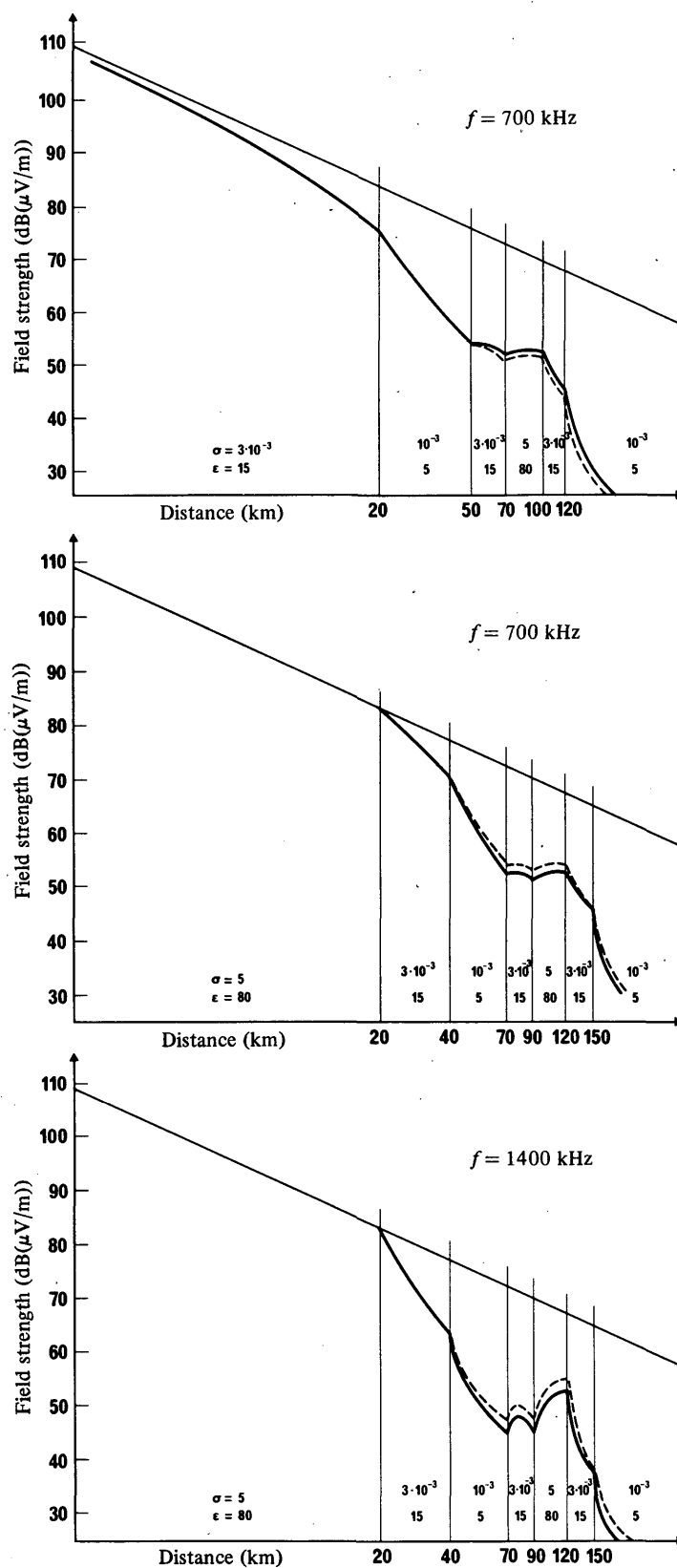


FIGURE 15 – Comparison of results

----- Approximate method
 ————— Millington's method

σ expressed in S/m

REPORT 878

**SPECIAL FEATURES OF THE CONCEPT OF TRANSMISSION LOSS
IN THE GROUND-WAVE PROPAGATION CASE**

(1982)

1. Introduction

The use of the terminology and notation defined in Recommendation 341 provides a standardised method for describing system loss and its various components which can be used for any radio circuit at any frequency. When antennas are installed on or near the ground and the ground-wave propagation mode is used (i.e. $h < \lambda$, particularly when using frequencies less than 30 MHz) the free-space value of the antenna radiation resistance is modified by the presence of the ground.

Consequently the power flux-density at the receiving antenna (resulting from the vector sum of direct and reflected rays) is dependent on the height of the transmitting antenna, and the effective capture area of the receiving antenna is dependent on the height of the antenna above the ground.

The basis for these statements is given below.

2. Transmission loss in free space (symbols: L_{bf} or A_0)

Consider the transmission loss between two loss-free isotropic antennas in free space. At a distance, d , very much greater than the wavelength, λ , the power flux-density expressed in watts per square metre is $p'_t/4\pi d^2$ since the power, p'_t , is radiated uniformly in all directions.

Since the effective capture area of the isotropic receiving antenna is $\lambda^2/4\pi$ the power available at its terminal is given by:

$$p'_a = \left(\frac{\lambda^2}{4\pi}\right) \left(\frac{p'_t}{4\pi d^2}\right) \quad (1)$$

Thus, in free space:

$$L_{bf} = 10 \log \left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{dB} \quad (2)$$

If short, loss-free, optimally orientated electric dipoles (having free-space gain $g_t = g_r = 1.5$) are substituted for the isotropic antennas the available power is given by:

$$p'_a = \left(\frac{1.5\lambda^2}{4\pi}\right) \left(\frac{1.5p'_t}{4\pi d^2}\right) \quad (3)$$

and transmission loss (symbols: L or A):

$$L = 10 \log \left(\frac{4\pi d}{\lambda}\right)^2 - 3.5 \quad \text{dB} \quad (4)$$

3. The influence of the environment on the antennas

The influence of the environment on the operation of a pair of antennas (forming an elementary circuit) is illustrated by considering the transmission loss between two vertical loss-free short electric dipoles at heights h_t and h_r above a plane perfectly conducting surface. The separation, d , along the surface is very large compared to the wavelength. The power flux-density S in W/m^2 at height h_r is given by:

$$S = \frac{p'_t \cos^4 \psi}{4\pi d^2 (1 + \Delta_t)} \times 1.5 \left[2 \cos(kh_t \sin \psi) \right]^2 \quad (5)$$

The following should be noted:

- the distance between the antennas is increased to $d \sec \psi$
- where

$$\psi = \arctan \frac{h_r - h_t}{d}$$

- the electric field due to the dipole varies as $\cos \psi$;
- the free-space radiation resistance is multiplied by $(1 + \Delta_r)$,

where

$$\Delta_r = \frac{3}{(2kh_t)^2} \left[\frac{\sin 2kh_t}{2kh_t} - \cos 2kh_t \right] \quad (6)^*$$

where

$$k = 2\pi/\lambda$$

when

$$h_t = 0, \Delta_r = 1; \text{ when } h_t > \lambda, \Delta_r \rightarrow 0;$$

- due to the vector addition of the direct and reflected rays the free-space value of the power flux is multiplied by:

$$\frac{[2 \cos(kh_t \sin \psi)]^2}{(1 + \Delta_r)}$$

This is equivalent to the change in directive gain due to the presence of the reflecting surface. The multiplying factor has the value of 2 when $h_t = h_r = 0$.

The effective capture area of the receiving antenna is given by:

$$a_e = \frac{1.5 \lambda^2 \cos^2 \psi}{4\pi (1 + \Delta_r)} \quad (7)$$

The following should be noted:

- the capture area in the direction of the transmitting antenna is decreased by $\cos^2 \psi$;
- the change in radiation resistance is based on equation (6), where Δ_r and h_t are replaced by Δ_r and h_r ;
- the free-space value of the capture area is multiplied by $\frac{\cos^2 \psi}{(1 + \Delta_r)}$; thus the presence of the reflecting surface reduces the capture area below its free-space value by a factor of 2 when $h_t = h_r = 0$;
- since g_t has the value 2×1.5 (by definition) when $h_t = h_r = 0$ it is important to note that this is not the appropriate value to use for g_r ; the correct value for g_r is $1.5/2 = g_t/4$.

4. Calculation of the value of the transmission loss (symbols: L or A)

Since $p'_a = Sa_e$ expressions (5) and (7) may be combined to give an expression for the transmission loss between two short vertical loss-free electric dipoles above a plane perfectly conducting surface.

$$L = L_{bf} - 6.0 - 10 \log \left[(1.5 \cos^2 \psi)^2 \frac{(\cos^2 kh_t \sin \psi)}{(1 + \Delta_r)(1 + \Delta_r)} \right] \quad \text{dB} \quad (8)$$

Consider two cases.

$$h_t = h_r = 0; \Delta_r = \Delta_r = 1; \psi = 0$$

$$L = L_{bf} - 3.5 \quad \text{dB}$$

Thus L is equal to the free-space value. See equation (4) above.

$$h_t = h_r \gg \lambda; \Delta_r = \Delta_r \rightarrow 0; \psi \rightarrow 0$$

$$L = L_{bf} - 3.5 - 6.0 \quad \text{dB}$$

* This relation is derived by S. A. Schelkunoff in Chapters VI and IX of the book *Electromagnetic Waves*, D. Van Nostrand Co., 1943.

REPORT 714-1 *

GROUND-WAVE PROPAGATION IN AN EXPONENTIAL ATMOSPHERE

(Question 3/5)

(1978-1982)

1. Introduction

In the older ground-wave propagation curves which were replaced by Recommendation 368, no account was taken of tropospheric refraction. The troposphere was taken as a vacuum so that its refractive index n and modified refractive index m are:

$$n = 1, \quad m = n + \frac{h}{a} = 1 + \frac{h}{a} \quad (1)$$

where h is height and a is the Earth's radius.

In the CCIR atlases of ground-wave propagation curves for frequencies above 30 MHz [CCIR, 1955 and 1959], the tropospheric refractive index is taken to decrease linearly with height, as described by:

$$n = n_s - \frac{k-1}{k} \cdot \frac{h}{a}, \quad m = n_s + \frac{h}{ka} \quad (2)$$

where $n_s \approx 1.0003$ is the surface value of n , and k is the effective earth radius factor, taken as 4/3 in the curves. Expression (2) encompasses expression (1) with $n_s = k = 1$.

In fact, the troposphere has a mean refractive index which varies exponentially with height as:

$$n = 1 + (n_s - 1) \exp(-h/h_s) \quad (3)$$

where h_s (≈ 7 km) is the scale height of the troposphere. This model is fully described by Bean and Dutton [1966] and accepted as the Reference Atmosphere of Recommendation 369. For $h \gg h_s$ it tends to expression (1). For $h \ll h_s$ it tends to expression (2) with $h_s = ka(n_s - 1)/(k - 1)$.

At frequencies below 10 MHz, the height-gain effects become small at moderate heights and it was partly for this reason that the ground-wave propagation curves have been made to refer only to the case in which both terminals are on the ground. On the other hand, below about 3 MHz, the range of height entering into the determination of the rate of attenuation of field strength with distance around the Earth has extended to the region where the refractive index of the troposphere begins to depart seriously from the value corresponding to a linear decrease with height appropriate to the use of a 4/3 Earth's radius. Thus the rate of attenuation of field strength with distance around the Earth no longer corresponds to the use of an atmosphere in which the refractive index decreases linearly to indefinitely great heights.

While at the upper limit of 10 MHz for the ground-wave propagation curves in Recommendation 368 it is still nearly correct to use an equivalent radius of 4/3 times the real radius of the Earth for both terminals on the ground, the troposphere can have very little effect at the lower limit of 10 kHz, where the range of height entering into the determination of the rate of attenuation of field strength with distance around the Earth extends to many kilometres above the Earth.

There is thus a transition that becomes marked at about 3 MHz and almost complete at 10 kHz, from the use of a 4/3 Earth's radius at 10 MHz to the use of the real radius of the Earth at 10 kHz. It has long been realized that this transition must occur, as is shown by the existence of the appropriate Question 3/5.

2. Theoretical analysis

In recent years a method of analysis has been developed in the United Kingdom [Rotheram, 1970] which enables the effects of a troposphere with an exponential height variation of refractive index to be taken into account. The following sections describe the methods used to calculate the field in various domains.

* This Report is brought to the attention of Study Group 8.

2.1 *The field near the surface at short ranges*

Close to the transmitter the field near the surface due to a source on the surface can be described by the Sommerfeld flat earth theory. As the range increases corrections due to the effective Earth's curvature can be applied as described by Bremmer [1949]. Further corrections must be applied for the exponential atmosphere. The extended Sommerfeld theory is useful out to distances of order $10 \lambda^{1/3}$ (km) and heights of the order of $35 \lambda^{2/3}$ m where λ is the wavelength in metres.

2.2 *The line-of-sight region*

In the line-of-sight region, the field is composed of the sum of the direct and reflected waves. These are found from an integral representation by the method of stationary phase which is equivalent to geometrical optics. This differs from the linear atmosphere in that the points of stationary phase and the phase integrals must be evaluated numerically.

2.3 *The diffraction region*

The diffraction region occurs at ranges greater than about $10 \lambda^{1/3}$ km (see § 2.1) near the surface or beyond the radio horizon for elevated terminals. Here the field can be represented by the residue or waveguide mode series. Associated with each mode is an eigenvalue, the propagation constant, and an eigenfunction, the height-gain function. The propagation constant determines the variation of the mode with range. The height-gain function determines the variation of the mode with height. The eigenfunction is the solution of a second order ordinary differential equation, and the eigenvalue is found by imposing the boundary conditions. There is an infinity of modes, but only a few are needed. Up to nine modes are used. An exact earth flattening method, Langer's transformation [1937] is employed. For the models in expressions (1) and (2) above, the solutions are known in closed form in terms of Airy functions. For the exponential model, the solutions are not expressible in terms of standard functions. The WKB Airy integral function [Bremmer, 1960 and 1962] approximations are used to give initial approximations to the eigenvalues. The Riccati differential equation of the wave impedance, or wave reflection coefficient, is then integrated numerically, and the eigenvalue found by Newton's method. The height-gain function is then found by numerical integration.

2.4 *Differences in propagation in linear and exponential atmospheres*

At heights above about 1 km, expression (3) differs significantly from expression (2), being less refractive. Thus for frequencies of 30 MHz and above, the refracting properties within the horizon and height-gain properties beyond the horizon, differ appreciably. A correction for the height-gain functions has been given previously by Millington [1958].

The waveguide modes have a vertical scale size or track width h_m . When $h_m \ll h_s$, which occurs above about 10 MHz, the propagation constant of a mode calculated from expression (3) tends to the same value as from expression (2). When $h_m \gg h_s$, which occurs below about 10 kHz, it tends to that from expression (1). As the frequency is changed from 10 kHz to 10 MHz there is a continuous transition from the propagation constant of expression (1) to that of expression (2). This may be interpreted as a continuous change in the effective earth radius factor from 1 to 4/3 as the frequency is increased. This has been described by Rotheram [1970] and Gerks [1971].

3. *The computer program*

A program GRWAVE written in FORTRAN IV has been developed using the methods outlined above [Rotheram, 1981]. The constants n_s and h_s in expression (3), the ground constants of the Earth, the radio frequency and the polarization are supplied as input data. In one mode of operation the minimum and maximum ranges of the calculation, the range increments and arrays of transmitter and receiver heights are supplied. Each array can have up to 50 elements. The field strength is calculated for all pairs of heights at all ranges. Of course only one eigenvalue and one integration of the height-gain differential equation suffices for each mode. A number of codes are input to control the mode of operation and the amount of output. The main output is the field strength at each point. This is given in $\mu\text{V/m}$ for a transmitter of dipole moment $5 \lambda/2 \pi$ (amp-metres) giving a field strength of $1.5 \times 10^5 \mu\text{V/m}$ at 1 km, which is the free-space field from a 3/4 kW isotropic radiator (which is the same as $1.732 \times 10^5 \mu\text{V/m}$ at 1 km from a 1 kW isotropic radiator). The transmission loss and field strength relative to free space are also output. Within the line-of-sight region information about the interference lobe structure is given. By using a code, other output can be supplied, such as the propagation constants and height-gain functions, or very detailed output for error diagnosis.

Note. — The program is available from the CCIR Secretariat, for use by administrations; if appropriate parameters are given the ITU computer service will be able to make the calculations.

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RECOMMENDATION 526-1

PROPAGATION BY DIFFRACTION

(1978-1982)

The CCIR,

CONSIDERING

that there is a need to provide engineering information for the calculation of field strengths over diffraction paths,

UNANIMOUSLY RECOMMENDS

that the information contained in Report 715 be used for calculation of field strengths over diffraction paths.

REPORT 715-1 *

PROPAGATION BY DIFFRACTION

(Study Programme 1A/5)

(1978-1982)

1. Introduction

In propagation over the Earth's surface diffraction paths are often encountered, and it is then necessary to estimate the transmission loss due to diffraction either over a spherical Earth surface or over irregular terrain, including different kinds of obstacles.

Although diffraction is produced only by the surface of the ground, account must be taken of the mean atmospheric refraction on the transmission path to evaluate the geometrical parameters situated in the vertical plane of the path (angle of diffraction, radius of curvature, height of obstacle). For this purpose, the path profile has to be traced with the appropriate equivalent Earth radius (Report 563). If no other information is available, an equivalent Earth radius of 8500 km may be taken as a basis.

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

2. Diffraction over a spherical Earth

2.1 Numerical calculation

For determining diffraction attenuation, A , relative to free space beyond the horizon, an approximate formula may be used over a smooth Earth [NBS, 1967].

$$A = \Gamma(\chi_0) - \Phi(\chi_1) - \Phi(\chi_2) - 20.5 \quad \text{dB} \quad (2.1)$$

where

$$\chi_0 = d_0 \cdot B_0 \quad (2.2)$$

$$\chi_1 = d_1 \cdot B_0 \quad (2.3)$$

$$\chi_2 = d_2 \cdot B_0 \quad (2.4)$$

$$B_0 = 670(f/a_e^2)^{1/3} \quad (2.5)$$

Where d_0 is the total distance in km, and d_1 and d_2 are the distances in km from each antenna to its radio horizon:

$$d_1 = \sqrt{2a_e h_1} \quad (2.6)$$

$$d_2 = \sqrt{2a_e h_2} \quad (2.7)$$

Where h_1 and h_2 are the antenna heights in km, a_e is the effective Earth radius in km, defined in Report 563 and f is the frequency in MHz.

The functions $\Gamma(\chi_0)$, $\Phi(\chi_1)$ and $\Phi(\chi_2)$ are plotted in Fig. 1. The factor K in this figure depends on the frequency and the electrical characteristics of the Earth. The curve labelled $K = 0$ is appropriate for horizontal polarization over water, or good and average grounds, at frequencies of 100 MHz or above. For horizontal polarization over poor ground, this same curve is applicable for frequencies of 600 MHz or above, and approximately so (within 2 dB) for frequencies down to 100 MHz. For vertical polarization over land, the curve labelled $K = 0.01$ is applicable for frequencies of 600 MHz or above. For vertical polarization over sea water, the curves labelled $K = 0.01$, 0.1, 0.3 and 1.0 are applicable for frequencies of 3300 MHz, 120 MHz, 30 MHz and 7.5 MHz, respectively, or less.

The error in A will be less than 1 dB if

$$\chi_0 - \chi_1 \cdot \Delta(\chi_1) - \chi_2 \cdot \Delta(\chi_2) > 320 \quad (2.8)$$

for horizontal polarization, or for vertical polarization on overland paths. For the error in A to be 1.5 dB or less for vertical polarization on overseas paths, the limit indicated as the right-hand side of (2.8) must be 320 for frequencies of 600 MHz or more ($K \leq 0.03$), 335 for 120 MHz ($K = 0.1$), and 115 for 7.5 MHz or less ($K \geq 1.0$).

The auxiliary functions $\Delta(\chi_1)$ and $\Delta(\chi_2)$ are given in Fig. 1. The inequality (2.8) assumes that the first term of the residue series is dominant.

Note. — In the case where polarization is not linear, it will not suffice to simply resolve the field into orthogonal linear components, due to the lack of phase information. Further investigation is warranted.

2.2 Calculation by nomograms

Under the same approximation condition (the first term of the residue series is dominant), the calculation may also be made using the following formula:

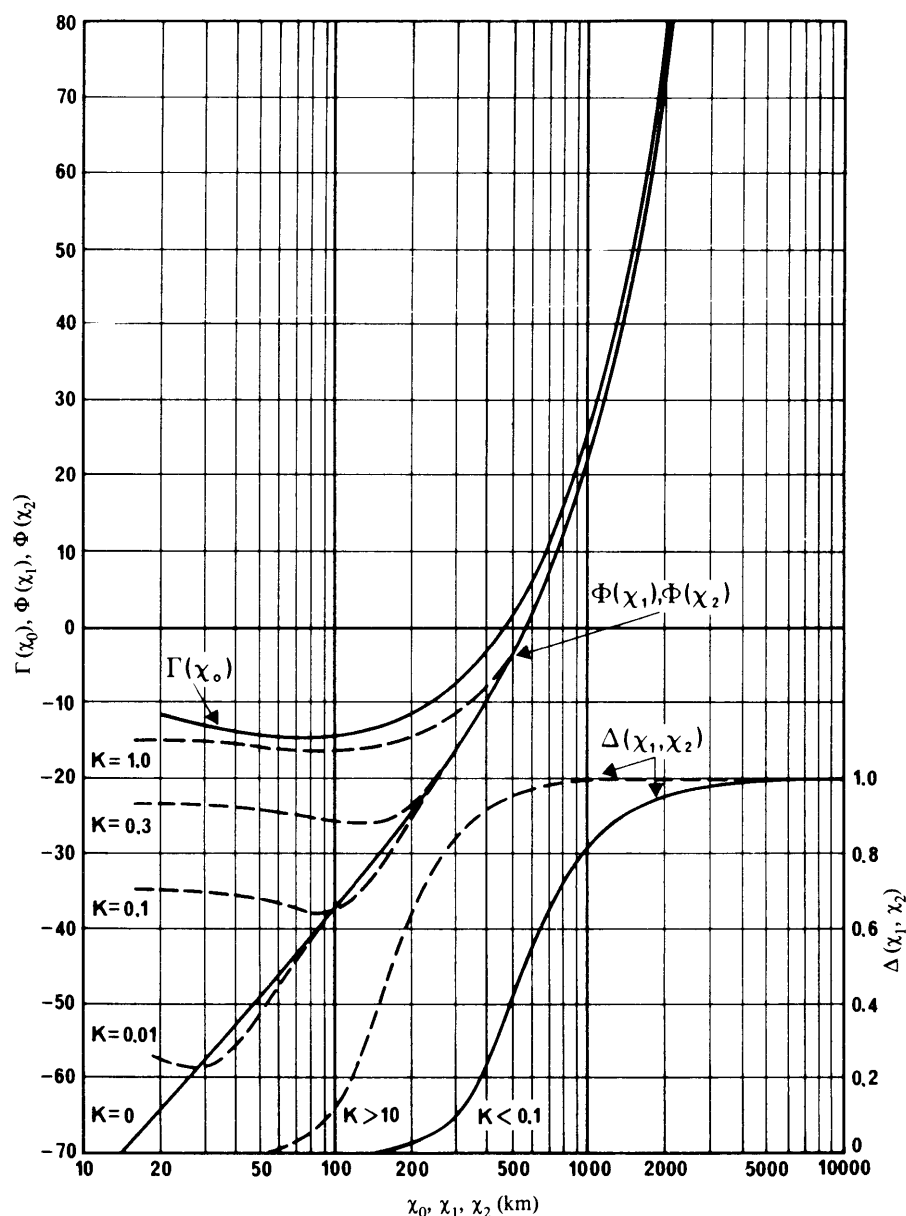
$$20 \log \frac{E}{E_0} = F(d) + H(h_1) + H(h_2) \quad \text{dB} \quad (2.9)$$

where

- E : the received field strength
- E_0 : the field strength in free space at the same distance
- d : the distance between the extremities of the path
- h_1 and h_2 : the heights of the antennas above the spherical Earth.

The function F , (influence of the distance) and H , (height-gain) are given by the nomograms in Figs. 2, 3, 4 and 5 [Boithias, 1972].

These nomograms (Figs. 2 to 5) give directly the received level relative to free space, for $k = 1$ and $k = 4/3$, and for frequencies greater than approximately 30 MHz. k is the effective Earth radius factor, defined in Report 563. However, the received level for other values of k may be calculated by using the frequency scale for $k = 1$, but replacing the frequency in question by a hypothetical frequency equal to f/k^2 for Figs. 2 and 4 and $f/\sqrt{k}$ for Figs. 3 and 5.

FIGURE 1 - The functions of Γ and Φ in expression (2.1)

Note. - For large values of χ
 $\Phi(\chi) \approx \Gamma(\chi) - 1.356$
 where $\Gamma(\chi) \approx 0.0575104\chi - 10 \log \chi + 2.066$

Very close to the ground the field strength is practically independent of the height. This phenomenon is particularly important for vertical polarization over the sea. For this reason Fig. 5 includes a heavy black vertical line AB. If the straight line would intersect this heavy line AB, the real height should be replaced by a larger value, so that the straight line just touches the top of the limit line at A.

Note. - Attenuation relative to free space is given by the negative of the values given by equation (2.9). If equation (2.9) gives a value above the free-space field, the method is invalid.

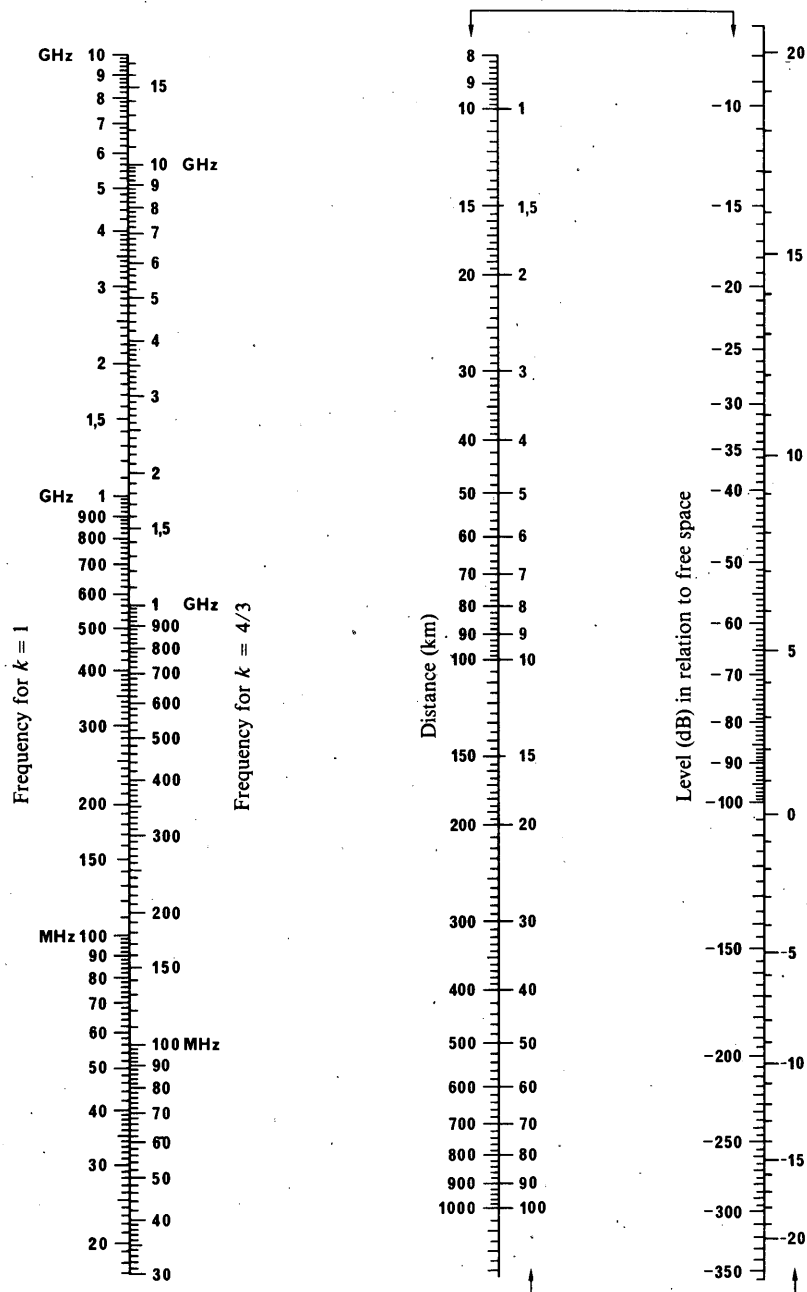


FIGURE 2 - Diffraction by a spherical earth - effect of distance

Horizontal polarization over land and sea

Vertical polarization over land

(The scales joined by arrows should be used together)

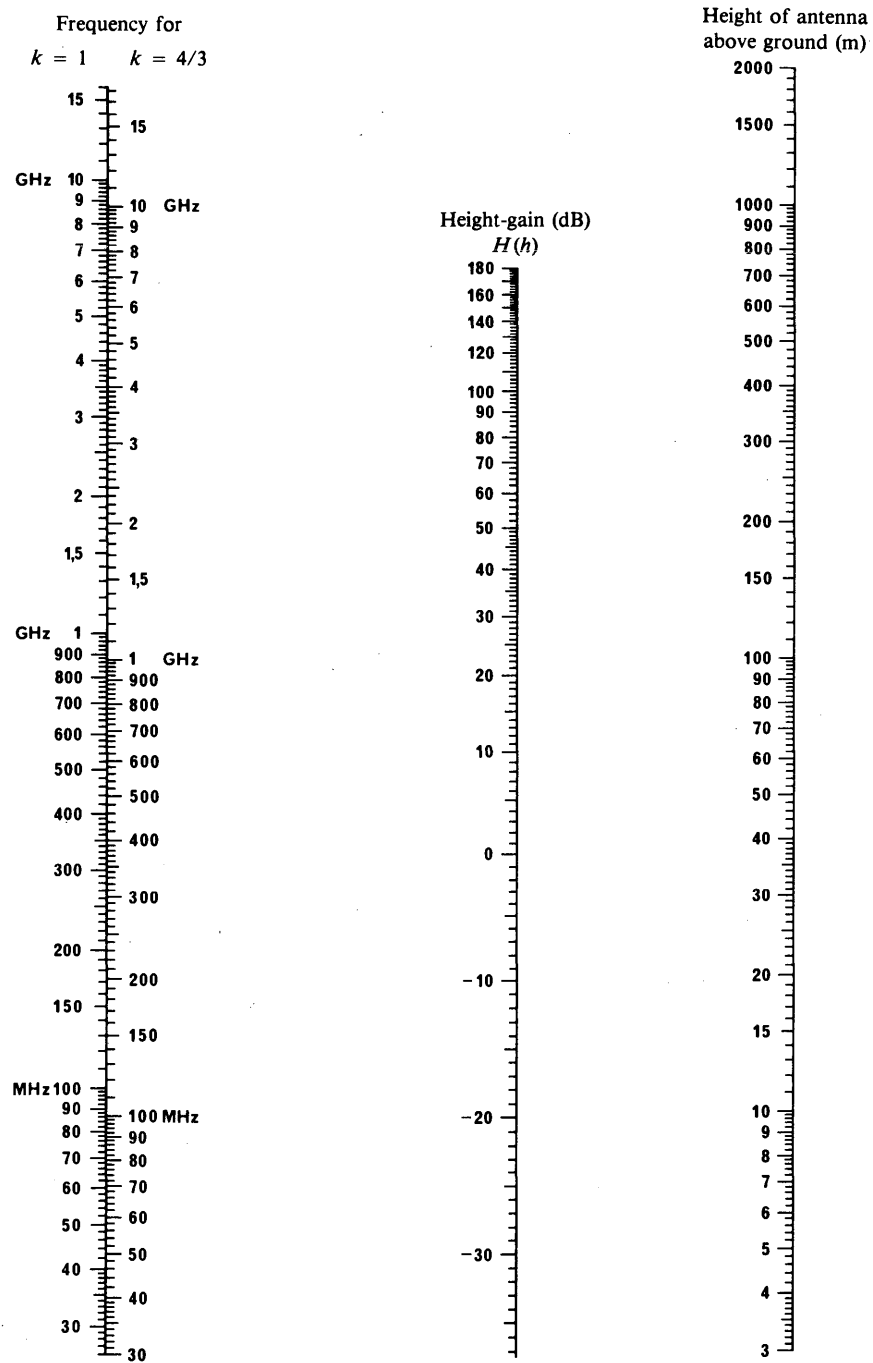


FIGURE 3 – Diffraction by a spherical earth – height-gain

Horizontal polarization – land and sea
 Vertical polarization – land

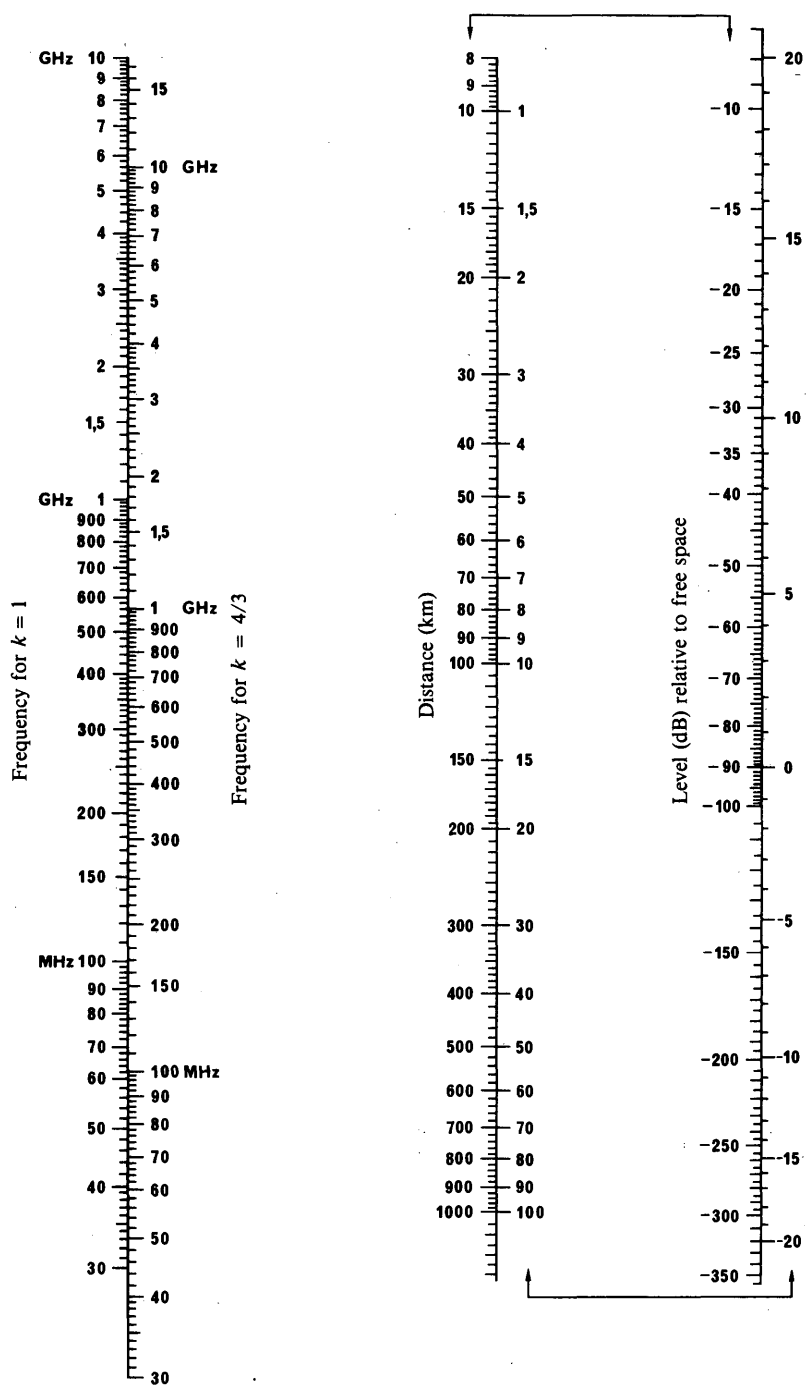


FIGURE 4 - Diffraction by a spherical earth - effect of distance

Vertical polarization over sea
(The scales joined by arrows should be used together)

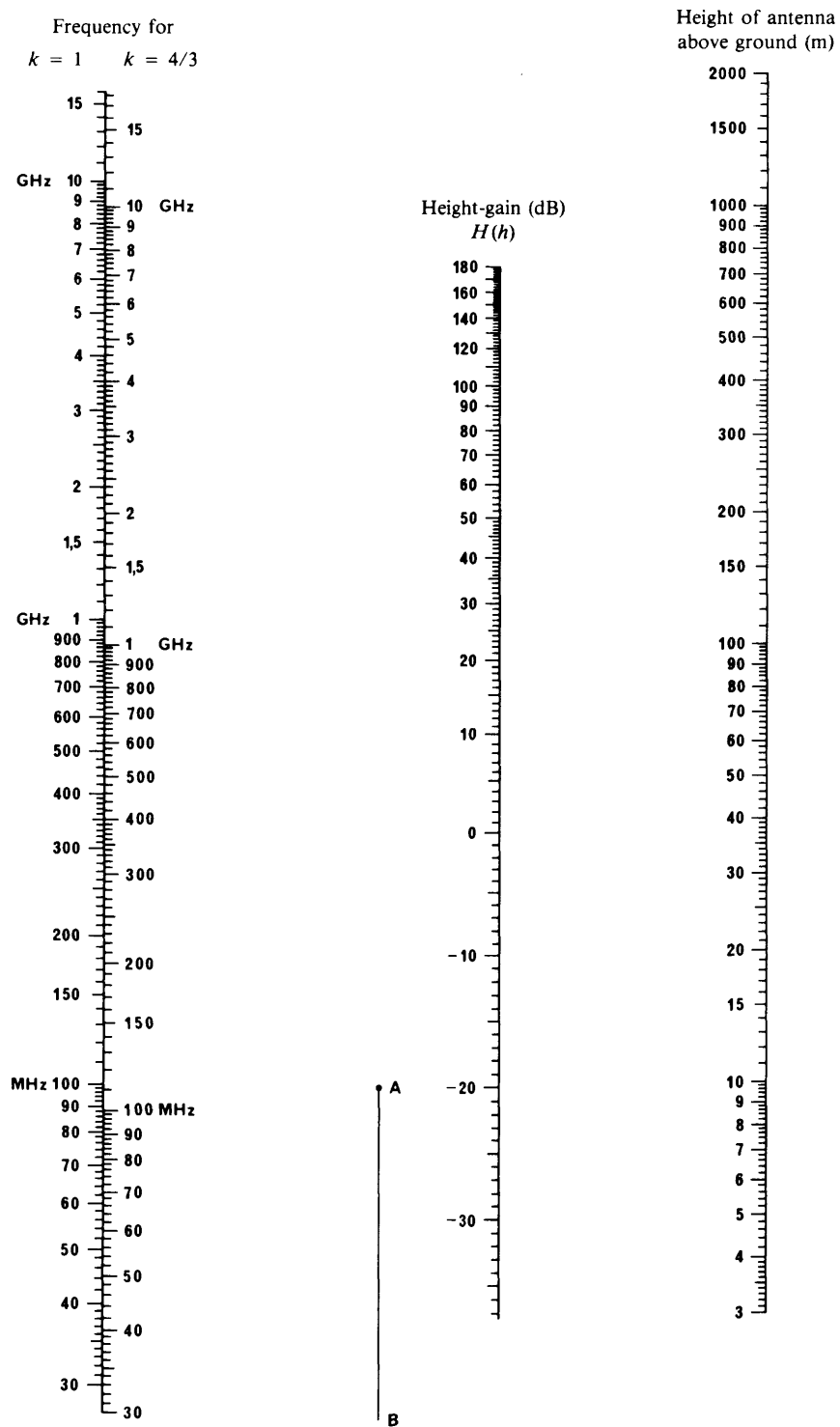


FIGURE 5 — Diffraction by a spherical earth — height-gain

Vertical polarization — sea

3. Diffraction over obstacles and irregular terrain

Many propagation paths encounter one obstacle or several separate obstacles and it is useful to estimate the losses caused by such obstacles. To make such calculations it is necessary to idealize the form of the obstacles, either assuming a knife-edge of negligible thickness or a thick smooth obstacle with a well-defined radius of curvature at the top. Real obstacles have, of course, more complex forms, so that the indications provided in this Report should be regarded only as an approximation.

The indications provided in this Report apply when the wavelength is fairly small in relation to the size of the obstacles, i.e., mainly to VHF and shorter waves ($f > 30$ MHz).

3.1 Diffraction over isolated obstacles

3.1.1 Knife-edge obstacles

In this extremely idealized case (Fig. 6), all the geometrical parameters are lumped together in a single dimensionless parameter normally denoted by v which may assume a variety of equivalent forms according to the geometrical parameters selected:

$$v = h \sqrt{\frac{2}{\lambda} \left(\frac{1}{d_1} + \frac{1}{d_2} \right)} \quad (3.1)$$

$$v = \theta \sqrt{\frac{2}{\lambda \left(\frac{1}{d_1} + \frac{1}{d_2} \right)}} \quad (3.2)$$

$$v = \sqrt{\frac{2h\theta}{\lambda}} \quad (v \text{ has the sign of } h \text{ and } \theta) \quad (3.3)$$

$$v = \sqrt{\frac{2d}{\lambda}} \cdot \alpha_1 \alpha_2 \quad (v \text{ has the sign of } \alpha_1 \text{ and } \alpha_2) \quad (3.4)$$

where

h : height of the top of the obstacle above the straight line joining the two ends of the path. If the height is below this line, h is negative.

d_1 and d_2 : distances of the two ends of the path from the obstacle.

d : length of the path: $d = d_1 + d_2$.

θ : angle of diffraction in radians; its sign is the same as that of h . The angle θ is assumed to be less than about 0.2 radian, or roughly 12° .

α_1 and α_2 : angles between the top of the obstacle and one end as seen from the other end. α_1 and α_2 are of the sign of h in the above equation; h , d , d_1 , d_2 and λ are expressed by the same unit.

Figure 7 gives, as a function of v the loss in decibels caused by the presence of the obstacle. For v more positive than -1 an approximate value can be obtained from the expression:

$$J(v) = 6.4 + 20 \log (\sqrt{v^2 + 1} + v) \quad \text{dB}$$

The error is within 0.5 dB.

A semi-empirical method [Furutsu, 1962; Furutsu and Wilkerson, 1971] has been proposed for estimating the gain caused by a ridge or a bluff on a spherical homogeneous Earth. This uses graphs of the "terminal gains" of obstacles which are defined by the asymptotic values of the (theoretical) obstacle gains for infinite propagation distance on one side of the obstacle, and assumes a finite distance on the other side. According to this method, the obstacle gains can be estimated by summing two terminal gains (dB) viewed from each side of the obstacle, and by subtracting its asymptotic value for infinite propagation distances on both sides. The errors of the gains thus estimated are within a few dB for important heights of the obstacles, and tend to zero as the propagation distance on either side of the obstacles becomes large.

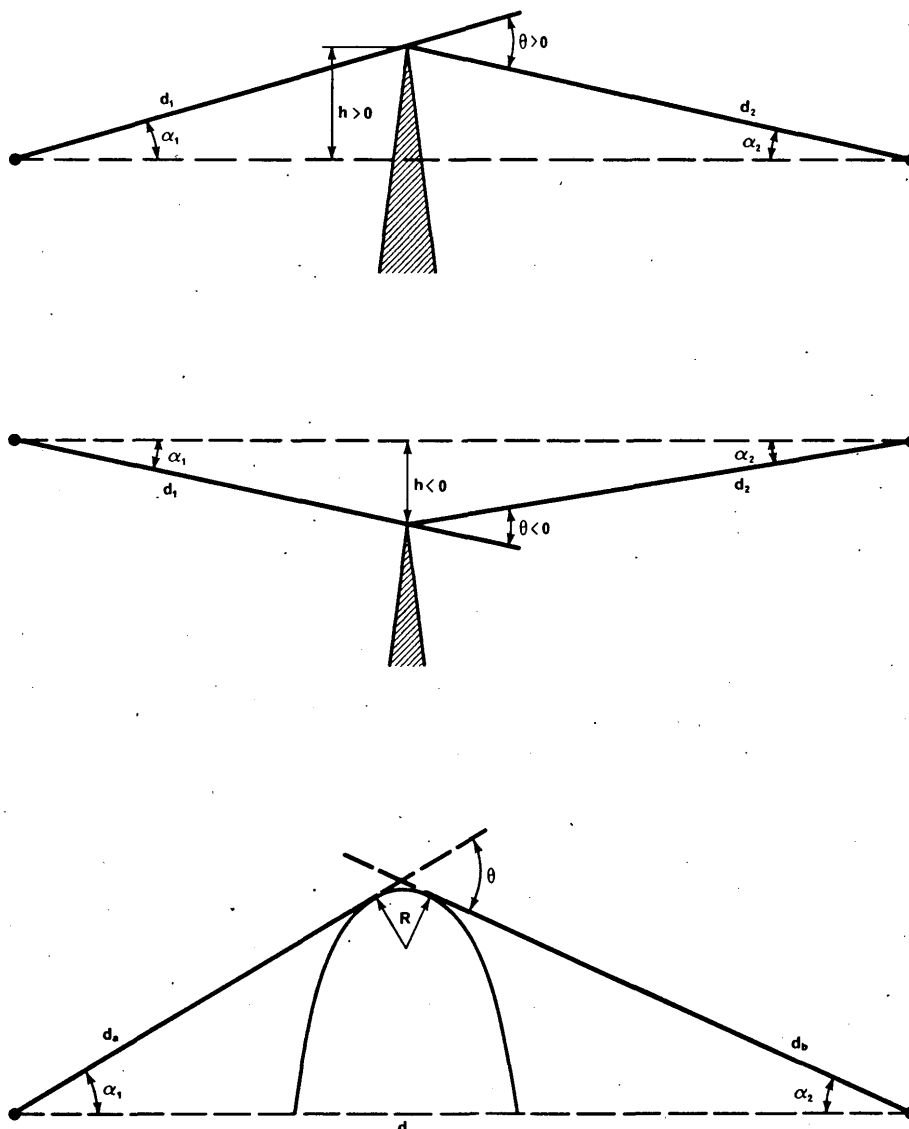


FIGURE 6 – Geometrical elements

(For definitions of θ , α_1 , α_2 , h , d , d_1 , d_2 , d_a , d_b and R , see § 3.1)

3.1.2 One rounded obstacle

A propagation path with a single isolated terrain feature, which provides the horizons for both terminals, may often be considered as having a single diffracting rounded knife-edge between the terminals. For $\theta \geq 0$, the diffraction attenuation, A (in decibels in excess of free space), may be evaluated from:

$$A = J(v) + T(\rho) + Q(\chi) \quad (3.5)$$

(a) The Fresnel-Kirchhoff Loss $J(v)$ is illustrated in Fig. 7 as a function of the dimensionless parameter:

$$v = 2 \sin \left(\frac{\theta}{2} \right) \left[\frac{2 (d_a + R \cdot \theta/2) (d_b + R \cdot \theta/2)}{\lambda \cdot d} \right]^{1/2} \quad (3.6)$$

where λ is the radio wavelength, and d_a and d_b are the distances from each terminal to their horizons on the terrain feature. R is the effective radius of curvature for the terrain feature between horizons as determined by the product of the geometrical radius and the earth-radius factor k . All distances and lengths are in the same units. For $R = 0$, (3.6) reduces to (3.2).

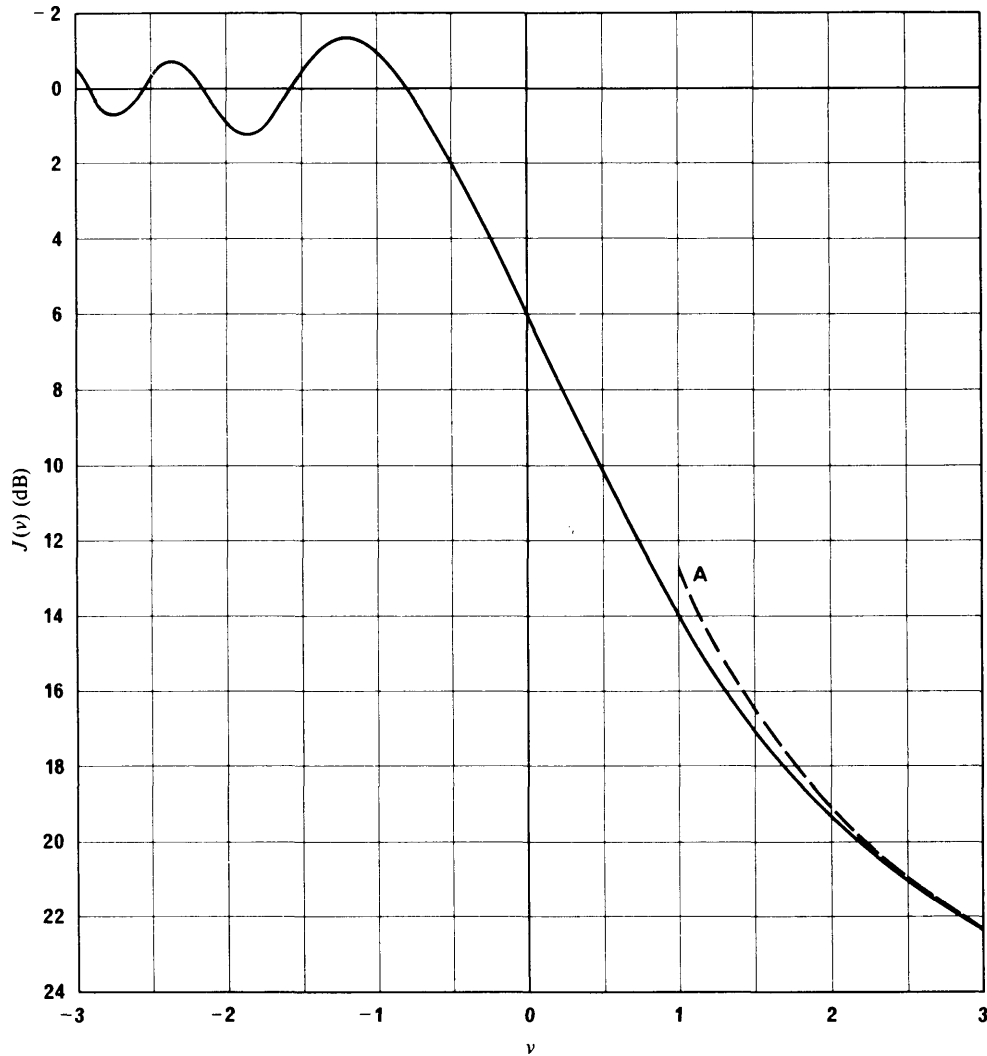


FIGURE 7 – Knife-edge diffraction, transmission loss relative to free space

Curve A: asymptote: $J(v) = 13 + 20 \log v$

- (b) $T(\rho)$, the loss in decibels for incidence upon the curved surface may be determined from: [Dougherty and Wilkerson, 1967].

$$T(\rho) = 7.2 \rho - 2 \rho^2 + 3.6 \rho^3 - 0.8 \rho^4 \quad (3.7)$$

where the ρ is given by

$$\rho^2 = \frac{d_a + d_b}{d_a d_b} \left/ \left[\left(\frac{\pi R}{\lambda} \right)^{1/3} \frac{1}{R} \right] \right. \quad (3.8)$$

- (c) $Q(\chi)$, the decibel loss for propagation along the surface between the horizons, is given by:

$$Q(\chi) = \begin{cases} T(\rho) \chi / \rho & \text{for } -\rho \leq \chi < 0 \\ 12.5 \chi & \text{for } 0 \leq \chi < 4 \\ 17 \chi - 6 - 20 \log \chi & \text{for } \chi \geq 4 \end{cases} \quad (3.9)$$

where

$$\chi = \left(\frac{\pi R}{\lambda} \right)^{1/3} \theta \approx \sqrt{\frac{\pi}{2}} v \rho \quad \text{if } \theta \ll 1 \quad (3.10)$$

For $R = 0$, ρ and χ go to zero and (3.5) reduces to the first term. For $\theta = 0$, $\chi = 0$ and (3.5) then gives the loss for grazing incidence upon the rounded knife-edge or obstacle.

The solution (3.5) results from the first term of an asymptotic formulation of the field in inverse powers of s . This assumes that the radio transmitting and receiving antennas are both remote from their horizon on the diffracting terrain feature [Dougherty, 1969].

That is,

$$s = \left(\frac{2\pi}{\lambda} \right) \left[d_a d_b \right]^{1/2} \geq 10 \quad (3.11)$$

and

$$\left[\left(\frac{\pi R}{\lambda} \right)^{1/3} / R \right]^2 d_a d_b \geq 0.1 \quad (3.12)$$

The above conditions are normally met for the frequency range of this Report for any polarization, and for the values of ground constants normally encountered for irregular terrain. The solution is also applicable to a spherical Earth, provided the above two conditions (3.11) and (3.12) are met; an exception is the special case of vertical polarization over sea water, unless the frequency is more than 1 GHz.

3.2 Multiple obstacles and irregular terrain

3.2.1 Multiple knife-edges

The theory of diffraction over two knife-edges has been fully treated [Millington *et al.*, 1962] and a rigorous method is available for predicting field strengths over a double knife-edge. The theoretical solution for diffraction over multiple successive knife-edges (three or more) requires the evaluation of a multiple Fresnel-type integral of a dimension equal to the number of edges; although this is complicated it is feasible with the aid of a computer. For engineering purposes, however, an approximate method is available [Deygout, 1966] which employs an extension of the single-edge diffraction theory.

3.2.2 Multiple rounded obstacles

No rigorous method exists for the prediction of field strength by diffraction over several rounded obstacles. An approximate method [Assis, 1971] is available which employs a simplified solution based on the assumption that each obstacle can be represented by a cylinder with a radius equal to the radius of curvature at the obstacle top.

3.2.3 Irregular terrain

Theoretical diffraction methods have been developed to deal with certain models of terrain features [Furutsu, 1957 and 1959; Dougherty, 1970]. Some paths can be treated as a succession of crests, which may be represented as knife-edges or cylinders according to the sharpness of the crests.

A fundamental theoretical approach to the problem of wave propagation over irregular terrain has also been made [Hufford, 1952] using an integral equation technique. This has been used to determine radiated space wave patterns as a function of the launch elevation angle and for determining the optimum positioning of an HF coastal antenna on a sloping beach [Ott, 1971].

An empirical diffraction propagation model has been introduced [Blomquist and Ladell, 1975; Blomquist, 1975]. In this model the diffraction loss for the particular terrain profile and frequency is first calculated assuming the equivalent spherical Earth and multiple knife-edge diffraction models separately. The losses for these two are then combined by a simple mathematical relationship.

A method for low time percentages is described in Report 569.

A numerical method [Assis, 1981] has been developed for use in those cases where a terrain feature can be modelled as a single knife-edge and terrain is irregular in a direction perpendicular to the direction of propagation. Measurements in the frequency range from 270 to 330 MHz indicate that knife-edge calculations can result in ± 10 dB errors if account is not taken of the lateral irregularities.

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RECOMMENDATION 527-1

ELECTRICAL CHARACTERISTICS OF THE SURFACE OF THE EARTH *

(1978-1982)

The CCIR,

CONSIDERING

- (a) that ground-wave propagation is mainly governed by the electrical characteristics of the ground, including its vegetation; and the extent to which lower strata influence the effective values of the electrical characteristics of the Earth depends on the depth of penetration of the radio energy;
- (b) that values of the relative permittivity and the conductivity are needed as a function of frequency for various types of surface;
- (c) that information on the variation of the penetration depth with frequency is required,

UNANIMOUSLY RECOMMENDS

that the curves in Annex I be used in the calculation of ground-wave field strength at the frequencies concerned and under the conditions stated.

ANNEX I

The following points are to be especially noted with regard to the curves:

- The values of relative permittivity (dielectric constant) and conductivity in Fig. 1 for different types of ground indicate the approximate range of values which may be met under different conditions, but in extreme cases values outside this range may occur. In very wet fertile areas higher values of conductivity will be found, while in mountainous and arctic regions the conductivity at frequencies below 100 MHz may be as low as 10^{-5} S/m. Also in cases of snow-covered ground, lower values of permittivity than shown in curve E of Fig. 1 may be encountered. The water in lakes and rivers has a conductivity that increases with the concentration of impurities.
- At low frequencies, except for sea water, strata down to a depth of 100 m or more must be taken into account as shown in Fig. 2. This is of particular importance when the upper strata are of lower conductivity and the energy can therefore penetrate more readily to lower levels. Such cases, for example, occur for ice-covered lakes and ocean areas.
- A description of forest attenuation is given in Report 236.

* See also Report 229.

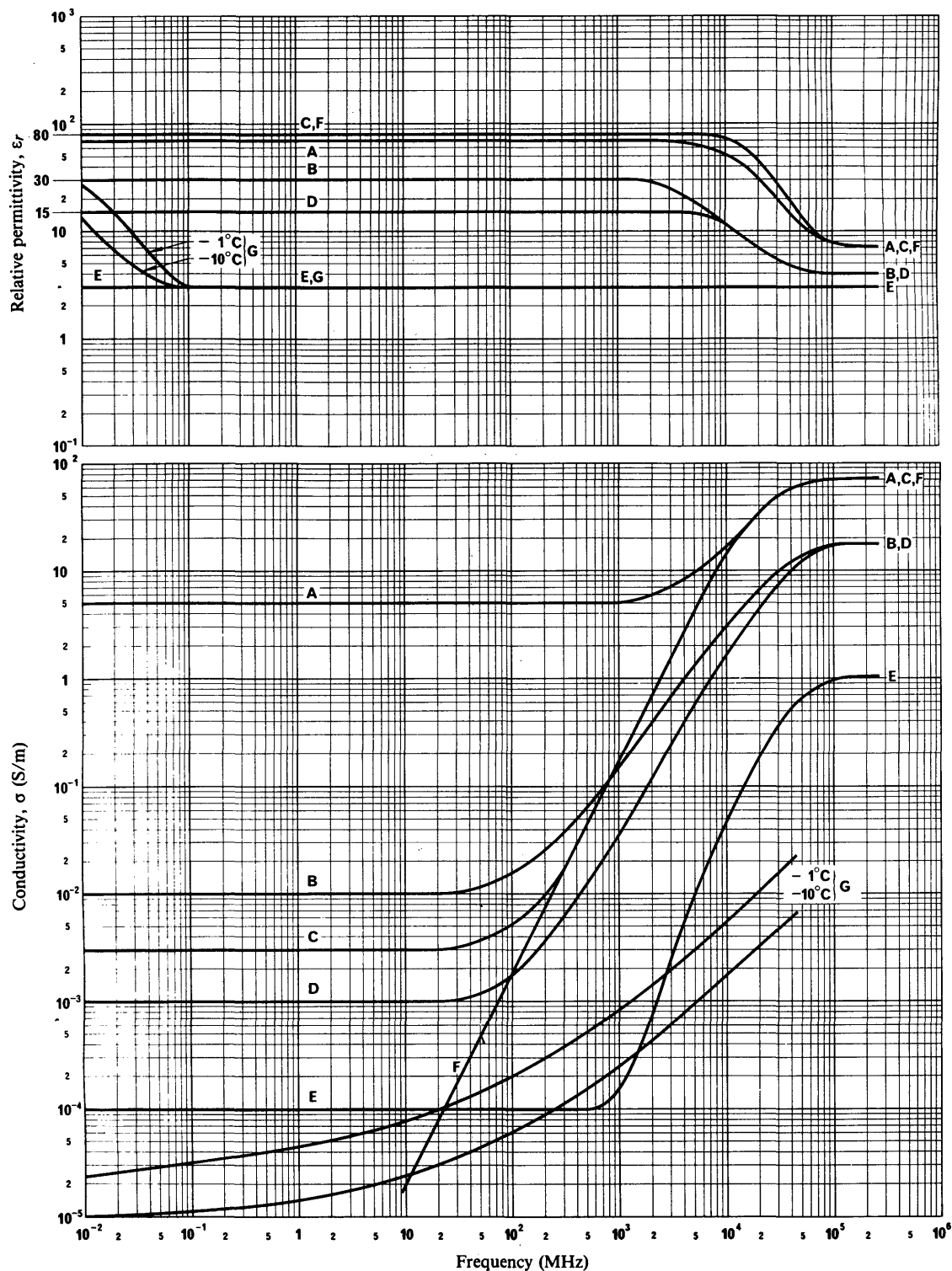
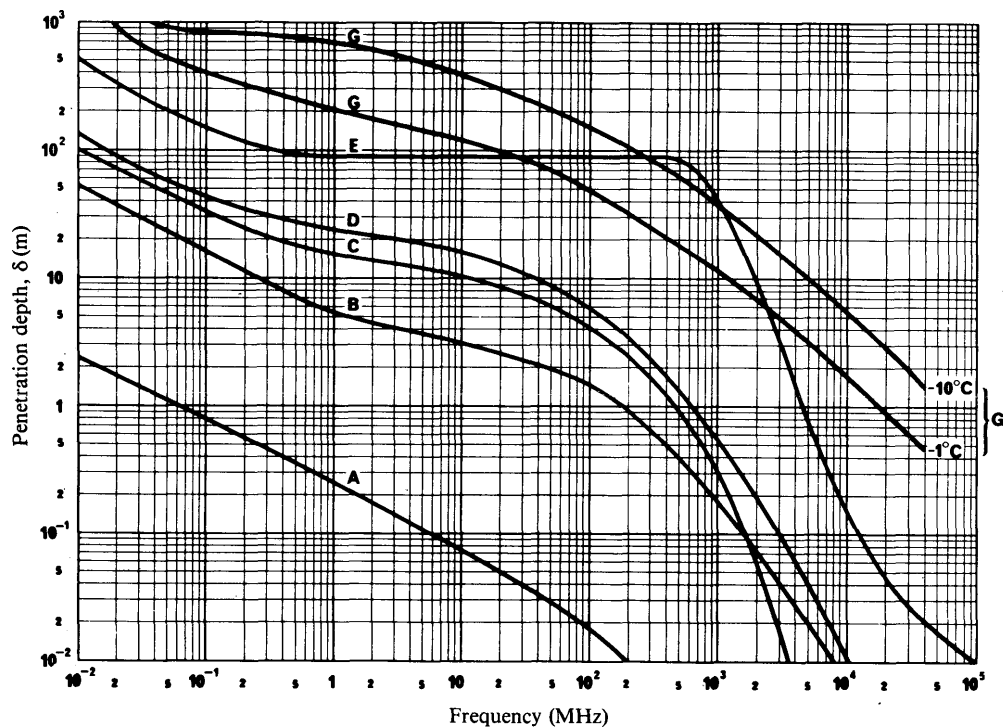


FIGURE 1 — Relative permittivity, ϵ_r , and conductivity, σ , as a function of frequency

- A: sea water (average salinity), 20° C
- B: wet ground
- C: fresh water, 20° C
- D: medium dry ground
- E: very dry ground
- F: pure water, 20° C
- G: ice (fresh water)

FIGURE 2 – Penetration depth δ as a function of frequency

- A: sea water
- B: wet ground
- C: fresh water
- D: medium dry ground
- E: very dry ground
- G: ice (fresh water)

REPORT 229-4

ELECTRICAL CHARACTERISTICS OF THE SURFACE OF THE EARTH

(Question 1/5)

(1959-1963-1970-1974-1978-1982)

1. Introduction

This Report discusses the physical factors upon which the electrical characteristics of the surface of the Earth depend. The methods for estimating and determining the values of the electrical characteristics in connection with the calculation of radio propagation are discussed in Report 879.

2. The characteristics of the ground

The electrical characteristics of any medium may be expressed by three parameters: the permeability, the permittivity and the conductivity. They jointly influence wave propagation in accordance with the following expression for the propagation coefficient

$$k = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} = j\omega \sqrt{\mu \left(\epsilon - j \frac{\sigma}{\omega} \right)} \quad (1)$$

where a time dependence of the form $\exp(j\omega t)$ is assumed.

The permeability of the ground, μ , can normally be regarded as equal to the free-space permeability so that in most propagation problems we are concerned only with permittivity, ϵ and the conductivity, σ . When referred to the ground, the propagation coefficient may be written

$$k = j \frac{2\pi}{\lambda} \sqrt{\epsilon_r - j60 \sigma \lambda} \quad (2)$$

where ϵ_r is the relative permittivity, σ is in S/m, and λ is the free-space wavelength in metres.

It may be noted that the displacement and the conduction current densities are in the ratio of ϵ_r to $60 \sigma \lambda$, from which their relative importance can be judged. It is seen that at frequencies above 100 MHz account must be taken of the variation of permittivity and conductivity with frequency (dipolar and ionic) [Saxton and Lane, 1952]. Furthermore, it should be noted that a value of 80 has often been used for the relative permittivity of sea water at low temperatures and frequencies below about 1 GHz. The actual value, even at low frequencies, depends on the temperature and composition of the sea water.

Typical values of conductivity and permittivity for different types of ground, as a function of frequency, are given in Recommendation 527. These values, frequently referred to as intrinsic values, refer to homogeneous sub-surface soil structures and can be determined by laboratory measurements of soil samples. They normally coincide with the values obtained with other surface impedance measurements in the case of homogeneous sub-surface structures.

However, the sub-surface structure is rarely homogeneous, but rather consists of two or more layers of different thickness and different conductivities and permittivities. This fact must be taken into account and this could be done by introducing the concept of effective parameters. This concept of effective parameters allows the use of the homogeneous smooth earth ground-wave propagation curves of Recommendation 368, the inhomogeneous sub-surface soil being replaced by an equivalent homogeneous structure whose parameters are the effective conductivity and effective permittivity. These parameters can be determined if the values of the parameters of each layer are known. These values coincide with the results obtained by surface impedance or antenna impedance measurements.

In some frequency bands, in which attention should be paid to other factors influencing the ground-wave propagation, such as terrain irregularities, vegetation cover, surface objects, etc., this concept can be extended by further modification of that effective value. Such values are obtained by application of the ground-wave attenuation method, or by analytical means.

3. Factors determining the effective electrical characteristics

The effective values of the constants of the ground are determined, not only by the nature of the soil, but also by its moisture content and temperature, by the frequency, by the general geological structure of the ground and by the effective depth of penetration and lateral spread of the waves.

3.1 Nature of the soil

Although it has been established by numerous measurements that the value of the electrical characteristics vary with the nature of the soil, it seems probable that this variation may be due not so much to the chemical composition of the soil as to its ability to absorb and retain moisture. It has been shown that loam, which normally has a conductivity of the order of 10^{-2} S/m can, when dried, have a conductivity as low as 10^{-4} S/m, which is of the same order as that of granite.

3.2 Moisture content

The moisture content of the ground is probably the major factor determining its electrical constants. Laboratory measurements have shown that, as the moisture content is increased from a low value, the values increase, rapidly reaching their maximum as the moisture content approaches the values normally found in such soils on site. At depths of one metre or more, the wetness of the soil at a particular site seems to be substantially constant all the year round and, although it may increase during rain, the drainage of the soil and surface evaporation soon reduces it to its normal value after the rain has stopped.

The moisture content of a particular soil may, however, vary considerably from one site to another, due to differences in the general geological formation which provide better drainage in one case than another.

3.3 Temperature

Laboratory measurements of the electrical characteristics of soil have shown that, at low frequencies, the temperature coefficient of conductivity is of the order of 3% per degree Celsius, while that of the permittivity is negligible. At freezing point, there is generally a large decrease in both permittivity and conductivity. Although these changes are appreciable, it must be borne in mind that the range of temperature variation during the year decreases rapidly with depth, so that temperature effects are likely to be important only at high frequencies where the penetration of the waves is small (see § 3.6), or when the ground is frozen to a considerable depth.

Figure 1 illustrates the dependence of the conductivity [Albrecht, 1963] and relative permittivity [Blomquist, 1968] on the water content and temperature of the soil. It should be emphasized that such changes will only occur in the intrinsic electrical characteristics. Changes in the effective electrical characteristics will depend on the extent to which changes in water content and temperature penetrate the surface.

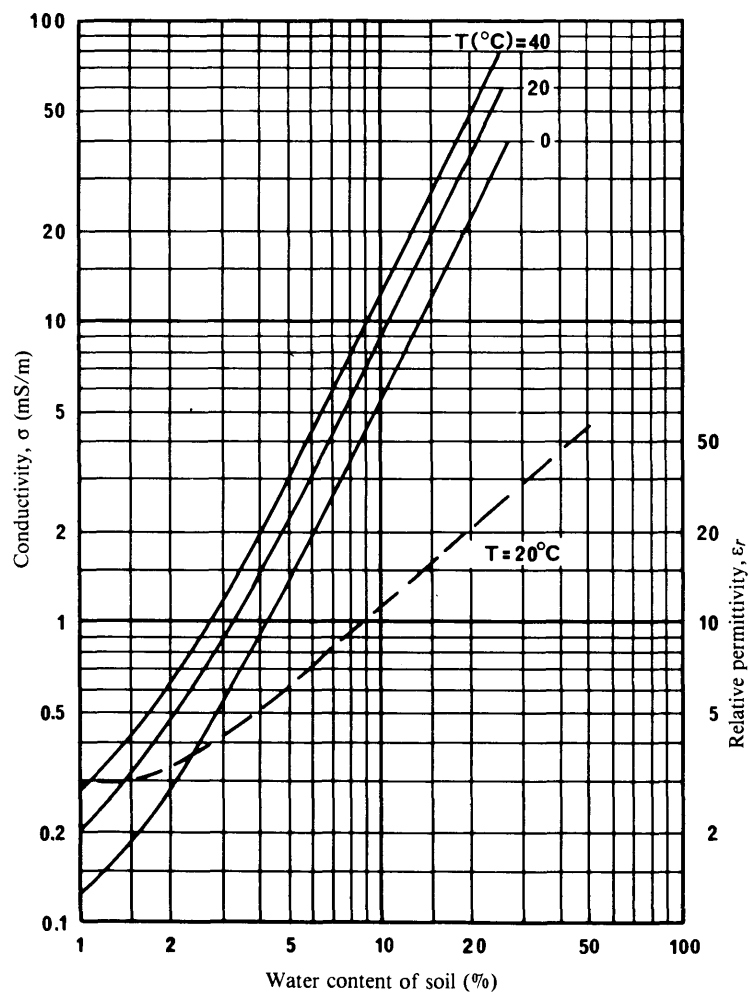


FIGURE 1 – The intrinsic conductivity and relative permittivity of soil as a function of water content

———— Conductivity, σ
 - - - - - Relative permittivity, ϵ_r

3.4 Seasonal variation

The effect of seasonal variation on ground-wave propagation loss depends upon the ratio of the depth of the soil exhibiting seasonal changes to the penetration depth. Any such seasonal effects will be frequency dependent. Very small seasonal variations, observed in Loran-C phase measurements [Doherty and Johler, 1975] at 100 kHz, have been interpreted as entirely caused by refractive index changes. Measurements at medium frequencies carried out in India [CCIR, 1974-78] have shown almost no variations in field strengths in the rainy monsoon season when compared with those recorded during the dry season. Temperate zone MF measurements in Finland [Koskenniemi and Laiho, 1975] have shown only a 1 to 2 dB change in field strength between summer and winter.

Actual measurements by radio amateurs [Sevick, 1978] of the conductivity of the first one-half metre of soil in the USA show a seasonal cyclic variation of a factor of two in the surface conductivity. These conductivity values seem to be a function of mean soil temperature with small fluctuations associated with measured rainfall.

3.5 Frequency

Laboratory measurements on soil samples show that there is a variation of the permittivity and conductivity with frequency which depends markedly on the moisture content. The values for fresh water and sea water can be calculated for any frequency from the data given [Saxton and Lane, 1952].

3.6 General geological structure

The ground involved in overland propagation is not usually homogeneous, so that the effective electrical characteristics are determined by several different types of soil. It is, therefore, of great importance to have a complete knowledge of the general geological structure of the region concerned. The effective electrical characteristics over an area or along a path are determined, not only by the nature of the surface soils, but also by that of the underlying strata. These lower strata may form part of the medium through which the waves travel or they may have an indirect effect by determining the water level in the upper strata.

3.7 Energy absorption by surface objects

Although surface objects have no direct influence on the electrical characteristics of the ground itself, they can contribute appreciably to the attenuation of ground waves, and the effects of such energy losses may be taken into account by using appropriately modified values of the electrical characteristics in propagation calculations.

Particularly high attenuation rates are associated with transmission loss in wooded terrain at frequencies above about 30 MHz [Blomquist, 1958; Rice, 1971; Saxton and Lane, 1955; Tamir, 1967]. Such attenuation may increase even more when the trees are covered with wet snow, and under conditions of rain when the trees are in leaf. A more detailed treatment of this subject is given in Report 236.

4. Penetration and spread of waves

4.1 The extent to which the lower strata influence the effective electrical characteristics depends upon the depth of penetration of the radio energy, δ , which is defined as that depth at which the wave has been attenuated to $1/e$ (or 37%) of its value at the surface. The penetration depth as a function of frequency is shown in Recommendation 527 for different types of ground and water.

4.2 If the penetration depth, δ , is less than the thickness of the layer, the underlying strata have little influence. If δ is much greater than the top layer thickness, propagation is determined by the electrical characteristics of the lower strata. In intermediate cases, the effective electrical characteristics can be determined by a theoretical relationship [Wait, 1970] and an appropriate model of the sub-surface structure.

4.3 The radio energy received at a point does not travel solely by the direct path from the transmitter, but also by a large number of indirect paths distributed on either side of it. It is necessary, therefore, to consider electrical characteristics not only along the path itself, but also over the area covered by the lateral spread of the wave paths. No definite limits can be put on this area, but it has been suggested that it is effectively the first Fresnel half-wave zone, i.e. the ellipse having the transmitter and receiver positions as its foci and axes of $(D + \lambda/2)$ and $\sqrt{D\lambda}$ respectively, where D is the length of the direct path and λ is the wavelength.

5. Sea water

The electrical conductivity of sea water is a function of the salt content (salinity) and temperature. At frequencies below 1 GHz its value is given by the expression:

$$\sigma = 0.18 C^{0.93} [1 + 0.02 (T - 20)] \quad \text{S/m} \quad (3)$$

where C is the salt content in parts per thousand and T is the temperature in degrees Celsius.

At 20 °C a value of 5 S/m is used as a world-wide average. In some areas of the Baltic Sea values of less than 1 S/m have been observed. In the Red Sea the conductivity may exceed 6 S/m.

The permittivity of sea water is also a function of salinity and temperature. A value of 80 has often been used for the relative permittivity of sea water at 20 °C although the actual low frequency value is about 75. However, at frequencies below about 100 MHz, ϵ_r is much less than $60 \lambda \sigma$, and either value may be used to calculate ground-wave propagation factors over the sea with no measurable differences in the results.

6. Sea ice

Sea ice is a complex substance whose electrical characteristics vary over a large range as a function of the temperature and age of the ice. There is good agreement between theoretical physical models of sea ice [Luchininov, 1968] and measured electrical characteristics [Wentworth and Cohn, 1964]. The range of values of these electrical characteristics is shown in Fig. 2 for frequencies between 0.1 and 30 MHz. Above about 30 MHz the electrical characteristics of sea ice asymptotically approach those of fresh water ice (Recommendation 527).

The impact of an ice layer on ground-wave propagation over a sea path depends on both the electrical characteristics of the ice and the ratio of the thickness of the ice layer to the penetration depth at the frequency of interest. In many cases, the thickness of the ice will be much smaller than the penetration depth.

The range of penetration depths in sea ice is also shown in Fig. 2 for frequencies between 0.1 to 30 MHz. The effective values of conductivity and permittivity of an ice layer over the ocean can be determined from the relationship discussed above in § 4.2 if the thickness of the ice layer is known.

Changes in ground-wave propagation over sea ice will also occur if a film of water forms on the ice due to rain or melting of the surface.

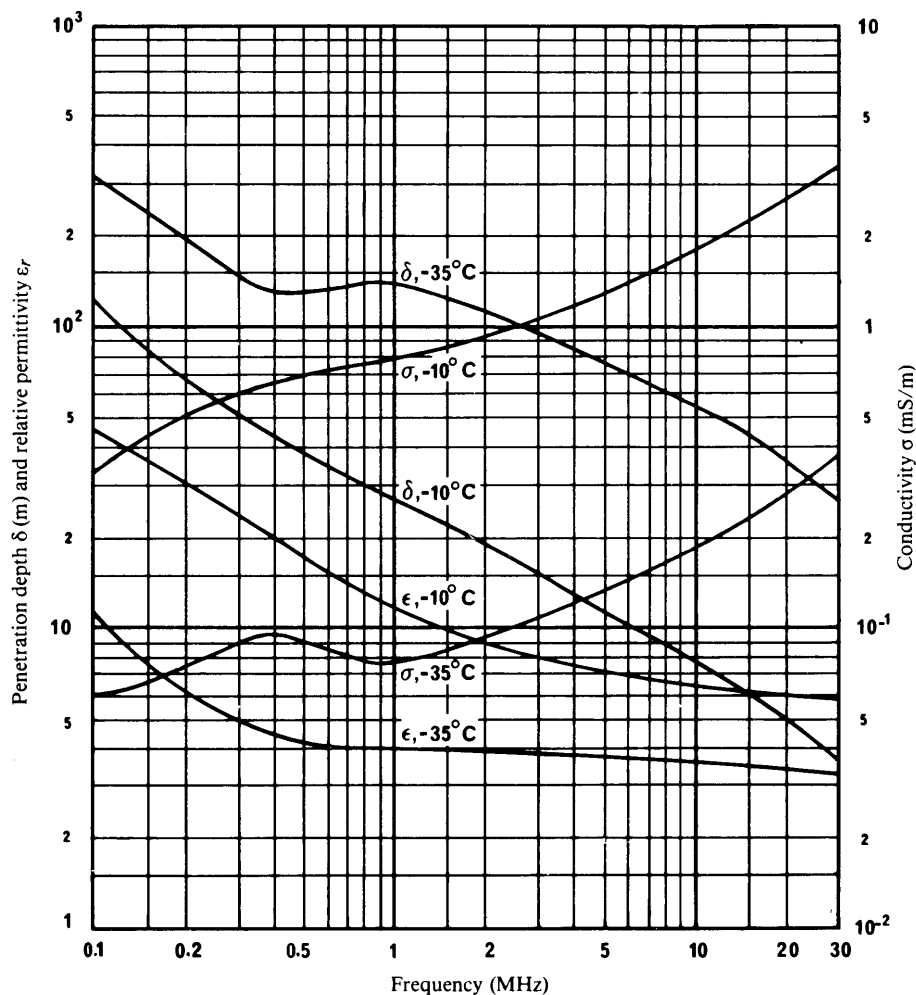


FIGURE 2 – Range of values of the penetration depth (δ), relative permittivity (ϵ_r), and conductivity (σ) of sea ice [Wentworth and Cohn, 1964]

(These extreme values occur for new ice at -10°C with an age of less than one month and old ice at -35°C with an age greater than one year).

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CCIR Documents

[1974-78]: 5/257 (India).

REPORT 879

METHODS FOR ESTIMATING EFFECTIVE ELECTRICAL CHARACTERISTICS OF THE SURFACE OF THE EARTH

(Decision 3)

(1982)

1. Introduction

This Report is concerned with the measurement of the effective electrical characteristics of the surface of the earth. A knowledge of these characteristics is especially important in MF and LF broadcast planning where the ground wave is the primary mode of propagation. The effective conductivity of the surface of the earth typically lies between 0.1 and 30 mS/m. From the curves found in Recommendation 368, it is seen that this range of conductivities results in a 44 dB difference in field-strength values for a 1 MHz signal at a distance of 100 km. Thus a knowledge of these characteristics is necessary both for accurate estimates of MF and LF broadcast coverage and for interference calculations.

2. Effective ground electrical characteristics

The term effective electrical characteristics is used in connection with ground-wave propagation to emphasize the fact that the values of conductivity, σ , and permittivity (dielectric constant), ϵ_r , which should be used for ground-wave field-strength calculations, may be different from those values which would be obtained from laboratory measurements. In many cases the values of the electrical characteristics at the surface must be modified because of the influence of terrain irregularities and sub-surface strata. At low frequencies and low surface conductivities, the ground-wave propagation loss may be determined by the value of the conductivity of the sub-surface strata.

2.1 Relative importance of conductivity and permittivity

For a homogeneous earth, the value of the permittivity, ϵ_r , has little influence on the MF and LF ground-wave transmission loss if $\epsilon_r \ll 60 \lambda \sigma$. In most cases it is sufficient to use the values of ϵ associated with the estimated conductivity ranges given in Recommendation 527. Alternatively, one can use the empirical relation found by Hanle [1966] $\epsilon_r = 50 \sigma^{1/5}$ where conductivity is expressed in units of S/m.

Over ground with horizontally stratified layers, however, the effective permittivity may become very large or even negative [Eliassen, 1957; Wait, 1970]. Thus, it is possible that the relation $\epsilon_r \ll 60 \lambda \sigma$ may not be satisfied for the effective electrical characteristics even though it may be satisfied for surface layer and the sub-surface layers. Wait [1970] has developed a theoretical relationship for the effective electrical characteristics over horizontally stratified ground. Report 716 discusses the necessity of using the total complex effective surface impedance when calculating the phase of the ground wave for precision radionavigation systems [Johler and Horowitz, 1974].

2.2 Frequency dependence of the electrical characteristics

The conductivity of soil samples shows a frequency dependence above 10 MHz as illustrated in Recommendation 527, Fig. 1. At lower frequencies, there is no inherent frequency dependence of the conductivity of the soil.

The effective electrical characteristics, however, will show a frequency dependence when the surface values are modified by sub-surface layers and irregular terrain. The frequency dependence of the effective electrical characteristics with underlying strata is a function of the ratio of top layer thickness to penetration depth. Thus the effective ground constants at LF may be significantly different from those at HF. The influence of terrain irregularities on the effective electrical characteristics is dependent on the ratio of terrain height variations to wavelength. Further information on this subject will be found in Report 236.

2.3 Penetration depth

From the above discussion it can be seen that the effective electrical characteristics are determined by the extent to which the electromagnetic field penetrates the soil. This extent is characterized by the penetration depth which is shown in Fig. 2 of Recommendation 527. In the MF band, the penetration depth is typically 5 to 100 m. Consequently, any measurement method used to measure effective electrical characteristics should either use radio methods at the appropriate frequency or measure the soil to a depth equivalent to the penetration depth at the frequency of interest.

3. First order estimates of effective conductivity

Initial estimates of the effective conductivity in a region for the MF band can be obtained from a knowledge of the geological and lithological structure in the region. This method is based on the observed association between measured MF effective conductivities in the United States of America and Canada and the structural properties of the ground [Barghausen *et al.*, 1966]. Table I can be used to form these initial estimates. Similar associations between conductivity and structure have also been made for the Soviet Union [Yakupov *et al.*, 1969] and for Norway [Eliassen, 1957].

Since these initial conductivity estimates cover broad ranges, ground-wave field-strength estimates in the MF band using the mid-range conductivity values will have up to a ± 10 dB uncertainty at distances less than 100 km. These estimates, however, are useful for estimating broadcast coverage where measured data do not exist and for planning actual field measurements of the effective conductivity. The UNESCO-FAO *Soil Map of the World* is a useful source for geological and lithological data.

TABLE 1 - *Expected ground conductivities*

Ground conductivity (S/m)	Type of ground
5	Sea water
10^{-2}	Very moist soil, cultivated soil, fresh water
10^{-3}	Dry soil, clay, forest soil, desert soil, soil in mountainous areas, fresh sea ice
10^{-4}	Granite, dry gravel and sand, mountainous areas in cold regions, old sea ice
10^{-5}	Dry glacier in mountainous areas, permafrost in northern polar areas

Note. - For areas in the interior of Antarctica, where the absolute humidity is very low, the conductivity may be of the order of 10^{-6} S/m.

4. Field measurement of effective electrical characteristics

In the following sections the wave tilt method and the attenuation method of measuring electrical characteristics are discussed. These are the preferred methods for propagation applications since the results can be related directly to the effective values needed for ground-wave field-strength calculations.

Over homogeneous ground these methods can be used easily. The wave tilt method requires the measurement of three quantities at each field point but the electrical characteristics can be found directly from this data. The attenuation method, on the other hand, requires only a single field-strength measurement at each field point but the analysis of the data requires matching a series of field points to the theoretical ground-wave propagation curves.

In the case of inhomogeneous ground, however, the interpretation of measurement data can be very difficult. The problem arises from the sudden change in field strengths at a boundary between two regions of different conductivity. These transition effects associated with a boundary tend to damp out as one moves further from the transmitter. Thus care must be exercised to make measurements at a sufficient distance from the boundary so that the "steady state" conditions which are characteristic of the soil and not of the boundary have been established. Since the behaviour of electromagnetic fields over horizontally inhomogeneous ground is well understood (Recommendation 368), the attenuation method is preferred in these cases. In either case, it is very important to make measurements at a number of points along a radial path outward from the transmitter so that the transition to a region of different conductivity can be easily identified.

4.1 Wave-tilt method

4.1.1 Measurement methods

The wave tilt method has been reviewed with a bibliography covering a forty-year period by King [1976]. Eliassen [1957] provides detailed practical advice on measurement techniques. The method is based on the fact that, at a surface with finite conductivity, the electric field due to a vertically polarized source will have a small horizontal component in the direction of propagation. This causes the total electric field vector to be inclined or tilted from the local vertical as shown in Fig. 1. Since the vertical, E_z , and horizontal, E_x , components of the field are not in phase, the field traces out an ellipse in the plane defined by the vertical and the direction of propagation. A simple relationship exists between the electrical characteristics and the two field components:

$$\epsilon_r = |E_z/E_x|^2 \cos 2\phi \quad (1a)$$

$$\sigma/f = |E_z/E_x|^2 (\sin 2\phi)/18 \quad (1b)$$

where ϕ is the electrical phase angle between the field components and f is the frequency of the ground wave in MHz.

In practice, however, it is very difficult to measure the horizontal component, E_x , of the field since it is generally much smaller than the vertical component E_z . A small misalignment of the measurement antenna introduces a large error component from E_z . In addition, the measurement of the phase angle, ϕ , requires expensive equipment.

A common method of making wave tilt measurements is to use a field strength meter (FSM) connected to a short dipole which can rotate about its centre on an axis normal to the field components. One then measures the maximum, E_1 , and minimum, E_2 , field strengths as the antenna is rotated and records their ratio $r = E_2/E_1$. In addition, the tilt angle θ , the angle between the vertical and the direction of E_1 is also recorded. Since only the ratio of the field-strength components, r , is required, this method has the advantage that a calibrated antenna and FSM need not be used.

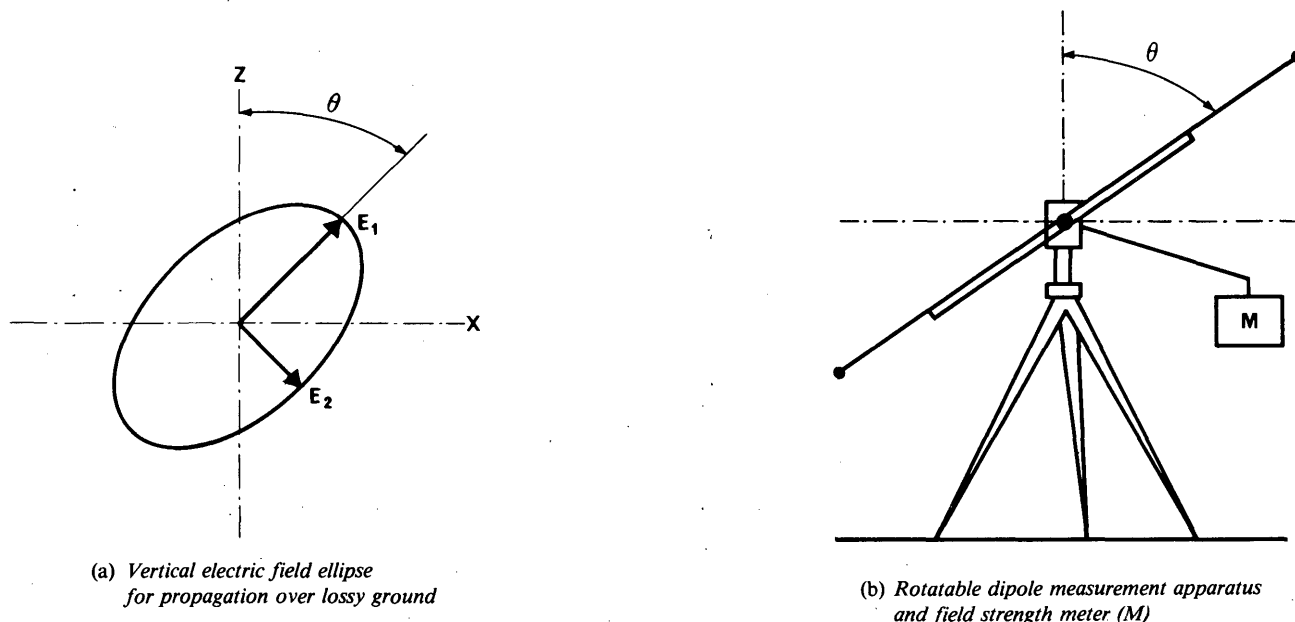


FIGURE 1

4.1.2 Analysis of wave tilt data

The variables of equation (1) are related to the measured quantities r and θ by the formula

$$|E_x/E_z| = \frac{r^2 + \tan^2 \theta}{1 + r^2 \tan^2 \theta} \quad (2a)$$

$$\cos 2\phi = \frac{(1-r^2) \sin 2\theta - 4r^2}{(1-r^2) \sin 2\theta + 4r^2} \quad (2b)$$

As an alternative to a numerical analysis of the data, the electrical characteristics can be obtained directly from r and θ by means of Fig. 2 [Eaton, 1976].

4.1.3 Accuracy of wave tilt measurements

The shaded rectangle A in Fig. 2 corresponds to a measurement error of $\pm 1^\circ$ in the tilt angle and ± 1 dB in the axial ratio. From the figure it can be seen that accuracy of the effective conductivity depends mainly on the accuracy of the tilt angle measurement. Similarly, the accuracy of the effective permittivity is closely related to the accuracy of the axial ratio. For telecommunications purposes, the impact of this experimental error must be further assessed in terms of the uncertainty it introduces into field-strength calculations.

While the wave tilt method gives values for the electrical characteristics from a measurement at a single point, it is important that a survey of an area include a series of measurements along a radial line from the source of the field. This is required in order that transitions from a region with one set of electrical characteristics to another region with different electrical characteristics can be identified. Over homogeneous ground, the tilt angle and axial ratio will be independent of the distance from the source

(this assumes the measurements are taken at a distance greater than several wave lengths). For inhomogeneous paths the tilt angle and axial ratio will change suddenly at a conductivity boundary. The values will then change slowly with radial distance until the final values are reached which are characteristic of the new region [Blomquist, 1975]. These distances can be very long. If a third conductivity region is encountered before the new equilibrium values have been established, the interpretation of wave tilt data can become very difficult. [Stokke, 1978].

However, if these limitations are taken into account, the wave tilt method gives satisfactory results. Measurements in the Federal Republic of Germany show very good agreement between the measured values and the values calculated from Millington's method, when the wave tilt method was used to measure the ground conductivity [Damboldt, 1981].

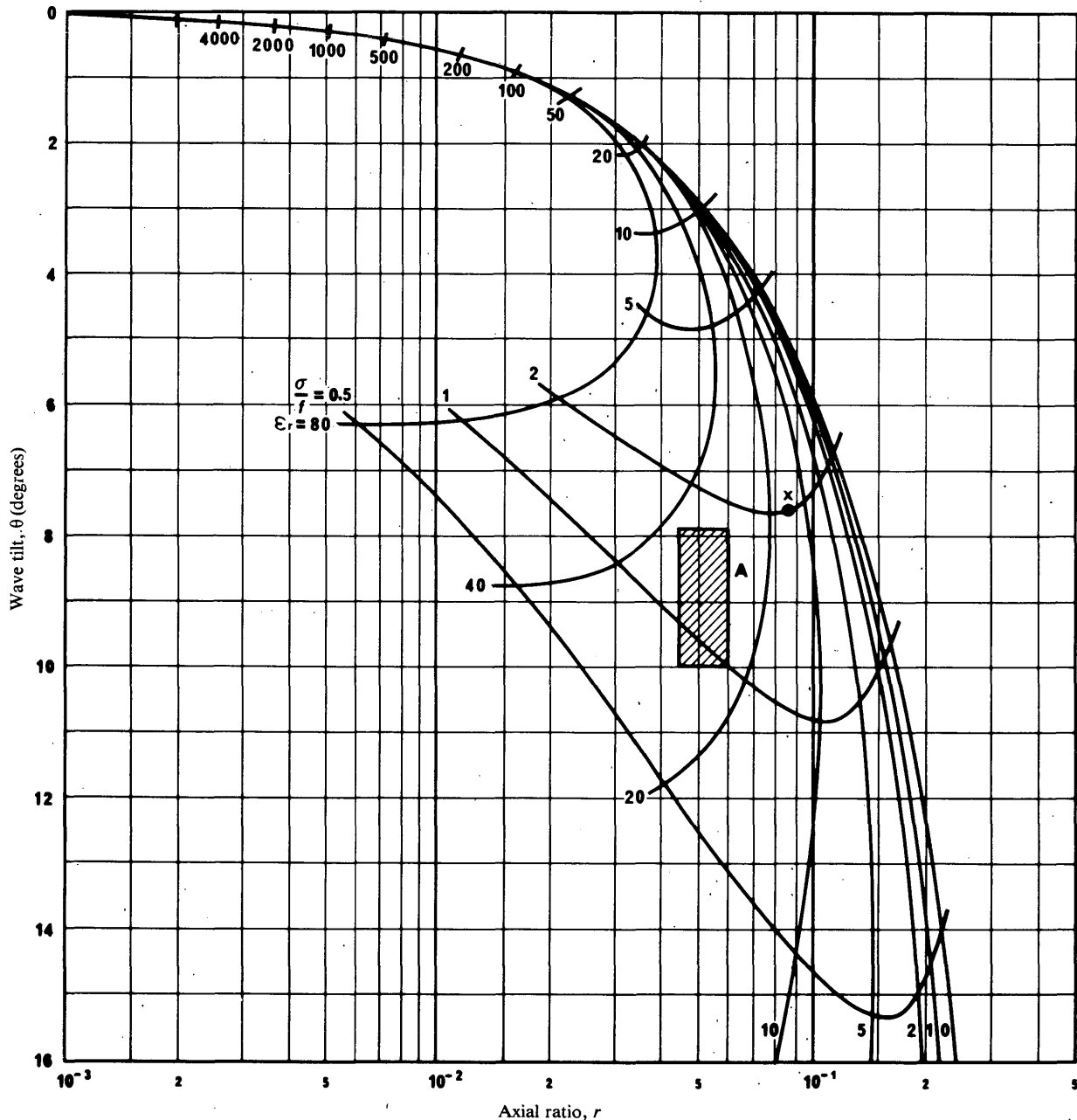


FIGURE 2 — Relationship between wave tilt angle (θ), axial ratio of ellipse (r) and the ground parameters

(The conductivity (σ) is in units of mS/m and f is the measurement frequency in MHz)

4.2 The attenuation method

The attenuation method of measuring effective electrical characteristics consists of making field-strength measurements along a radial line from a vertically-polarized transmitting antenna and matching the experimental data to theoretical curves such as those found in Recommendation 368. If the curves match, the effective ground constants along the radial are the same as those used to calculate the theoretical curves.

4.2.1 Measurement methods

General methods of measuring field strengths are described in Report 227. It is important that field-strength measurements be made at a sufficient number of points along a radial so that a smooth experimental curve can be drawn and so that rapid changes in the slope of the curve will be recognized. This latter point is important in identifying the boundary between regions of different conductivity or inhomogeneous paths. A practical difficulty in using the attenuation method is finding a sufficient number of roads or other accesses to a number of points along a given radial path.

A modern approach to making attenuation method measurements has been successfully used in Finland [Laiho, 1976; Koskenniemi and Laiho, 1975]. The field-strength measurement apparatus is carried out on a small aircraft such as a light airplane or helicopter with the measurement antenna mounted externally on the aircraft. Field strength and navigation data can be recorded continuously as the aircraft flies along a radial by means of a strip chart recorder. Measurements of this kind tend to be very economical since a large area can be covered in only a few flight hours using only a pilot and a navigator/equipment operator.

The altitude at which these aircraft measurements are taken is important because of height gain considerations. Most theoretical ground-wave curves are computed for both terminals on the surface. If the receiving terminal is elevated, the measured field will be higher than the surface value because of the height gain effect. Height gain corrections cannot be made to the measured data since this requires a knowledge of the ground constants. Laiho [1976] estimates, however, that the height gain is less than 1 dB for frequencies below 1400 kHz and heights below 100 m. This suggests that MF effective conductivity measurements with an aircraft should be made using the lowest frequency transmitter available and the lowest altitude consistent with flight safety.

4.2.2 Analysis of attenuation method data

The theoretical curves such as those found in Recommendation 368 are computed for an assumed reference radiated power. Thus, the measured data must be normalized to this reference. If the curves of Recommendation 368, which are based on a 1 kW effective monopole radiated power (e.m.r.p.) are used, a factor of $20 \log p_{eff}$ must be added to the measured data in dB(μ V/m) before analysis. p_{eff} is the e.m.r.p. of the transmitter used for the measurement. If this power is not known, it is suggested [Laiho, 1976; Gregorač and Budin, 1976] that the slope of the experimental curve be matched to the theoretical curves for distances close to the transmitter. Then, taking the measured field strengths, E_r , at n points along a radial path and the calculated values at the same distances, A_{sr} , which correspond to the conductivity curve whose slope matches the measured data, one can determine the effective radiated power from the relation,

$$p_{eff}^{1/2} = \left(\sum_{r=1}^n A_{sr} E_r \right) / \sum_{r=1}^n A_{sr}^2 \quad (3)$$

and determine the average conductivity in the vicinity of the transmitter.

This method of data analysis can be used very easily over homogeneous paths. For inhomogeneous paths the analysis becomes very difficult for more than one change in conductivity along a radial. In the case of the measurements in Finland mentioned above [Laiho, 1976], the analysis was performed using a digital computer to make theoretical calculations over mixed paths using Millington's method (Recommendation 368) in a least-squares curve fitting procedure. A nearly identical procedure has been used in Yugoslavia [Gregorač and Budin, 1976].

Figure 3 illustrates the difficulty in analyzing mixed path data. This figure is derived from the work of Stokke [1975] in developing a graphical method for calculating ground-wave transmission loss over mixed paths which is found in Annex II of Recommendation 368. The figure illustrates the simple case of the electric field over a path which has a change in conductivity at a distance d_1 , from the transmitter.

When the conductivity changes from a value to a lower value, note that the field-strength curve goes through the mean between the two homogeneous earth curves at the distance $d = 2d_1$, and approaches a value which is parallel to the lower homogeneous earth curve. This asymptote is located above the lower homogeneous curve by a value equal to one-half the difference in dB between the two homogeneous curves at $d = d_1$.

A detailed description of how the measurements may be interpreted when there are many arbitrary changes in the conductivity, is given by Stokke [1978].

If the computational resources are not available or are not economical then a conductivity map should be made by using data from a series of transmitters. The data from each transmitter is used to define the boundaries of the homogeneous regions about each transmitter.

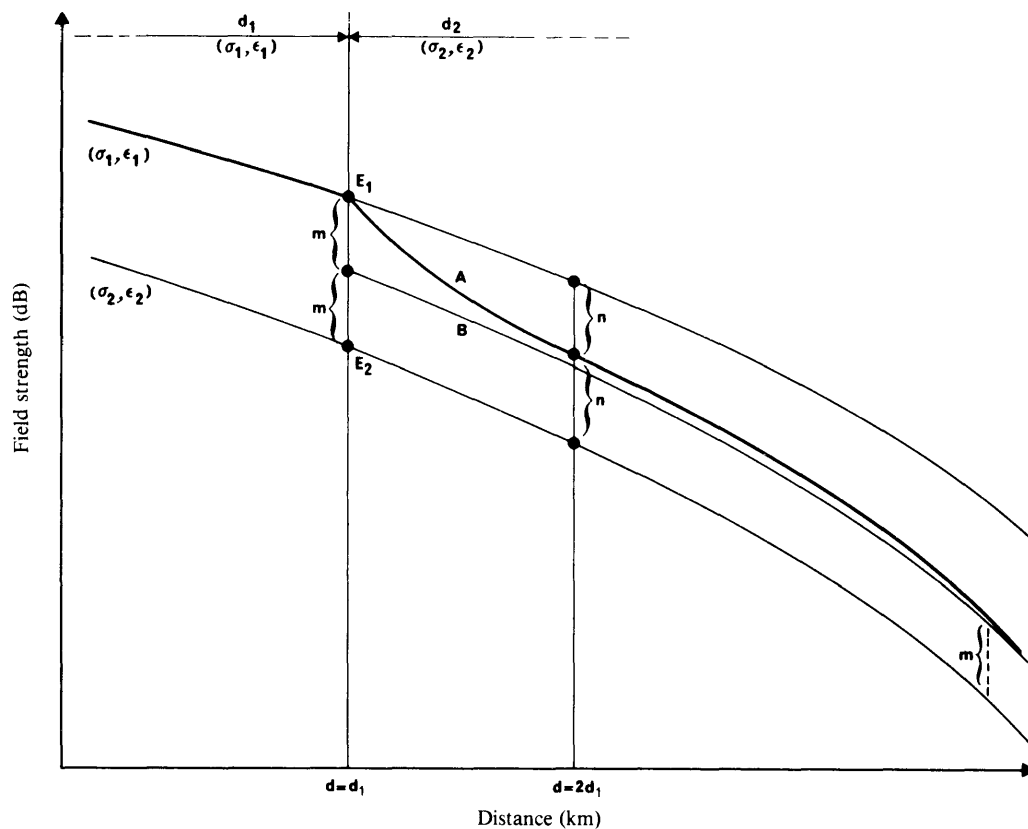


FIGURE 3 – Electric field behaviour at near a boundary between regions of different effective ground parameters

4.2.3 Accuracy of the attenuation method

Field-strength measurements in the MF band can generally be made to an accuracy of ± 2 dB. This implies an analysis error of ± 2 dB in the conductivity over homogeneous ground for the MF band as can be seen by reference to the figures of Recommendation 368. Additional errors will be introduced into the conductivity estimates on mixed paths for the reasons discussed above. Terrain irregularities will introduce more errors if the height of terrain features above the mean value along the path is much greater than a wavelength. Small terrain irregularities will result in a lower effective conductivity than would be measured for smooth terrain having the same soil structure [Barrick, 1971].

Moreover, the results will apply only to the particular path used, or to one very similar. The method is not suitable for detailed measurements of the electrical characteristics of earth over given small areas.

5. Other methods

Among other methods intended for telecommunication purposes one can identify the method of measuring the antenna input impedance. This method is based on the fact that the electrical characteristics of the earth can be deduced from measurements of the antenna input impedance. These measurements can be performed for antennas situated below, on, or just above the surface of the earth. Some laboratory measurements [Iizuka, 1964] and recent theoretical investigations [Popović and Gavrilov, 1976] indicate the possibility of deducing the electrical characteristics of the ground from a cylindrical (or equivalent strip) antenna impedance measurement, the antennas being pressed on the air-ground interface. In the application of this method, particular attention should be paid to the alignment of the antenna axis exactly at the interface. The advantage is that immersing is no longer necessary.

Various other methods exist for measuring the conductivity or dielectric constant of the surface of the earth. Some of these are described in Report 229. General descriptions of these methods together with extensive bibliographies can be found in a review by Lytle [1974] and IEEE Standard 356 [IEEE, 1974].

These methods are usually not suitable for broadcast planning purposes. Many are designed for geophysical exploration and cannot be used economically for wide area mapping of ground constants. Other methods give values for the electrical ground constants which are difficult to relate to the effective values which should be used for ground-wave propagation loss calculations. For this reason, the attenuation or wave-tilt methods are preferred.

The probe methods, however, may be useful in planning antenna installations. A detailed knowledge of the ground conductivity about a proposed HF antenna site is useful in determining the requirements for a ground screen system to maximize antenna efficiency. When making these measurements, the probe separations should be adjusted so that the measurements result in an effective conductivity [Grant and West, 1965] of a layer equal in depth to the penetration depth at the frequency of interest.

6. Measurement results

Actual field measurement of effective electrical characteristics will have a significant variation in the results due to various factors which influence the effective values. The effective MF conductivity map for the United States of America [Fine, 1954] was constructed from attenuation method data. Data from over 7000 radial measurements using 621 MF broadcast stations were analyzed with manual methods. The effective conductivity shows at least a factor of two variations for different radials about each transmitter even over paths which are geographically similar. Computer aided data reduction with mixed path corrections [Laiho, 1976] in Finland gave a higher resolution map with less data. The overall results of this experience is to suggest that MF field-strength calculations using the homogeneous smooth earth calculations will have a 5 dB uncertainty associated with the errors in the ground conductivity data.

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REPORT 236-5

INFLUENCE OF TERRAIN IRREGULARITIES AND VEGETATION ON TROPOSPHERIC PROPAGATION

(Study Programme 1A/5)

(1951-1953-1956-1959-1963-1966-1970-1974-1978-1982)

1. Introduction

The object of this Report is to describe how terrain characteristics affect the propagation of tropospheric radio waves between arbitrary antenna locations over irregular terrain.

It is not possible to make any general statement on the influence of the terrain and the vegetation on propagation. This influence is a complex function of frequency, electrical characteristics of the ground, tropospheric variations, path geometry, season and vegetation density.

2. General characteristics and idealizations

2.1 Electrical characteristics of the terrain

In principle, tropospheric propagation depends on the electrical characteristics of the Earth, as discussed in detail in Report 229. This dependence is of increasing importance with decreasing frequency, but at the higher frequencies it is often difficult to distinguish the effect of the lack of homogeneity of earth constants from that of the irregularities of the terrain, the latter becoming dominant when the irregularities are large in comparison with the wavelength concerned.

2.2 *Interaction between the terrain and the troposphere*

Texts of Section 5C of this Volume discuss the influence of the troposphere. Many effects of terrain and the troposphere are closely interrelated, but it is convenient to separate them as much as possible. It is observed that an increase in atmospheric refraction increases long-distance diffraction or forward-scatter fields but may also lead to multipath fading over shorter paths. Increased turbulence of the atmosphere may result in either an increase or a decrease of radio transmission loss, depending on the geometry of a particular path and the dominance of various propagation mechanisms associated with stratification of the refractive-index structure.

2.3 *Comparison between idealization and terrain factors*

Just beyond the radio horizon of a transmitting antenna, the observed radio fields result from diffraction over ridges, hills, or the bulge of the Earth. At one extreme is the case of diffraction over obstacles so high and so isolated that knife-edge diffraction theory gives theoretical results that agree fairly well with observations, as discussed in this Section. Field strengths may be near free-space values, showing a low rate of attenuation with distance (see Report 715). At the other extreme is diffraction over a smooth spherical earth (see Report 715). This condition results in low field strengths which are soon exceeded, as one progresses beyond the horizon of a transmitting antenna, by radio fields produced by reflection from elevated layers or by forward-scatter radio waves.

Theoretical methods have been developed to handle certain idealizations of terrain features, such as bluffs, cliffs, and knife-edge obstacles in a transmission path.

The conditions under which these idealizations may be employed are considered in Report 715.

However, in most cases of propagation over land, it has been found extremely difficult to take full account of the roughness and irregularities of terrain features and of environmental clutter such as vegetation, buildings, bridges and electric power lines.

2.4 *Integral equation methods*

Integral equation methods can be employed at frequencies below about 30 MHz for paths with both irregular terrain and non-homogeneous electrical characteristics. Hufford [1952] and Ott [1971] have formulated methods for applying the basic integral equation. These authors have jointly provided a computer code for making propagation predictions [Ott *et al.*, 1979]. A version of this code in the FORTRAN language with the name "INTEQ", is available from the CCIR Secretariat. The 30 MHz limitation is based on using field points that are not necessarily optimum, but yield reasonable computational time. Computational times and memory requirements tend to become uneconomical at higher frequencies.

3. **Prediction accuracy**

The most important parameter for distinguishing between great circle path terrain profiles for trans-horizon paths of a given length is usually the angular distance, θ . This is defined as the angle between radio horizon rays in the plane of the great circle containing the antennas, and is the minimum angle of diffraction or angle of scattering unless antenna beams are elevated.

Among all paths corresponding to a given set of values of frequency, distance, angular distance, and effective antenna heights, there remains an inevitable path-to-path variability of transmission loss which is accepted as part of the error of prediction. In most broadcast and mobile service applications, on the other hand, the path variability is part of the prediction process instead of being part of the error of prediction.

Measurements [Wise, 1965] have shown that there is a close correlation between the field strength measured in UHF channels separated in frequency by up to 200 MHz when the transmissions are from adjacent sites. The value of the correlation coefficients is approximately 0.9 in flat terrain and 0.8 in hilly terrain.

Similar measurements in the frequency range 100 MHz to 1000 MHz showed that over average terrain the correlation coefficient was still as great as 0.7 even when the ratio of frequencies was 1 to 3. On the other hand when transmitters are sited at widely different locations, the correlation coefficient between field strengths at a receiving site is close to zero even when there is virtually no frequency separation. It is convenient for most point-to-point applications to predict simply the cumulative distribution in time of received power from wanted and unwanted signal sources, with expected values of cross-correlation [NBS, 1967]. Since wanted and unwanted

signal power will usually change diurnally and seasonally in the same direction, the cumulative distribution in time of the wanted-to-unwanted signal ratio will extend over a somewhat smaller range than if this positive correlation did not exist.

4. Mountainous terrain

Some paths can be treated as passing over a succession of crests, which may be replaced by knife-edges or cylinders, according to the sharpness of the crests. Report 715 offers suggestions for dealing with such cases.

On long paths, tropospheric-scatter may occur well above a mountain ridge, and the scattered and diffracted waves must be combined. With transmitting and receiving antennas elevated above the surrounding terrain, there can be waves reflected both before and after diffraction. When a wave passes close to the ground, there can arise an additional transmission loss due to finite ground conductivity [Furutsu, 1957 and 1959].

Mountain ridges can effectively reduce both transmission loss and the fading below the values to be expected in the absence of the obstacle. This occurs when the direct path is non-optical, but both transmitter and receiver can be seen from the top of the mountain. The phenomenon is known as obstacle gain. When using this term quantitatively, it must be stated whether it refers to gain relative to the calculated field over a homogeneous spherical earth, where only diffraction and standard atmospheric refraction are involved (propagation curves of the CCIR Atlases), or whether scattering and super-refraction are considered as well (curves of Recommendation 370). The latter case occurs when it is possible to compare propagation over two neighbouring paths of comparable distances and antenna heights, one of which has a mountain ridge which causes knife-edge diffraction and the other is clear of obstacles. Measurements made under such conditions have confirmed that such gains do occur [Dickson *et al.*, 1953; Norton *et al.*, 1955; Iwai *et al.*, 1959; Fukami *et al.*, 1961; Kirby *et al.*, 1955].

It will be further noted that the direction of arrival of the strongest signal need not be the direction of the great circle path between the transmitter and the receiver. This is most noticeable when the receiving station is very near to the diffraction ridge (a few kilometres). This indicates that, in estimating the quality of transmission across a mountain ridge, consideration must be given, not only to the profile of the terrain in the great circle path, but also to the diffraction or scattering properties of the ridge outside this plane. However, if the mountain obstacle is only a little removed from the great circle path, it no longer introduces an appreciable gain [Kirby *et al.*, 1955].

Small irregularities in the crest of mountain ridges cause spatial non-homogeneities in the diffraction field. The changes in the diffraction field in the presence of these irregularities give rise to spatial fading. These irregularities cause a widening of the diffraction field of the ridge. This leads to a degradation in the effective antenna gain as well as frequency and phase distortion of the signal [Troitsky, 1975 and 1977].

For propagation over high mountain ridges, a large part of the path may be above the regions of the troposphere in which rapid changes in the index of refraction occur. Also, there may be marked differences in the weather on the two sides of a mountain ridge, so that the conditions which give rise to fading may occur only on one half of the path at a time.

Theoretical and experimental studies carried out in the U.S.S.R. [Troitsky, 1976 and 1977] have shown that SHF and UHF waves may be propagated into the shadow zone of mountain ridges by wave refraction and anisotropic scattering in the dielectric layer formed by the snow cover. This phenomenon may result in a significant increase in the field strength in the shadow of mountain peaks and ridges over the diffraction field strength.

These factors may limit the effects of the troposphere on the individual components of the diffracted wave and tend to minimize the fading which occurs at a receiving point where a high value of field strength is found [Dickson *et al.*, 1953; Kirby *et al.*, 1955; Stark, 1964; Okumura and Hara, 1965].

5. Small and medium irregularities in terrain

Most irregularities in a terrain profile are not isolated obstacles [NBS, 1967; Beckmann and Spizzichino, 1963; Thiessen, 1964], free of the influence of nearby hills and valleys. The descriptive analysis of broadcast data reported in Report 239 and in Recommendation 370 shows that, to a first order of approximation, such irregularities can be characterized by the difference Δh of terrain heights exceeded for 10% and 90% of a propagation path in the range 10 km to 50 km from the transmitter. This parameter Δh is defined in Recommendation 370.

Experience has shown that improved predictions of cumulative distributions of transmission loss in a broadcaster's service area, may be obtained by the use of additional parameters noted in Report 239, which summarizes comparisons with data. It has been shown [Thiessen, 1964; EBU, 1965] that an improvement in prediction accuracy may be achieved by including on an empirical basis, the mean slope of the terrain in the vicinity of the receiving point. The principle upon which this work is based is that improved illumination of the receiving point will be obtained when the direction of arrival of the incident ray makes a greater angle with the local terrain. This reasoning follows firstly from simple geometric ray theory and secondly from the fact that the transmission will have to pass through a shorter scattering path due to buildings and trees, etc., when the angle referred to above is large.

If the variation in terrain height about some mean value is small in comparison to a wavelength and the slopes of the terrain are small, then one can use the smooth earth curves of Recommendation 368 if the actual terrain surface impedance is replaced with a higher effective value [Barrick, 1971]. This effective surface impedance can be anisotropic since the additional attenuation is greater for paths which cross a series of ridge lines than that for paths which are parallel to the ridge lines. Hansen [1977] has obtained excellent experimental confirmation of this method over a sea path in the 2 to 20 MHz range.

6. Forested terrain

Conceptually, the vegetation of dense forests and jungles over level ground can be modelled as the weak, lossy dielectric slab of Fig. 1. [Wait *et al.*, 1974; Tamir, 1977 and 1967; Sachs and Wyatt, 1968]. The slab thickness, h , is the effective height of the vegetation. The slab is characterized by a semi-empirical mean value of its complex dielectric constant $\epsilon' = n^2$ where n is the corresponding index of refraction, $n_r + jn_i$, with $n_r \approx 1$ and $n_i \leq 1$. For direct propagation paths of length d within the slab, the transmission loss contains an additional factor $\exp(-k_0 d \sqrt{\epsilon'})$ over and above the $1/d^2$ spreading loss, where $k_0 = 2\pi/\lambda_0$ and λ_0 is the free space wavelength.

Reflection and refraction of radio waves by the air-forest interface leads to the establishment of the propagation paths indicated in Fig. 1. At longer ranges, in the absence of sky waves, only the lateral wave is significant.

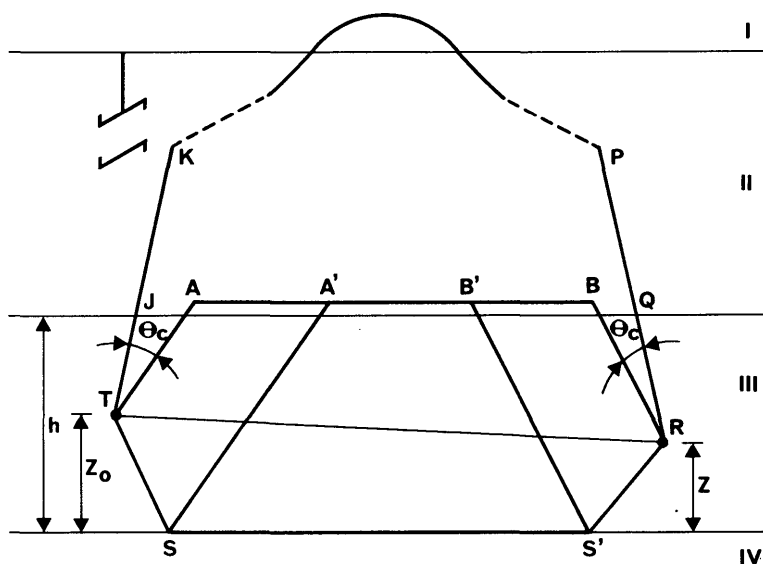


FIGURE 1 - Propagation in an idealized forest environment

T-R direct wave; T-S-A'-B-R, T-A-B'-S'-R reflected waves;
T-A-B-R lateral wave; T-J-K-P-Q-R ionospheric sky wave.

Regions I, II, III, IV represent the ionosphere, troposphere,
forest and ground, respectively.

The formal ray picture of the propagation mechanism has ray-energy from transmitter T, at height $z_0 < h$, travelling at grazing angle $\theta_c = \sin^{-1}(1/\sqrt{\epsilon'})$, which is the critical angle for total internal reflection at the top surface of the model slab. This energy is coupled to the lateral wave spreading with horizontal distance d (field strength $\sim 1/d^2$, power flux $\sim 1/d^4$). The lateral wave continually leaks energy back into the vegetation at θ_c , and the ray of interest (B-R in Fig. 1) arrives at the receiver R at height $z < h$. Precise theory for the lateral-wave field strength is available [Tamir, 1977]. The validity of this homogeneous slab model is limited by the wavelength of the radiation. Below about 2 MHz the forest height is much smaller than λ_0 so that the forest has little effect on the ground wave. This is confirmed by extensive empirical data [Wait *et al.*, 1974]. Above about 200 MHz, the vegetation can no longer be considered homogeneous over distances of the order of λ_0 [Tamir, 1977]. However, measurements for a deciduous rain forest in India at 50 to 800 MHz confirm the general $1/d^4$ signal power dependence [Swarup and Tewari, 1975]. Earlier work by several investigators [Saxton and Lane, 1955; Josephson and Blomquist, 1958; Head, 1960; Herbstreit and Crichlow, 1964] suggests that in the 30 to 2000 MHz range the average additional attenuation through woodland, $\exp(-k_0 d \sqrt{\epsilon'})$, (dB/m) is given by Fig. 2. Considerable variation can be expected in these values due to the density of the vegetation, the moisture content of the leaves, and the presence of snow on the branches. An increase of 0.1 dB/m has been observed for the higher frequency part of the curve.

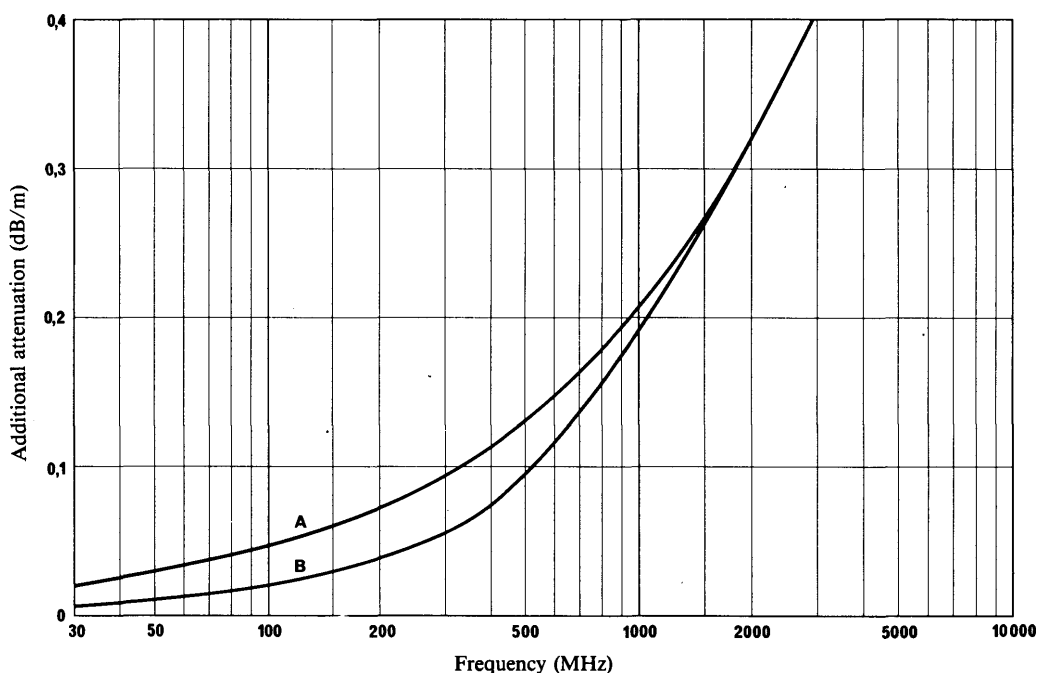


FIGURE 2 - Additional attenuation through woodland

A: vertical polarization
B: horizontal polarization

The model described above applies to the field strength at points within the forest. For points outside the forest or separated from the transmitter by a clear zone, the field may be estimated by a more general treatment [Tamir, 1977]. The case where both the transmitter and receiver are located above the forest, as in broadcast and radio-relay systems, is not considered here (see Reports 239 and 567).

There are two categories of temperate-forest problems for which other procedures have been shown to be accurate [Weissberger, 1981]. The first involves geometries in which either the transmitting or receiving antenna is near enough to a small (less than 400 m deep) grove of trees so that the majority of the signal propagates through the trees. The additional loss caused by the trees can be predicted by the modified-exponential-decay equation:

$$L = 0.187 f^{0.284} d^{0.588} \quad \text{dB}$$

where L is the loss due to the grove of trees in dB, f is the frequency in MHz, and d is the depth of the grove in metres. The equation is applicable to problems in which $200 < f < 95\,000$ MHz.

In the second category of problem [LaGrone, 1977], both antennas are far enough from the trees so that the majority of the coupling occurs as a result of diffraction over the foliage. These data are predicted by using the knife-edge diffraction model (see Report 715) with the assumption that the obstacle is at the edge of the forest that is nearest to one of the antennas. The predictions include the effects of ground reflections as well as diffraction. Computed values compare favorably with measurements in the 80 to 3000 MHz range. The effective height of the diffracting obstacle is less than the physical height of the trees; for example, differences range from 4.5 m. at 80 MHz to 0.5 m. at 3000 MHz.

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REPORT 336-2 *

**PROPAGATION ON THE MOON AND THE DEFINITION OF ITS
RADIO-QUIET ZONE**

(Study Programme 7B/2)

(1966-1974-1982)

1. Introduction

As there is effectively no atmosphere or ionosphere associated with the Moon, radiocommunication between points on or near the Moon's surface is essentially similar to ground-wave propagation over the Earth regarded as an inhomogeneous sphere with an irregular surface. It is therefore possible to adapt the principles of ground-wave propagation discussed in the texts of Study Group 5 to a sphere with the radius of the Moon and with ground constants and irregularities appropriate to the Moon's surface.

This will result in a problem of reception on the Moon from near-Earth transmitters, that is from transmitters on the Earth or associated with the Earth in space vehicles or orbiting satellites when the reception point is on the far side of the Moon with respect to the transmitter, so that signals can only be received by diffraction round the limb of the Moon. On the other hand it has been suggested that advantage might be taken of the fact that there is a considerable area of the Moon that is never visible from any point on or near to the Earth, to establish a radio-quiet zone on the Moon that might be used for siting an observatory for radioastronomy and space research free from the natural and man-made interference experienced on Earth.

It is the purpose here to review these aspects of radio reception on the Moon by discussing diffraction over the surface and round the limb of the Moon, and by defining the area within which the radio-quiet zone must lie.

2. Diffraction formulae for lunar propagation

The classical propagation formulae for diffraction around a smooth spherical body such as those found in Report 715 can be used in the case of the Moon for all frequencies greater than 300 Hz. This lower limit is determined by the diffraction condition that $2\pi a/\lambda \gg 1$ where a is the radius of the sphere and λ is the wavelength. It is important, however, to substitute the actual radius of the Moon (1738 km) for the radius of the sphere in these formulae.

It thus appears that all the essential information needed for the solution of this problem is available in a form that is readily adaptable to the parameters considered to apply to the curved surface of the Moon. Some work has in fact already been done along these lines for certain assumed electrical characteristics of the Moon [Vogler, 1965].

3. The area for the radio-quiet zone

3.1 General considerations

As the Moon rotates about its axis with a period that is identical with its period of revolution about the Earth, it always presents the same side or face to the Earth. However, because of the librations of the Moon and the ellipticity and inclination of its orbit, about 59% of the Moon's surface can be seen at one time or another from the surface of the Earth. Nevertheless, there is a considerable area of the far side of the Moon which is very well shielded from radio waves from Earth-based or near-Earth transmitters.

* This Report is brought to the attention of Study Group 2.

As the required radio-quiet zone may not occupy the whole of this shielded area, this area itself will be called the "shielded cap", since with the criteria to be adopted for its definition, it is approximately a cap of a sphere of radius equal to that of the Moon.

3.2 *Criteria for deciding the size of the shielded cap*

It is clearly necessary to limit the distance from the Earth of a near-Earth transmitter, and all such transmitters will be considered to lie within a sphere of radius 100 000 km centred on the Earth's centre of mass. It will then be stipulated that no part of the shielded cap can ever receive line-of-sight transmission from an Earth-based or near-Earth transmitter. These two criteria lead to a fairly simple definition of the spherical cap in terms of the cone angle subtended at the centre of the Moon.

3.3 *The size of the shielded cap*

The approximate size of the shielded cap can be derived by assuming the Moon to be a smooth sphere of radius 1738 km moving in its elliptical orbit around the Earth [Allen, 1962]. The effects of the normal optical librations, which amount to 7.6° in longitude and 6.7° in latitude, must be added to the parallactic libration as seen from a spacecraft at 100 000 km from the centre of the Earth. There are other smaller libration effects that can be neglected here.

It can then be shown that the cone defining the area of the shielded cap has a semi-angle of 66.8° with its axis along the line joining the centres of the Earth and the Moon, and that the area of the cap is $1.15 \times 10^7 \text{ km}^2$ representing 30% of the total surface area of the Moon.

3.4 *The effectiveness of the shielding*

Lunar surface material has a dielectric constant of about 2.6 and a very low conductivity [Gold *et al.*, 1970; England *et al.*, 1968]. Radio waves are attenuated quite rapidly when they are vertically incident on the Moon; typical figures for the absorption length (the depth at which the field is reduced by a factor of 2.71828) are 10 to 20 wavelengths for a range of wavelengths from a few centimetres to a kilometre.

As described above, diffraction effects at the edge of the shielded cap will allow the radio waves to propagate for some distance into the shielded area, but for the wavelengths under consideration they are not likely to cause serious disturbance beyond about 100 km inside the boundary of the shielded cap.

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REPORT 716-1

THE PHASE OF THE GROUND WAVE

(Decision 3)

(1978-1982)

1. Introduction

1.1 The phase of the ground wave is important for two major reasons. The stability of this phase makes possible precision radionavigation systems such as Decca and Loran-C. Conversely, the precision with which the phase of the ground wave is measured by these navigation systems makes possible precise experimental verification of ground-wave propagation theories.

1.2 It is convenient to define the phase of the ground wave, Φ , as the sum of a primary phase and a secondary phase, Φ_s . At a distance, d , from a transmitter, the phase of the ground wave may be written:

$$\Phi = nkd + \Phi_s$$

where n is the surface value of the refractive index of the atmosphere and $k = 2\pi/\lambda$, where λ is the free-space wavelength of the ground-wave signal. In this equation, the secondary phase Φ_s is in units of radians. However, in most applications it is expressed in microseconds according to the relationship:

$$\Phi_s (\mu s) = \frac{\Phi_s (\text{rad.}) \cdot 3 \times 10^2}{2\pi\lambda}$$

where λ is in metres.

The remainder of this Report is concerned with the various factors which influence the secondary phase and with methods of calculating this secondary phase.

2. Smooth homogeneous earth

The basic starting point for the calculation of the secondary phase is the theory of ground-wave propagation over a smooth homogeneous earth [Johler *et al.*, 1956]. Current methods are identical to that used to compute the ground-wave amplitude curves found in Recommendation 368. This basic method can also be applied to pulsed radionavigation systems [Johler *et al.*, 1979].

In order to extend this basic method to more general cases, it is useful to formulate the calculations in terms of a general surface impedance [Hill and Wait, 1980]. Many of the methods used to calculate the phase of the ground wave employ an effective surface impedance concept which incorporates an effective conductivity and permittivity.

3. Secondary phase perturbations

At frequencies below about 3 MHz, the smooth homogeneous earth theory can be used to calculate the phase of the ground wave, to the degree of accuracy required for navigation systems, over sea paths including those with large waves. On land paths, however, the secondary phase is modified by changes in the electrical characteristics along the path, terrain irregularities, and sub-surface layers. Various methods have been developed for predicting the perturbation in the secondary phase due to these factors [Samaddar, 1979].

3.1 Sub-surface layers

The effect of sub-surface layers on ground-wave propagation is described in Report 229. The same effective impedance method [Wait, 1970] used to calculate the ground-wave amplitude can be used to calculate the phase of the ground wave if an appropriate model of the sub-surface electrical characteristics [Johler and Horowitz, 1974] exists for calculating the effective ground impedance. This same method can be used over sea paths to predict the effect of sea ice on the phase [Bourne *et al.*, 1970].

3.2 Non-homogeneous paths

When the electrical characteristics or surface impedance along a path change (e.g. at a land-sea boundary) there is a corresponding sudden change in both the amplitude and phase of the ground wave. The phase in this case can be calculated by the Millington-Pressy method [Pressy *et al.*, 1953]. This method is completely analogous to the Millington method for computing the ground-wave amplitude over non-homogeneous paths. The phase of a ground-wave signal over a two section path can be calculated from the Millington method formula found in Annex II of Recommendation 368 if the amplitudes in the formula are replaced with the corresponding homogeneous earth phases.

3.3 Terrain irregularities

Report 236 contains a description of an effective impedance theory for calculating ground-wave propagation factors over irregular terrain. The accuracy desired for navigational applications, however, requires very complex calculations. In this case, it is more efficient to use the integral equation method to compute the phase of the ground wave.

3.4 Integral equation method

The integral equation method is described in Report 236. This method can be used to calculate the phase of the ground wave over terrain which is both irregular and non-homogeneous. Figure 1 shows a comparison of computational methods and experimental measurement [Samaddar, 1979]. The path shown crosses both Death Valley, California with an elevation of 100 m below sea level and the Sierra Nevada mountain range. The Millington-Pressey method calculation used a two-layer smooth earth effective impedance model.

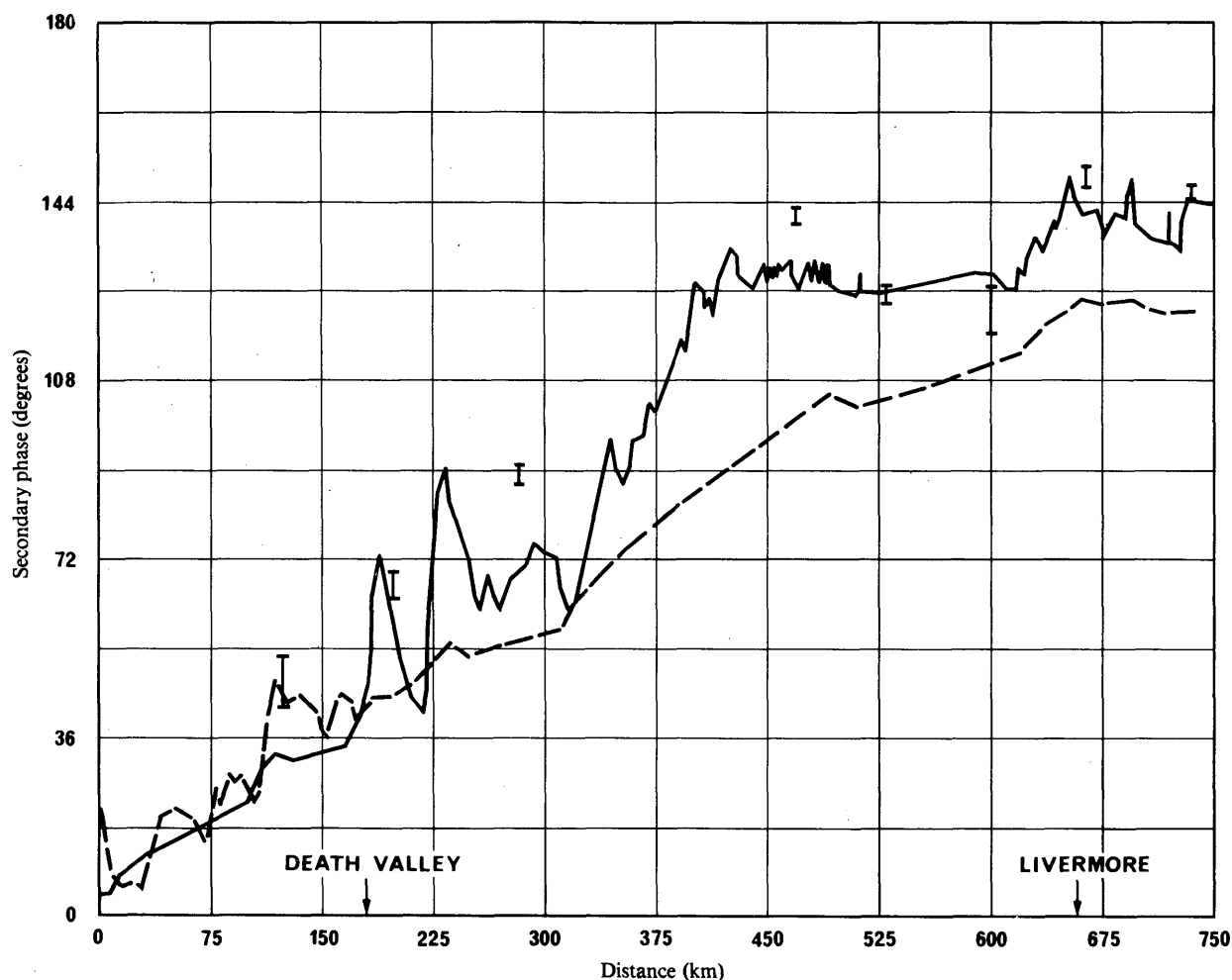


FIGURE 1 – A comparison of the measured and calculated phase for the USA West Coast Loran-C system.

(The measured points are shown by the symbol (I). The solid line was calculated by means of the integral equation method. The dotted line was calculated by means of the Millington-Pressey method with effective surface impedances for a two-layer model. At 100 kHz, a secondary phase of 36° corresponds to 1 μ s (see § 1.2 above)).

4. Meteorological effects

Several investigations of the stability of Loran-C signals have revealed phase variations corresponding to time-of-arrival variations of as much as $\pm 0.5 \mu$ s [Doherty and Johler, 1975; Samaddar, 1980]. These variations have both a diurnal and long-term characteristic and are correlated with changes in the gradient of the dry term of the refractive index. The longer term variations are associated with the passage of a weather front along the measurement path.

Changes in the phase of the ground wave are found to precede the passage of a warm front. Similar changes associated with the passage of a cold front occur after its passage. It appears that the correction of navigational data in an average sense for meteorological effects may be possible in the future with the use of weather station and system monitoring station data.

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REPORT 717-1 *

WORLD ATLAS OF GROUND CONDUCTIVITIES

(Decision 3)

(1978-1982)

1. Introduction

This Report gives information about the ground conductivities in various areas of the world, and is intended to form the first stage in the presentation of the World Atlas of Ground Conductivities called for in § 4 of Decision 3.

2. General considerations

2.1 If ground-wave field strengths are to be calculated, it is essential to know the ground characteristics along the path. In cases involving coordination between administrations, it is therefore often necessary to know the ground characteristics existing outside national boundaries.

2.2 The most important electrical characteristic of the ground is conductivity. As shown in Recommendation 527, ground conductivity varies with frequency, and it is therefore desirable to have conductivity maps for different frequency ranges.

It must also be noted that seasonal variations in the ground constants may be expected (see Report 229).

3. Preparation of conductivity maps

3.1 In its work on the World Atlas, the CCIR will require information from every administration. Conductivity maps have been presented in different ways, but in future it would be helpful if they were presented with the same values of conductivity as set out in the latest version of Recommendation 368.

3.2 In preparing conductivity maps, the methods mentioned in Report 879 may be used. More detailed descriptions of how the maps may be evaluated are given by [Täumer, 1973; Koskenniemi and Laiho, 1975; Stokke, 1978].

* This Report is brought to the attention of Study Groups 6, 8 and 10.

4. The Atlas

4.1 The conductivity maps for the VLF part of the spectrum (Figs. 1 to 6) are subject to the following conditions:

- they are limited in application to frequencies up to 30 kHz,
- they contain no allowance for seasonal variations,
- they have been calculated from physiographical and geological data used to define boundaries of the land areas of given conductivity, together with actual conductivity data derived from measurements from many workers [Morgan, 1968; Krulc, 1968],
- they represent effective ground conductivities (the effect of terrain is included in the values),
- as it seems likely that seasonal variations will become more important with increasing frequency (as the penetration depth decreases), maps for higher frequencies may need to be presented in such a way that the annual variations are shown. However, data recorded by the Administration of India indicate that at frequencies as high as 1 MHz seasonal variations in the tropics have a negligible influence on propagation.

4.2 Provisional information for MF use is shown in Fig. 7 [Albrecht, 1967]. It is expected that this information will be later superseded by the World Atlas to be published by the ITU.

4.3 Resolution 73 calls on the Director of the CCIR to publish a comprehensive World Atlas of ground conductivities covering at least VLF and MF. This Atlas will refer to the conductivity steps as indicated in Recommendation 368, and will be based on measured information where available for Regions 1 and 3. In the case of Region 2 the World Atlas will be based on the CITEL maps as approved at the regional MF Broadcasting Conference, First Session, Buenos Aires, 1980.

5. Revision of the Atlas

It is urgently requested that all administrations provide either measured or estimated conductivity data to revise this Atlas.

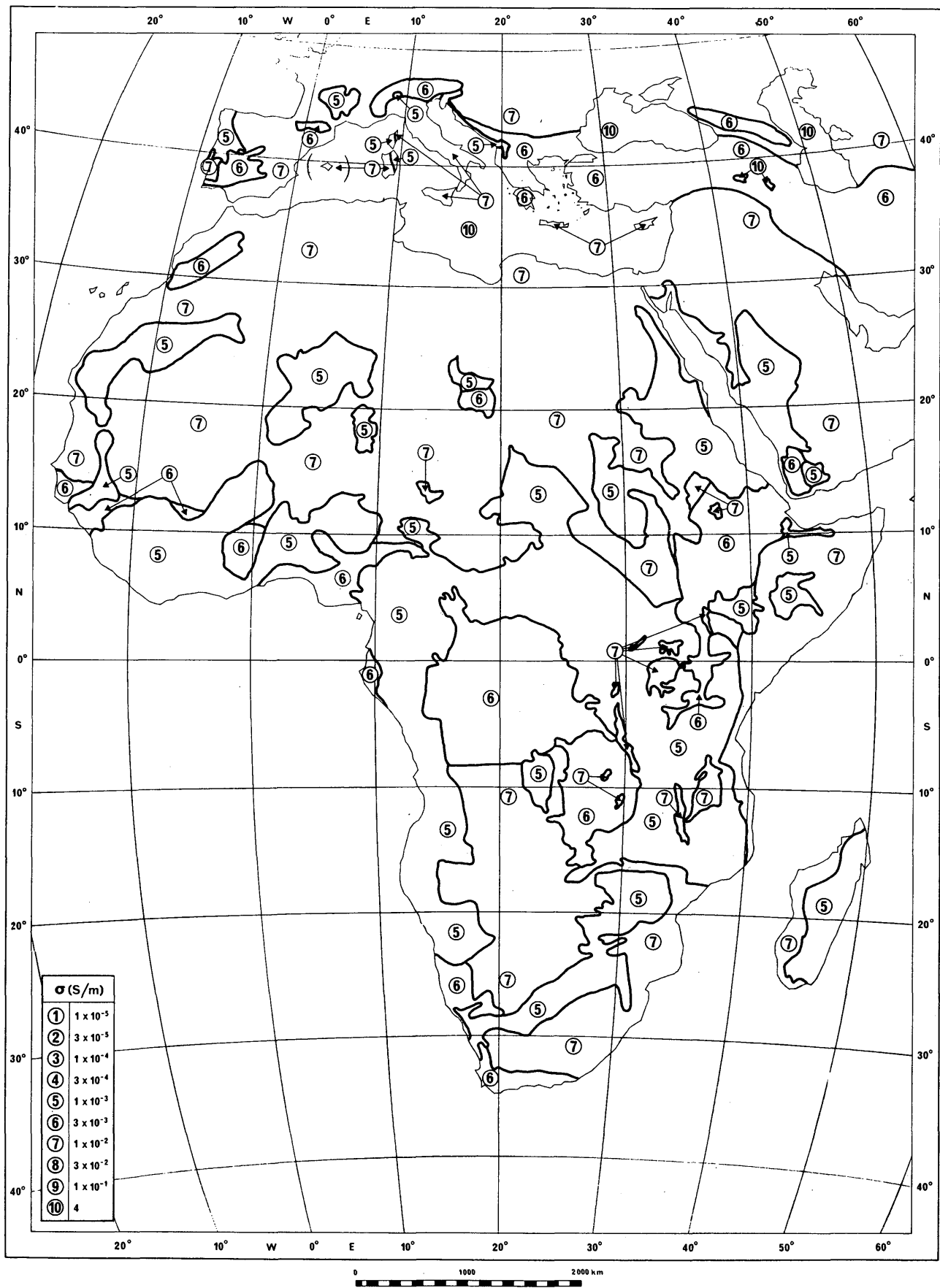


FIGURE 1 - Africa

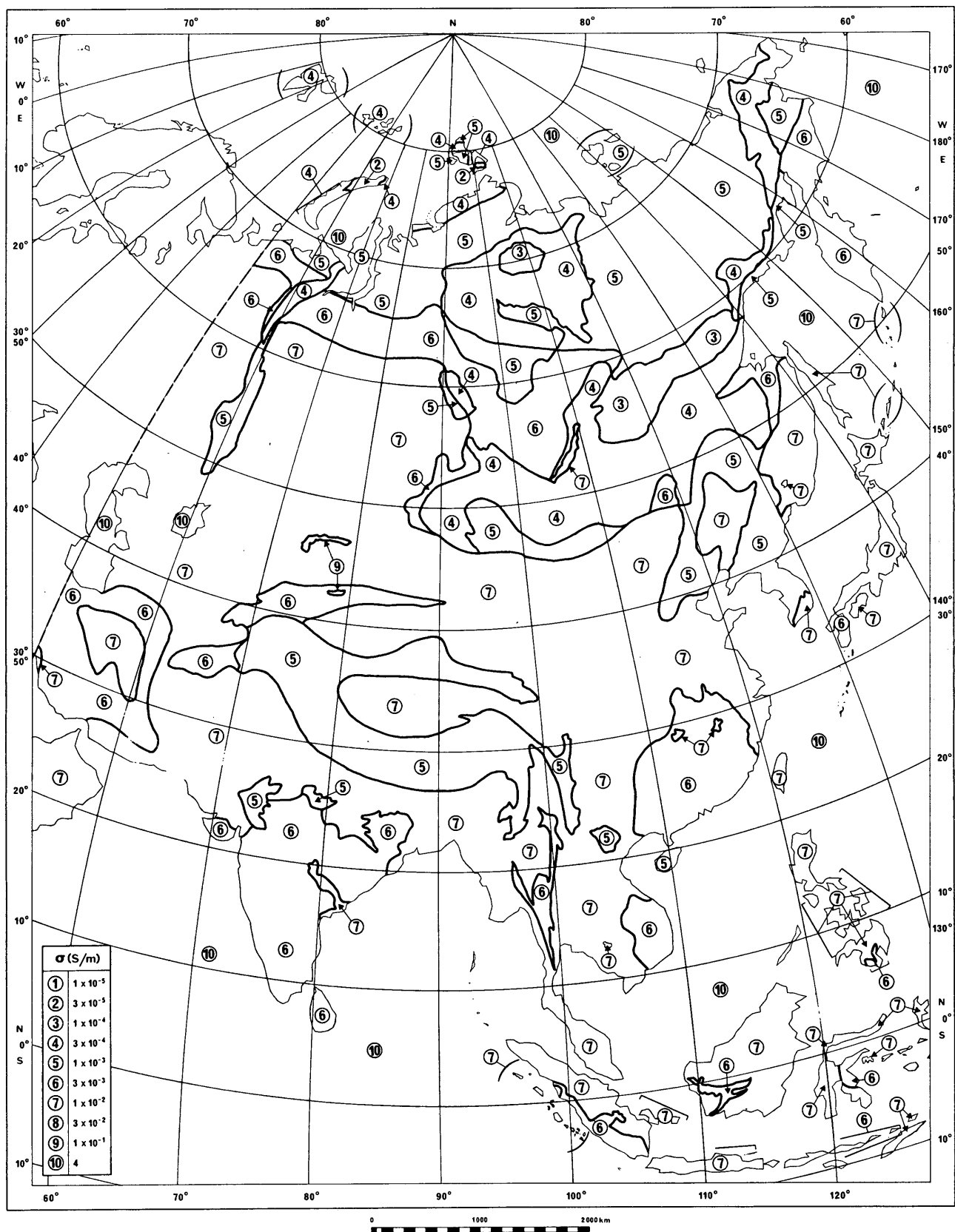


FIGURE 2 - Asia

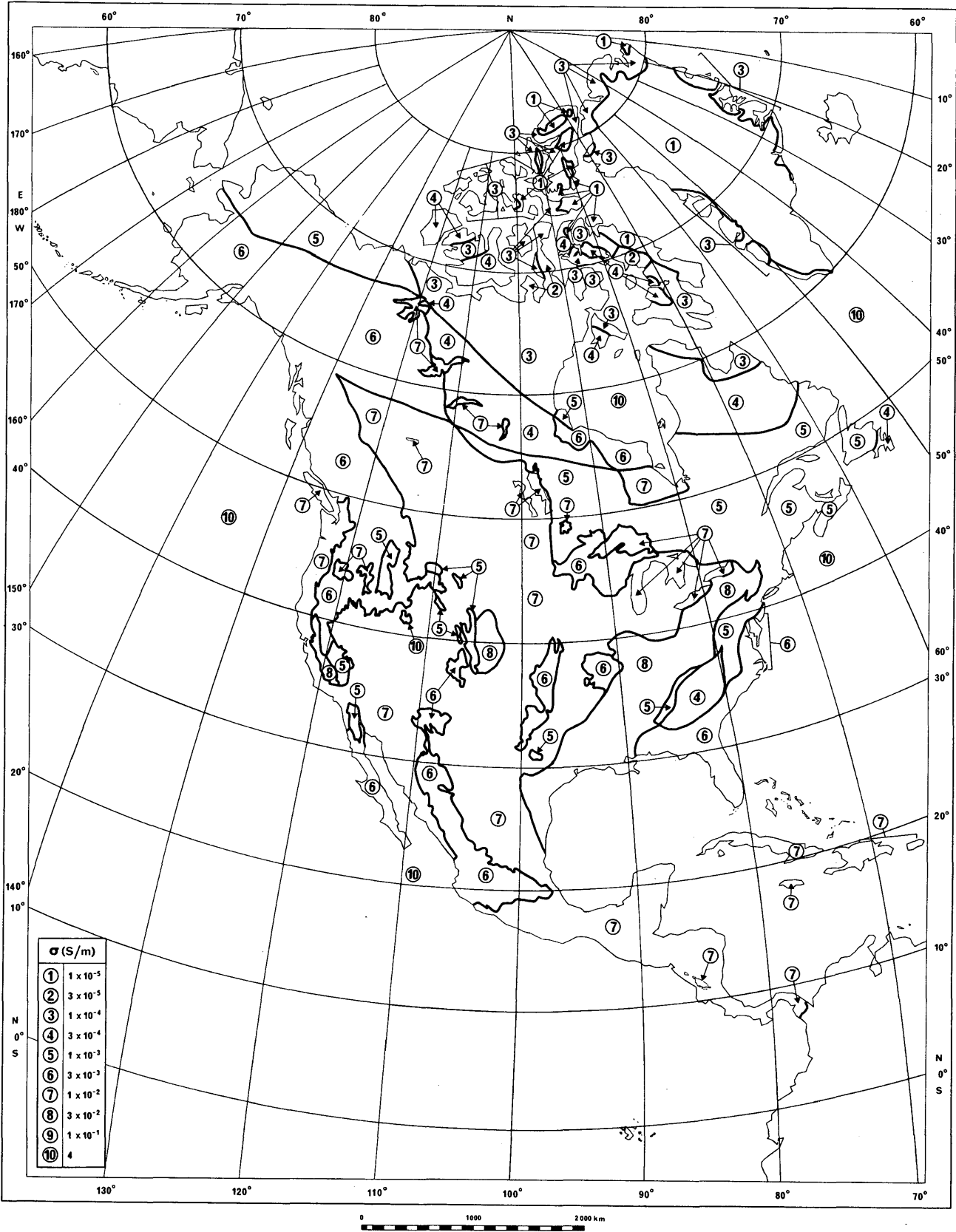


FIGURE 3 – North America

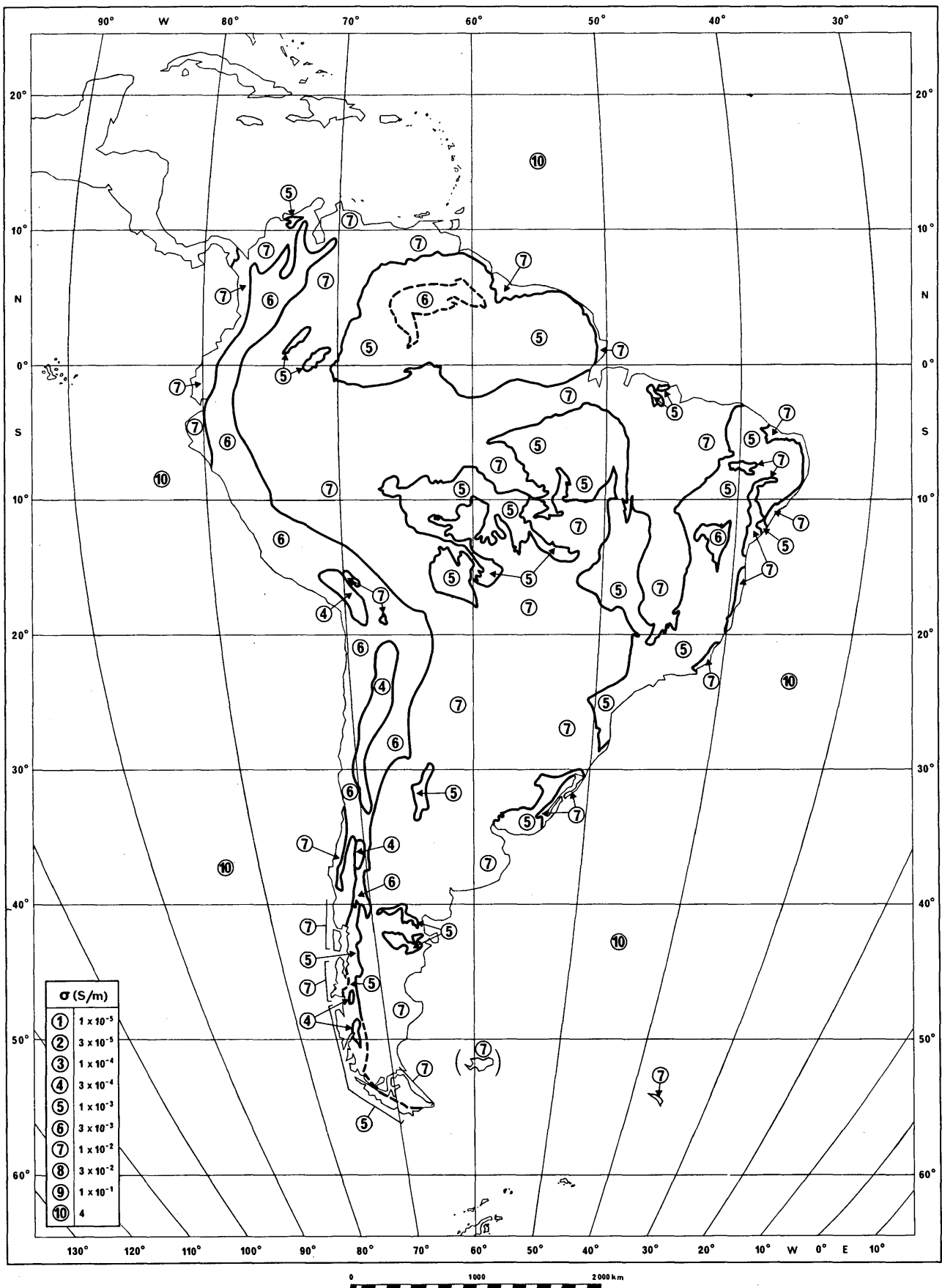


FIGURE 4 – South America

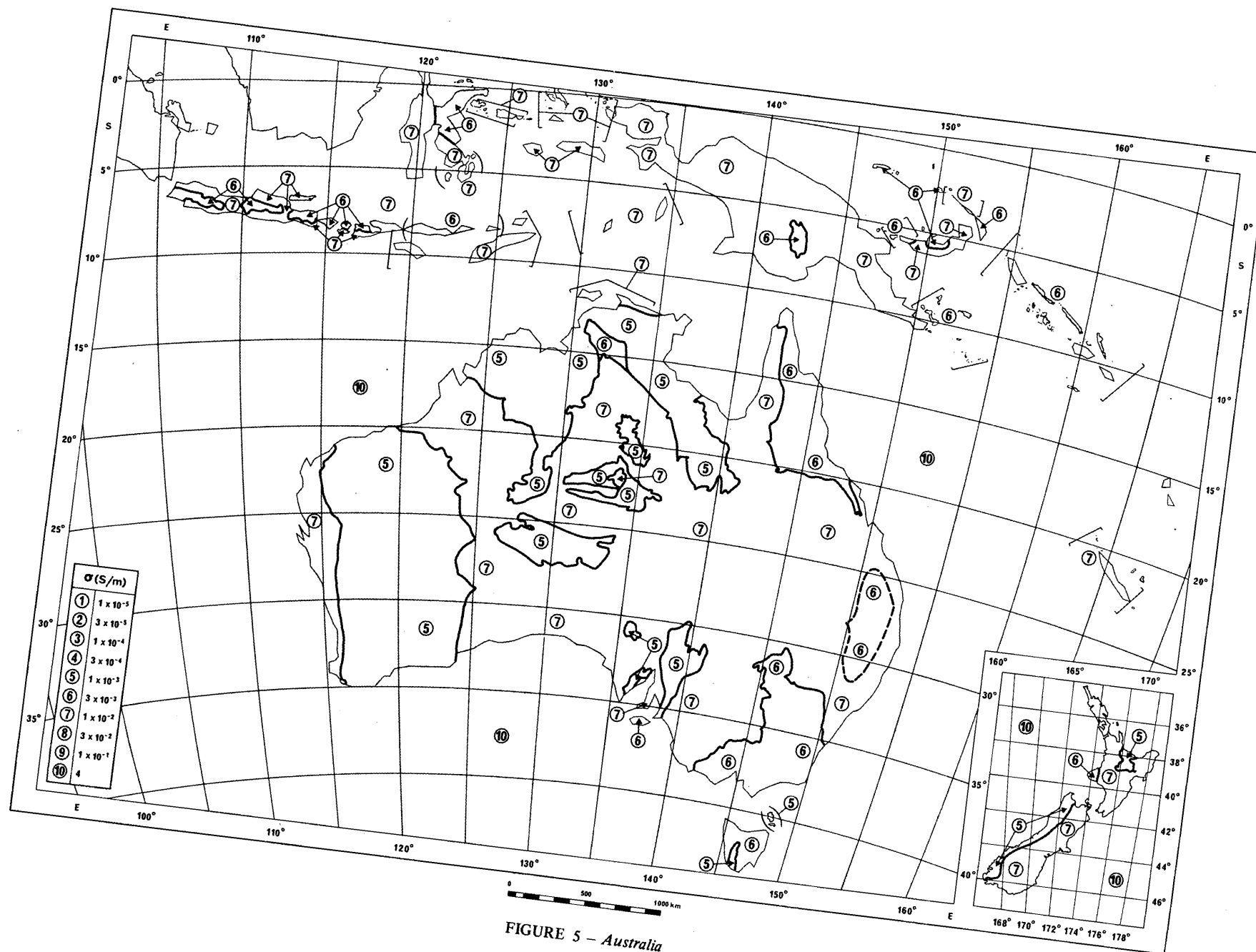


FIGURE 5 - Australia

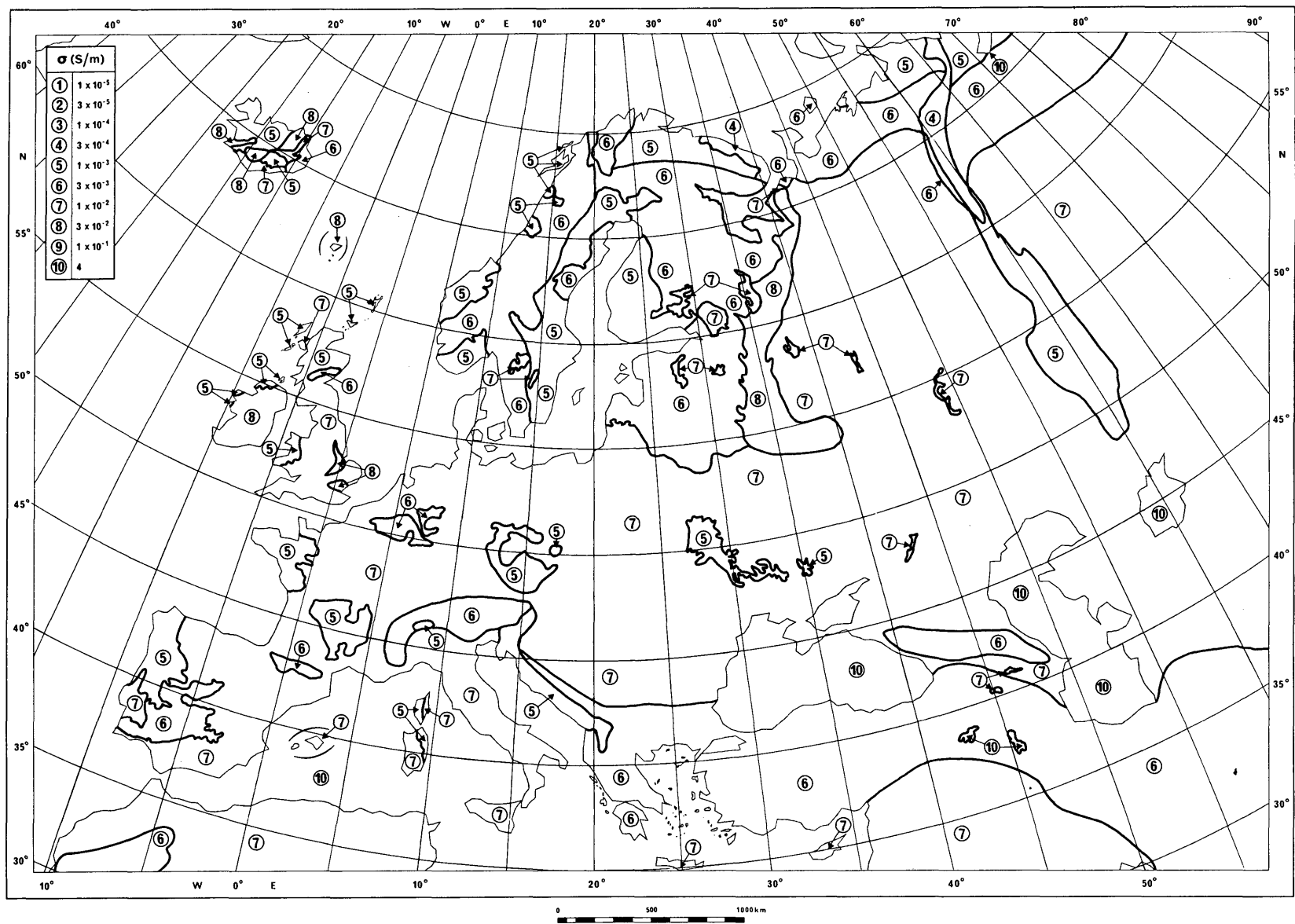
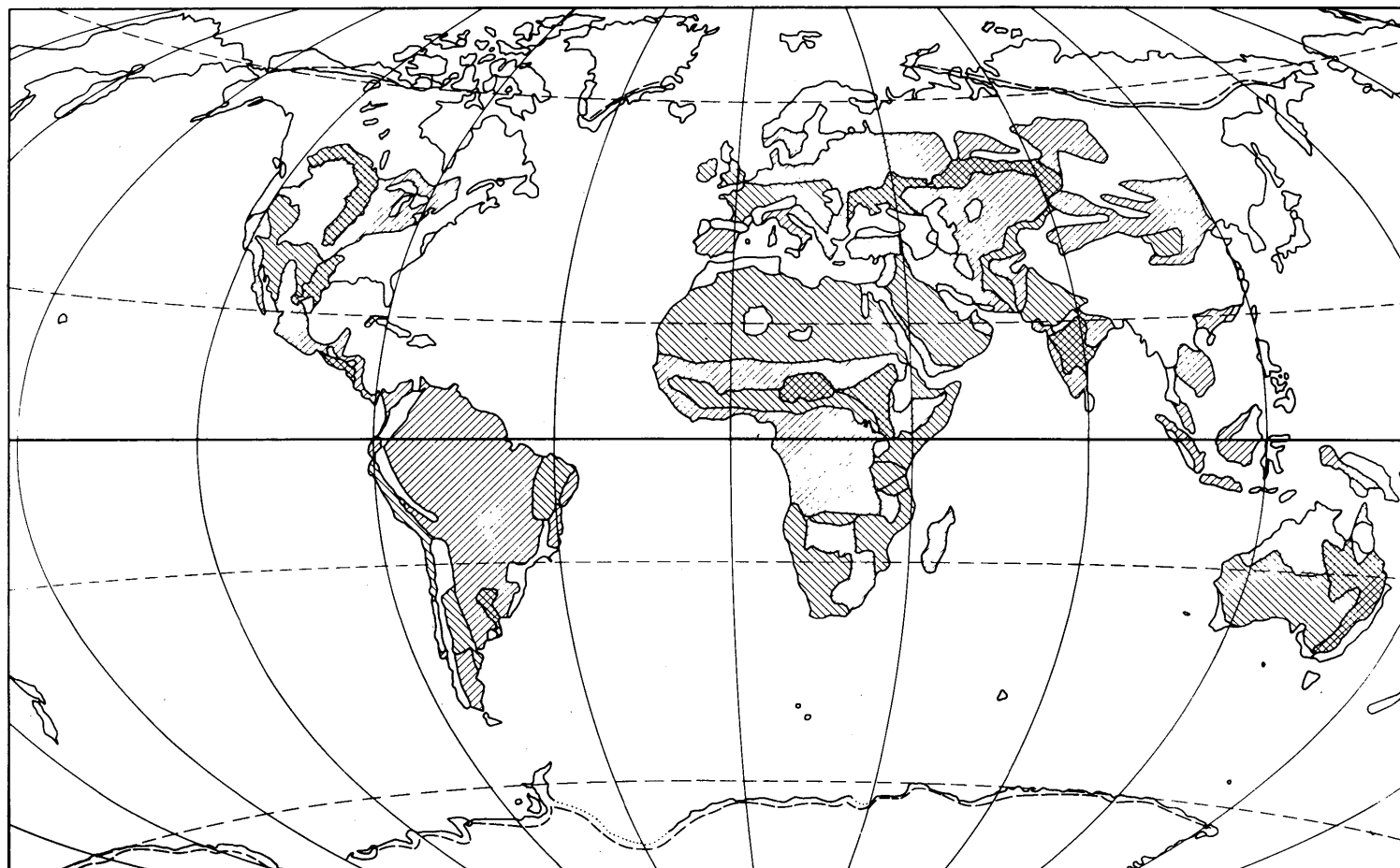


FIGURE 6 - Europe



Values of σ :

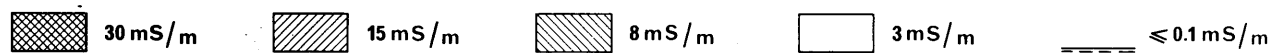


FIGURE 7 – Provisional MF conductivity map for land areas [Albrecht, 1967]

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REPORT 880

PROPAGATION IN TUNNELS AND MINES

(Study Programme 1A/5)

(1982)

The propagation of radio signals in tunnels and mines (see also Report 902) depends primarily on the geometry of the walls and, to a lesser degree, on the electrical characteristics of these walls. Two propagation mechanisms are of practical importance. These two mechanisms have a complex theoretical basis, but they are now well understood [Delogne, 1980].

The first mechanism has been described as a natural propagation mode in which the tunnel or mine shaft behaves like a multimoded waveguide with lossy walls. This mechanism favours the use of frequencies above the equivalent waveguide cut-off frequency. This mechanism has the disadvantages of poor coupling of the waveguide modes to the usual type of antennas and of high losses around corners.

The second mechanism, described as guided propagation modes, requires the use of a radiating cable suspended near the roof of the tunnel. Single wires, balanced open wire transmission lines, and coaxial cables with a controlled degradation in their shielding (leaky feeders) are used. At frequencies below the waveguide cut-off, the tunnel and cable support two TEM-like modes (transverse electromagnetic). At higher frequencies many waveguide-like modes can propagate [Seidel and Wait, 1978].

Both mechanisms are characterized by an exponential propagation loss with distance which is expressed in dB/m. A complete analysis of both mechanisms becomes complex due to the coupling of the various modes by irregularities and losses in the walls.

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SECTION 5C: EFFECTS OF THE ATMOSPHERE (RADIOMETEOROLOGY)

Recommendations and Reports

RECOMMENDATION 310-5

DEFINITIONS OF TERMS RELATING TO PROPAGATION
IN THE TROPOSPHERE

(1951-1959-1966-1970-1974-1978-1982)

The CCIR,

CONSIDERING

that it is well known that the propagation of waves of frequencies greater than 30 MHz is greatly influenced by meteorological conditions in the troposphere,

UNANIMOUSLY RECOMMENDS

that the list of definitions annexed hereto be adopted for incorporation in the vocabulary;

VOCABULARY OF TERMS USED IN RADIO PROPAGATION THROUGH THE TROPOSPHERE

Term	Definition
1. <i>Troposphere</i>	The lower part of the Earth's atmosphere extending upwards from the Earth's surface, in which temperature decreases with height except in local layers of temperature inversion. This part of the atmosphere extends to an altitude of about 9 km at the Earth's poles and 17 km at the equator.
2. <i>Tropopause</i>	The upper boundary of the troposphere, above which the temperature increases slightly with respect to height, or remains constant (a more detailed definition given by the WMO is mentioned in Doc. [CCIR, 1966-69]).
3. <i>Temperature inversion</i>	An increase in temperature with height.
4. <i>Mixing ratio</i>	The ratio of the mass of water vapour to the mass of dry air in a given volume of air (frequently expressed in g/kg).
5. <i>Relative humidity with respect to water (or ice)</i>	Percentage ratio of the vapour pressure of water vapour in moist air to the saturation vapour pressure with respect to water (or ice) at the same temperature and pressure.
6. <i>Refractive index (n)</i>	Ratio of the speed of radio waves in vacuo to the speed in the medium under consideration.
7. <i>N (refractivity)</i>	One million times the amount by which the refractive index exceeds unity.
8. <i>N-unit</i>	A dimensionless unit in terms of which <i>N</i> (refractivity) is expressed.
9. <i>Modified refractive index</i>	For a given altitude: the sum of the refractive index of the air at this altitude and the ratio of this height to the radius of the Earth.
10. <i>Refractive modulus</i>	One million times the amount by which the modified refractive index exceeds unity.
11. <i>M-unit</i>	A dimensionless unit in terms of which refractive modulus <i>M</i> is expressed.
12. <i>Standard refractivity gradient</i>	A standard value of vertical gradient of refractivity used in refraction studies; namely -40 N/km. This corresponds approximately to the median value of the gradient in the first kilometre of altitude in temperate regions.
13. <i>Standard radio atmosphere</i>	An atmosphere having the standard refractivity gradient.
14. <i>Reference atmosphere for refraction</i>	An atmosphere in which <i>N</i> (refractivity) decreases exponentially with height (see Recommendation 369).
15. <i>Standard refraction</i>	The refraction which would occur in a standard radio atmosphere.

16. *Sub-refraction* Refraction for which the refractivity gradient is greater than standard refractivity gradient.
17. *Super refraction* Refraction for which the refractivity gradient is less than standard refractivity gradient.
18. *Radio horizon* The locus of points at which direct rays from the antenna become tangential to the Earth's surface, taking into account the curvature due to refraction.
19. *Standard radio horizon* Radio horizon in the case of standard refraction.
20. *Effective radius of the Earth* Radius of a hypothetical spherical Earth, having no atmosphere, for which propagation is rectilinear and for which the distance to the horizon is the same as that for the actual Earth enveloped in an atmosphere having a constant vertical gradient of refractivity.

Note 1. — For the standard radio atmosphere the effective radius is 4/3 that of the true radius.

Note 2. — The concept of equivalent Earth radius implies that the angle made by the radio ray with the horizontal plane at the point considered is not large.
21. *Ducting layer* An atmospheric layer characterized by a negative M gradient.
22. *Tropospheric radio-duct* A quasi-horizontal stratification in the troposphere within which radio energy of a sufficiently high frequency is substantially confined and propagated with abnormally low attenuation.

Note. — The tropospheric duct consists of a ducting layer and, if present, a portion of the underlying standard or sub-refractive atmosphere. It extends vertically from a relative M -profile minimum M_1 , defining the top of the ducting layer, down to either a reflecting surface or the elevation at which the value M_1 is again attained, whichever is higher.
23. *Ground-based duct (Surface duct)* A tropospheric radio-duct in which the lower boundary is the surface of the Earth.
24. *Elevated duct* A tropospheric radio-duct in which the lower boundary is above the surface of the Earth.
25. *Duct thickness* The difference in height between the upper and lower boundaries of a tropospheric radio-duct.
26. *Duct height* The height above the surface of the Earth of the lower boundary of an elevated duct.
27. *Trapped mode (ducting)* A mode of propagation within a radio-duct. At sufficiently high frequencies several such modes may exist (as in a wave-guide).
28. *Trans-horizon propagation* Propagation over paths extending beyond the normal radio-horizon. It may include a variety of mechanisms such as diffraction, forward scatter, specular and diffuse reflection, and ducting.
29. *Tropospheric-scatter propagation* Propagation involving scattering from many inhomogeneities and discontinuities in the refractive index of the atmosphere.
30. *Precipitation-scatter propagation* Propagation by scattering from precipitation particles.
31. *Multipath propagation* Propagation by way of a number of transmission paths.

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[1966-69]: V/9 (URSI).

RECOMMENDATION 369-3

REFERENCE ATMOSPHERE FOR REFRACTION

(1959-1963-1966-1978-1982)

The CCIR,

CONSIDERING

that the dependence of the refractive index n of the atmosphere at radio frequencies upon the height h is well expressed by the law

$$n(h) = 1 + a \times \exp(-bh) \quad (1)$$

where a and b are constants that can be determined statistically for different climates,

UNANIMOUSLY RECOMMENDS

that the reference atmosphere for refraction be given by the following formula:

$$n(h) = 1 + 315 \times 10^{-6} \times \exp(-0.136h) \quad (2)$$

where h is the height above sea level (km).

RECOMMENDATION 453

THE FORMULA FOR THE RADIO REFRACTIVE INDEX

(Question 2/5)

(1970)

The CCIR,

CONSIDERING

- (a) the necessity of utilizing a single formula for calculation of the index of refraction of the atmosphere;
- (b) the desirability of expressing this formula in a coherent system of units,

UNANIMOUSLY RECOMMENDS

that the atmospheric radio refractive index, n , be given by the following formula:

$$n = 1 + N \times 10^{-6} \quad (1)$$

where

N is the refractivity expressed by:

$$N = \frac{77,6}{T} \left(p + 4810 \frac{e}{T} \right) \quad (2)$$

P : atmospheric pressure (mb),
 e : water vapour pressure (mb),
 T : absolute temperature (K).

REPORT 563-2

RADIOMETEOROLOGICAL DATA

(Question 2/5)

(1974-1978-1982)

1. Introduction

Certain propagation calculations can only be made on the basis of radiometeorological data. Summary data and models for the temporal and spatial variation of the required parameters – radio refractivity, water vapour concentration, rainfall statistics and sand and dust-storm characteristics – are presented in this Report. These data are to provide guidance on the worldwide behaviour of each parameter and should only be used for calculation when detailed data are not available for a particular region. *

2. Radio refractivity

2.1 Definition

The index of refraction of air is very close to unity. The radio refractivity, N , is defined as:

$$N = (n - 1) \times 10^6 \quad (N \text{ units}) \quad (1)$$

where n is the index of refraction. N is the parameter generally used to describe the spatial and temporal variation of the index of refraction. At radio frequencies, the radio refractivity may be approximated by [Bean and Dutton, 1966]:

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (2)$$

where

P : atmospheric pressure (mb)

T : absolute temperature (K)

e : water vapour pressure (mb)

This expression may be used for all frequencies; for frequencies up to 100 GHz, the error is less than 0.5%.

The radio refractivity at a point in space varies primarily due to variations in temperature and water vapour concentration. The variations may occur on time scales ranging from seconds to months. It is common usage to refer to fluctuations on time scales of less than several minutes or spatial scales of less than several kilometres as turbulent fluctuations or as small scale irregularities. Variations on larger spatial or temporal scales are considered to be variations in the macroscopic properties of the medium.

2.2 Variation of N in model atmospheres

N varies primarily with height. The height dependence for an average mid-latitude atmospheric profile is depicted in Fig. 1 [U.S. Standard Atmosphere Supplements, 1966; Crane, 1976]. Also shown in this figure is the average exponential atmosphere. The vertical variation of N is the principal cause for atmospheric refraction effects such as ray-bending and defocusing (see Report 718). The vertical variation in the lowest layer of the atmosphere is of most importance to the calculation of refraction effects. The average exponential atmosphere is shown to provide a good fit to the model atmosphere in this most important region for the estimation of ray-bending.

The average exponential atmosphere is defined by:

$$N(h) = N_A \times \exp(-b_A h) \quad (3)$$

where $N(h)$ is the N value at height h measured in km, and the constants N_A and b_A are given by:

$$\begin{aligned} N_A &= 315 & N \text{ units} \\ b_A &= 0.136 & \text{km}^{-1} \end{aligned}$$

N_A is the average value of radio refractivity at the surface of the Earth.

The radio refractivity is assumed to be horizontally stratified (depends only on height) for most model atmospheres.

* These regions must not be confused with the tropospheric scatter climatic classifications set out in Report 238.

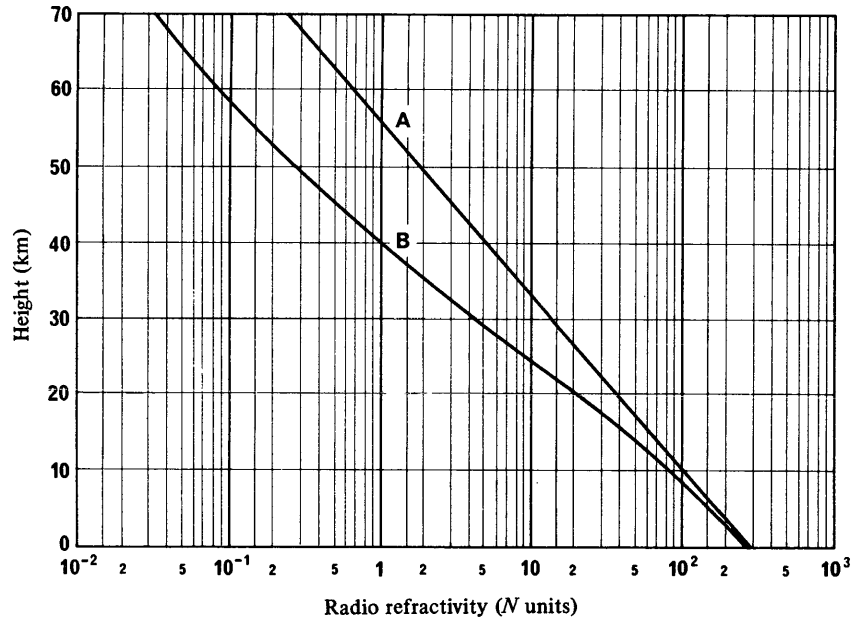


FIGURE 1 – Radio-refractivity profiles for model atmospheres

A : Average exponential model
 B : Mid-latitude model (dry atmosphere)

2.3 World charts of surface radio refractivity reduced to a reference level

The surface value of radio refractivity, N_s , is an important parameter for the prediction of many propagation effects (see Report 718). To minimize the effect of surface height variation (topography) on maps of N_s , the refractivity values can be transformed to a convenient reference level using the exponential model. The reference level refractivity values, N_0 , may be transformed back to N_s values by:

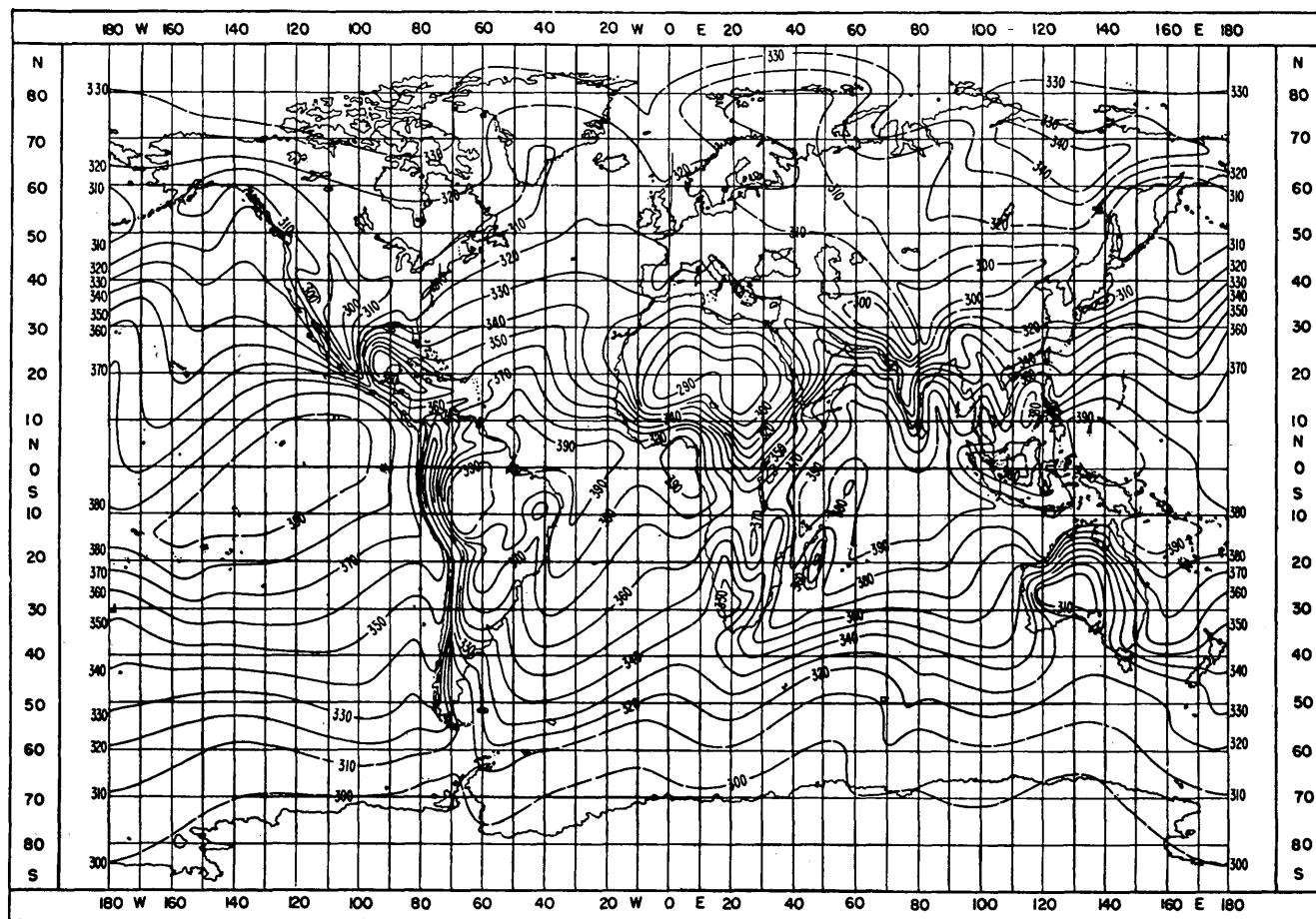
$$N_s = N_0 \times \exp(-b_A h_s) \quad (4)$$

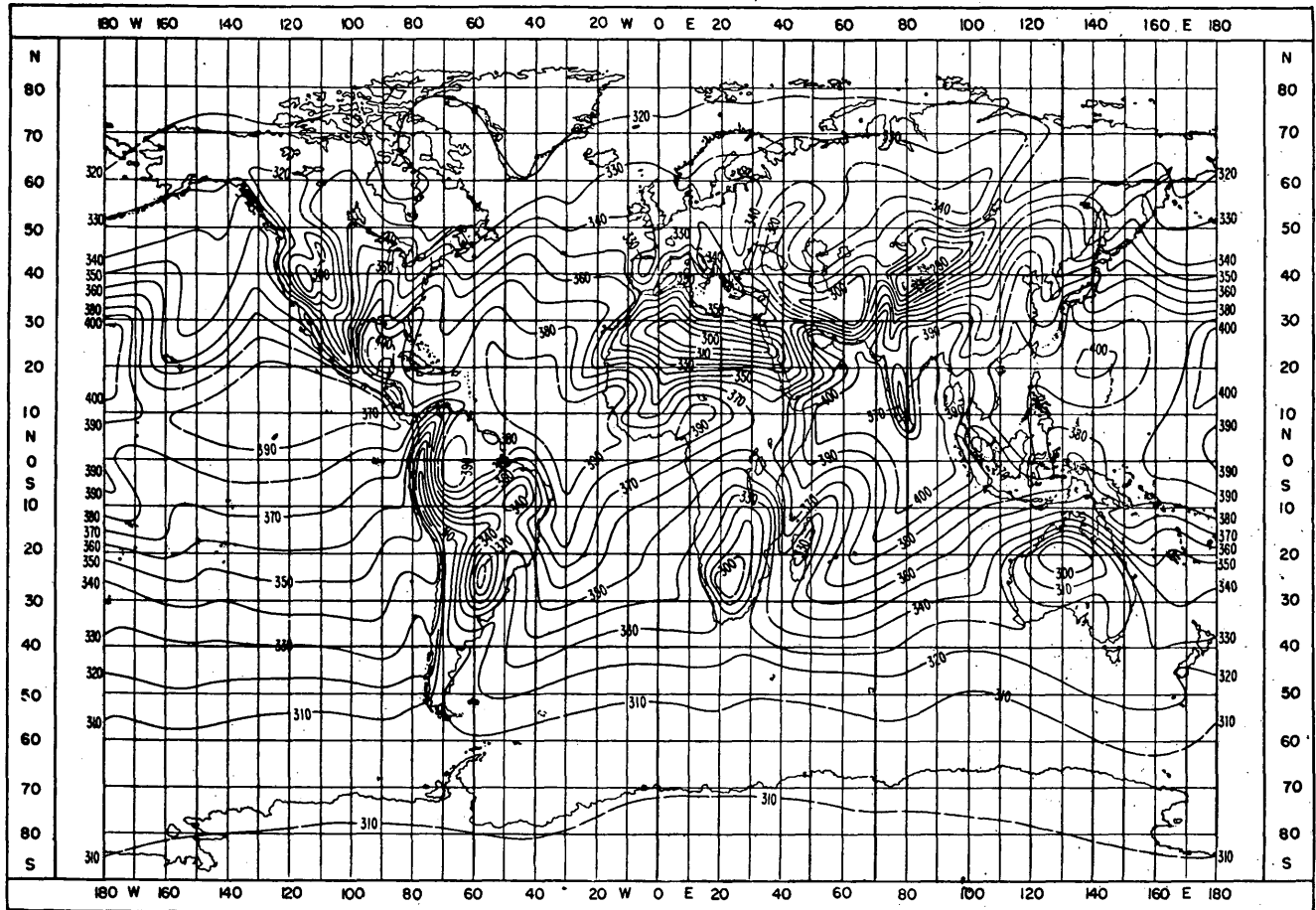
where h_s is the surface height above sea level.

World charts of monthly mean values of N_0 are presented in Figs. 2 and 3 for February and August respectively. Figure 4 depicts areas where the mean monthly values of N_0 exceed 350 N units for at least one month of the year and for every month of the year. A compendium of charts and graphs of monthly mean values of N_0 for selected months is available [Bean *et al.*, 1960].

Data have also been obtained for Venezuela (in a tropical climate), where a considerably smaller annual variation in N_s was observed than that for temperate climates (35 compared with 80 N -units).

Caution should be exercised in the use of these charts for the estimation of a mean monthly value for a particular month and season because the year to year variability for a particular month can exceed the seasonal differences indicated on the charts.

FIGURE 2 - World-wide mean value of N_0 : February

FIGURE 3 – World-wide mean value of N_o : August

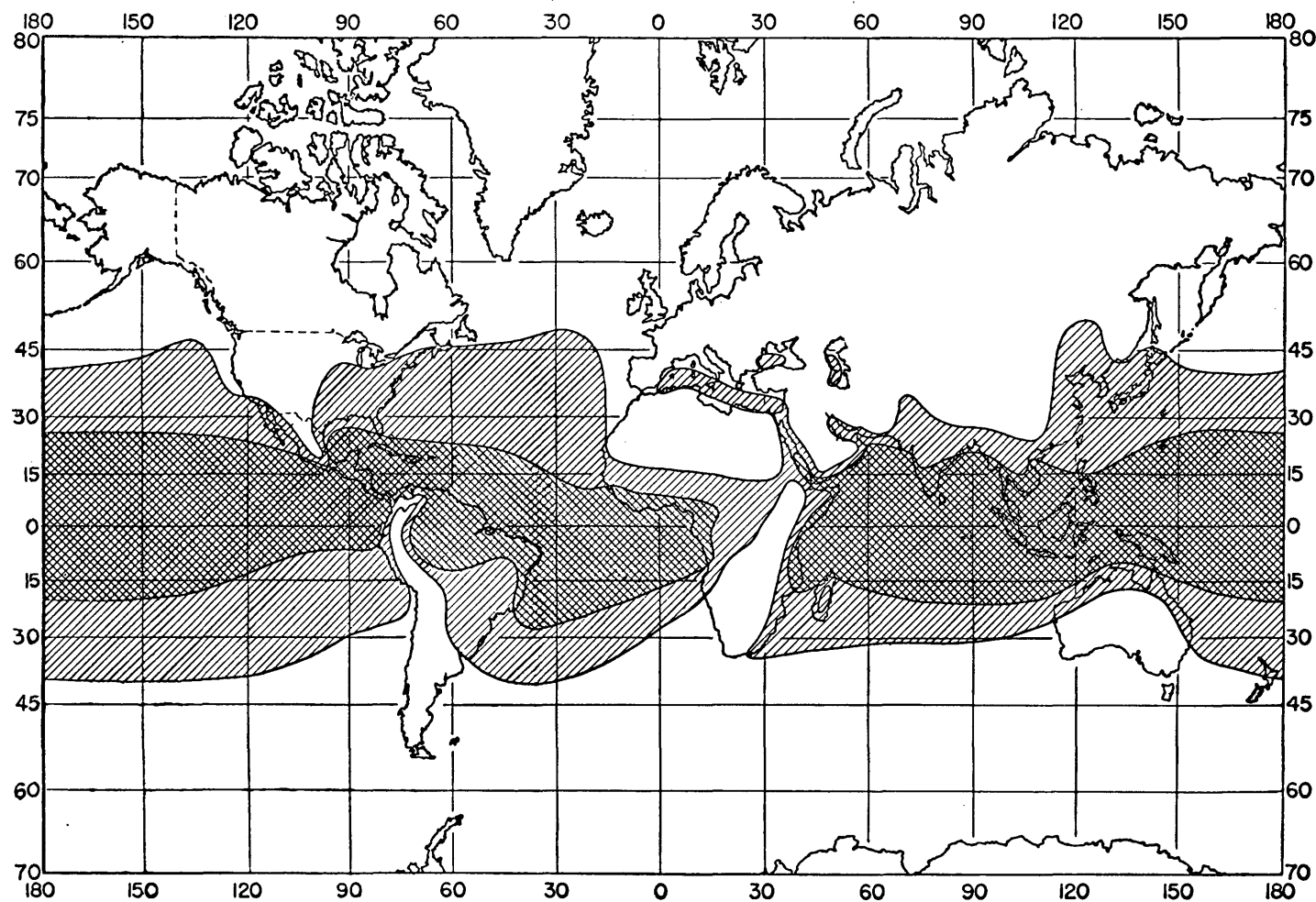


FIGURE 4

-  Mean monthly value of $N_0 > 350$ N -units during all months
 Mean monthly value of $N_0 > 350$ N -units during at least one month

2.4 Radio refractivity gradients

The vertical gradient of radio refractivity in the lowest layer of the atmosphere is an important parameter for the estimation of refraction effects such as ducting (see Reports 569 and 718). Statistical analyses have been made to describe the variation of N over the first km and first 100 m of the atmosphere.

2.4.1 World charts of ΔN — the decrease in N over a 1 kilometre layer

Charts of the monthly mean decrease (lapse) of radio refractivity over a 1 km thick layer based at the surface are presented in Figs. 5 to 8 [Bean *et al.*, 1966]. The change in radio refractivity, ΔN was calculated from:

$$\Delta N = N_s - N_1 \quad (5)$$

where N_1 is the radio refractivity at a height of 1 km above the surface. The ΔN values were not reduced to a reference surface.

Statistical data on ΔN , and the influence of synoptic factors, have been obtained for Poland [Pawlowski, 1975].

2.4.2 Vertical gradients averaged over the lowest 100 metres

Measurements of the vertical refractive-index gradient in the lower layers of the atmosphere show that the range of values is extremely large. In the United States, at Cape Kennedy, Florida, the vertical gradient was measured in the first 100 m near the surface of the Earth. It was found that a value of 230 N/km was exceeded during 0.05% of the time, and -370 N/km was exceeded during 99.9% of the time [Dougherty, 1968]. Probability density functions of positive gradients for both well-mixed and stratified atmospheric conditions are given by Schiavone [1981].

In France, studies carried out in the Paris area produced results very similar to those mentioned above.

In Japan and in the United Kingdom [Hall and Comer, 1969] measurements were very similar and showed that, for the first 100 m, values of about 70 N/km and -200 N/km were exceeded respectively for 0.1% and 99.9% of the time.

Measurements in the U.S.S.R. [Kalinin and Nadenenko, 1975] have shown that the statistical distribution of the effective gradient of the refractive index in the 0-200 m layer approaches the normal law for most climatic regions of the U.S.S.R. (except mountainous and coastal regions).

The following distribution function for $\alpha = -\Delta N/\Delta h$ was derived for South-East Asia by analyzing precisely measured meteorological data [Akiyama, 1971].

$$\left. \begin{aligned} F(\alpha) &= 0.5 \exp [4(\alpha - \alpha_m)/3\sigma] & \text{for } -\infty < \alpha \leq \alpha_p \\ &= 0.5 \operatorname{erfc} [-(\alpha - \alpha_m)/\sqrt{2}\sigma] & \text{for } \alpha_p < \alpha < \infty \end{aligned} \right\} \quad (6)$$

where

$$\alpha_p = \alpha_m - 1.48\sigma, \quad \alpha_m = \Delta N, \quad \sigma = \sigma_{\Delta N}/\sqrt{\Delta h}$$

and ΔN and $\sigma_{\Delta N}$ are the monthly mean value and standard deviation of α for the first one kilometre layer above the Earth's surface respectively, and Δh is the thickness in km of the layer considered. The relation between $\sigma_{\Delta N}$ and N_s is derived, and ΔN and $\sigma_{\Delta N}$ are expressed as a function of latitude for South-East Asia [Akiyama and Hatano, 1977; Akiyama, 1977].

A survey of 5 years of radiosonde data for selected tropical stations [Dougherty and Hart, 1977] indicates a percentage of extreme vertical refractivity gradients (measured as the mean over the first few hundred metres above ground) lying outside the range 0 to -157 N-units/km, larger than encountered at most temperate zone locations. Although a seasonal distribution of the maximum and minimum occurrence of extreme gradients is evident at temperate locations, the tropical stations show no such patterns.

Correlation has also been observed between the vertical gradient of the refractive index and the value of this index at the surface of the Earth [Bean and Meany, 1955; Misme, 1958; Lane, 1961; Misme *et al.*, 1960] at least for monthly mean values [Wickerts, 1968].

However, this correlation does not exist all the time and at all points. More particularly, it may not exist in certain regions when N_s reaches very high values, e.g. values above 350 [Boithias and Misme, 1964].

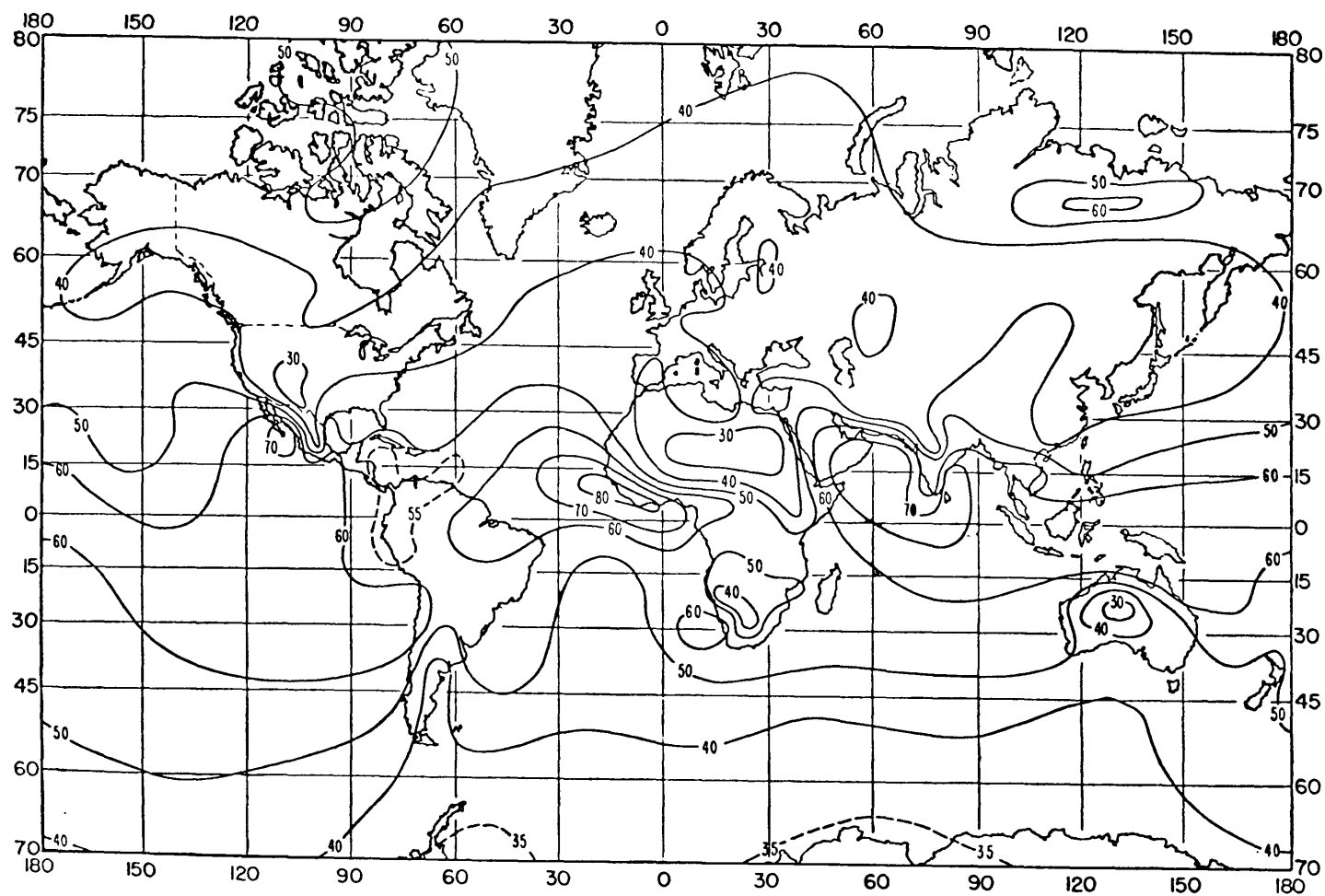


FIGURE 5 – Monthly mean values of ΔN : February

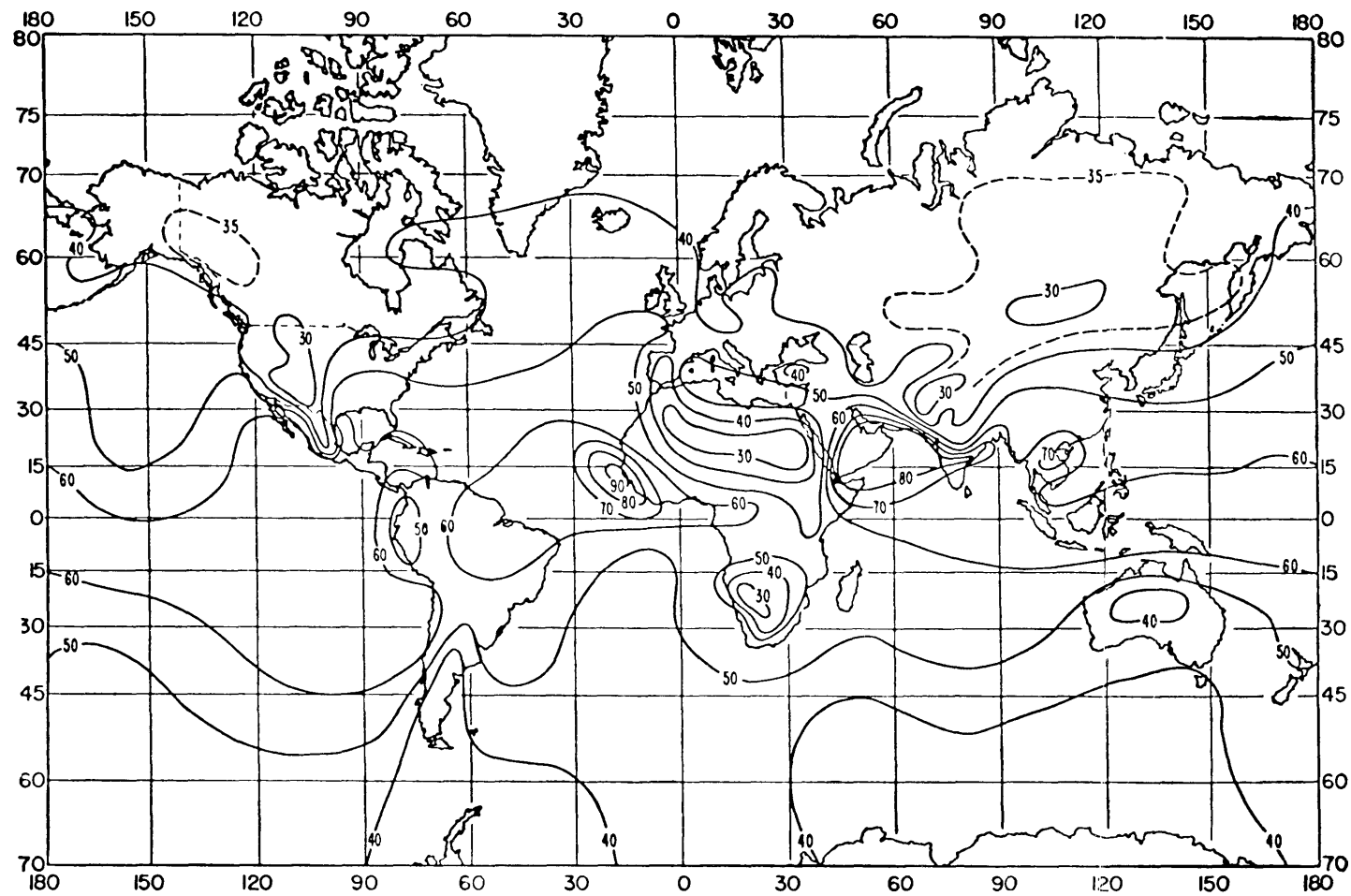


FIGURE 6 – Monthly mean values of ΔN : May

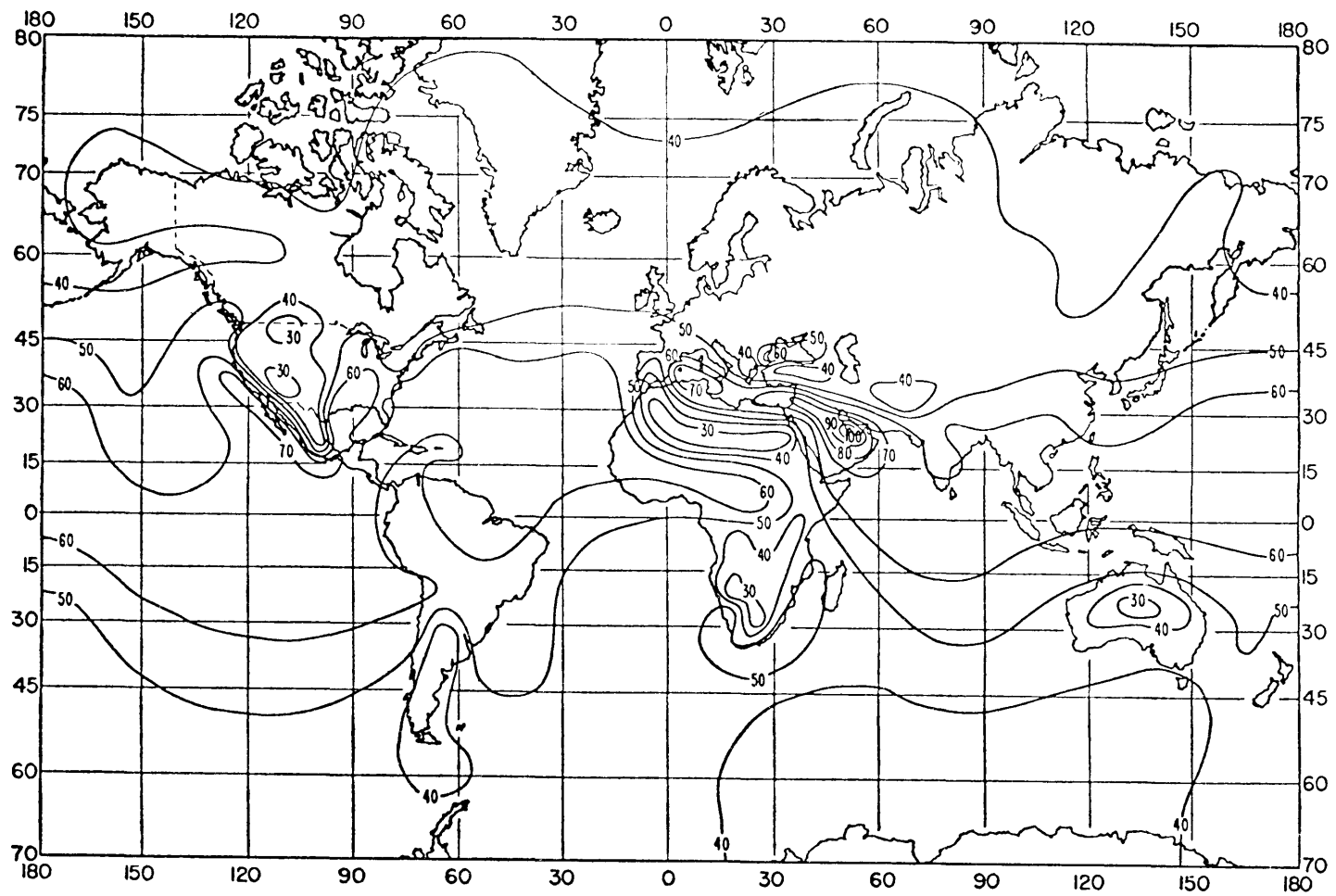


FIGURE 7 – Monthly mean values of ΔN : August

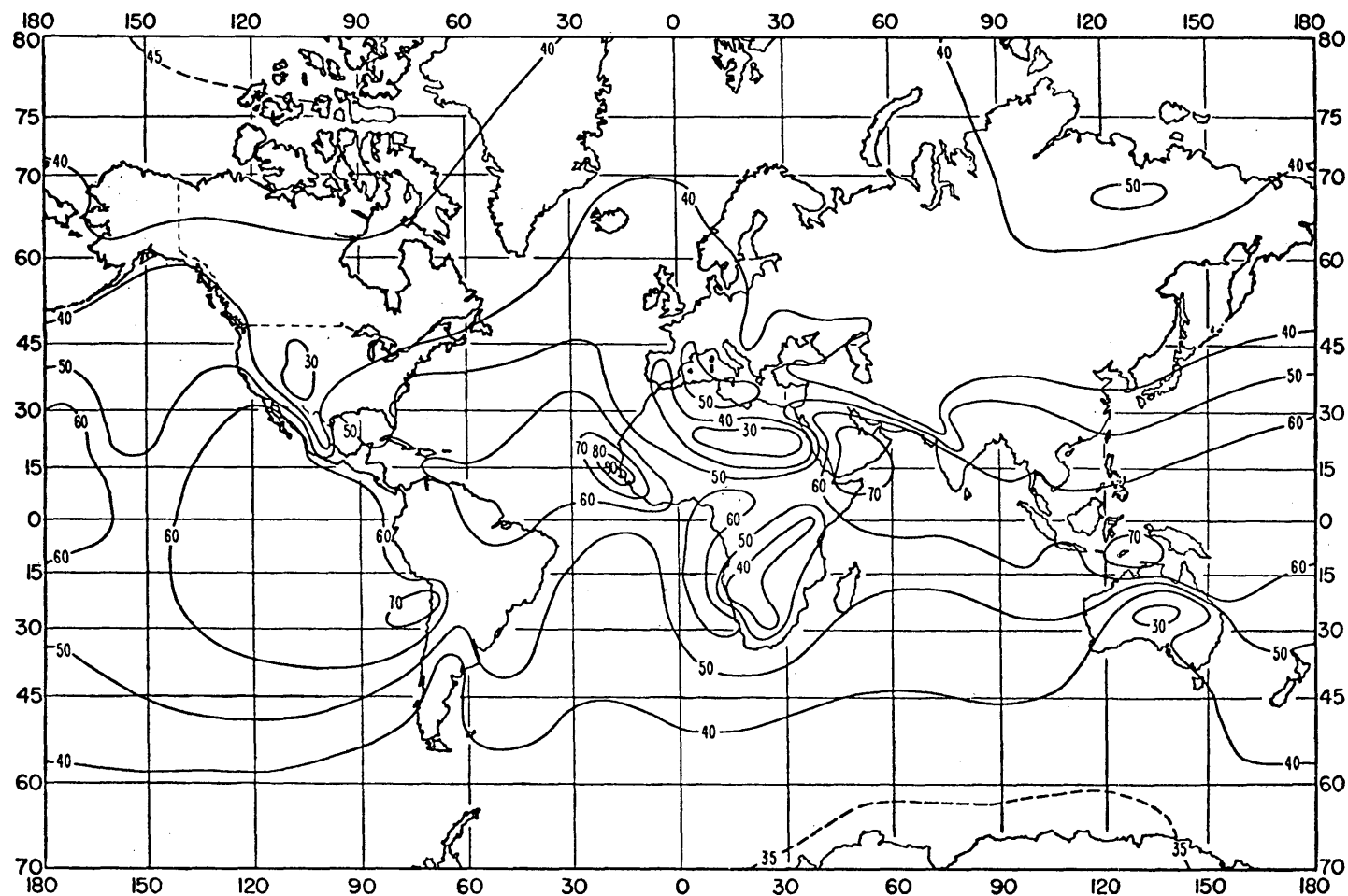


FIGURE 8 – Monthly mean values of ΔN : November

2.5 Small scale irregularities

The small scale turbulent radio refractivity irregularities can cause scattering of radiowaves giving rise to tropospheric forward scatter and to scintillation (see Report 881). The statistical variation of n at small spatial scales (less than 10 m) may be represented by the three-dimensional power spectral density

$$\Phi_n(\underline{s}) = \Phi_n(s) = 0.033 C_n^2 s^{-11/3} \quad (7)$$

where Φ_n is the power spectral density, $\underline{s}$ is the vector wavenumber, s the magnitude of the wavenumber, $s = 2\pi/l$ where l is the scale size and C_n^2 is the refractivity structure parameter. This description assumes that the turbulent fluctuations are isotropic and that s is in the inertial subrange [Tatarskii, 1967]. Refractive index fluctuations at larger scale sizes may be highly anisotropic and cannot be simply modelled using this expression.

C_n^2 is a macroscopic parameter that varies in space and time. C_n^2 varies primarily with height. C_n^2 values at a given height may vary several orders of magnitude over time periods of tens of minutes. The turbulent layers are thin and patchy. The highest values of C_n^2 are found in the planetary boundary layer (extending from the surface to a height varying from 1 to 2 km depending on climate region, season, and time of day). Observed C_n^2 values range from 10^{-15} to $10^{-10} \text{ m}^{-2/3}$ [Gossard, 1977; Gossard, 1978a and b] in the planetary boundary layer decreasing abruptly, then more slowly to values ranging from 10^{-20} to $10^{-17} \text{ m}^{-2/3}$ at a height of 20 km.

More detailed information on these topics can be found in [IUCRM Symposia, 1969, 1973; Radio Science, 1980].

3. Variability of water vapour concentration and oxygen density at ground level

Atmospheric water vapour and oxygen cause absorption at mm wavelengths especially in the region of absorption lines (see Report 719). The concentration of atmospheric oxygen is relatively constant whereas the concentration of water vapour is not.

Monthly mean values for the water vapour concentration, ρ , (also known as absolute humidity or water vapour density) are given in Figs. 9 and 10 for the months of February and August respectively [Bean and Dutton, 1966].

For ready reference, the relationship between water vapour concentration and water vapour pressure is given by:

$$\rho = 216.7 \frac{e}{T} \quad (8)$$

where

ρ : is water vapour concentration (g/m^3)

e : is water vapour pressure (mb) and

T : is absolute temperature (K).

Water vapour concentration is highly variable. To a first approximation, the temporal fluctuations of ρ may be assumed to follow a normal law with a standard deviation about one quarter the mean value.

It is noted that the statistical variation of water vapour concentration is affected by atmospheric temperature. The relative humidity rarely exceeds 100 per cent implying that the maximum water vapour concentration will not exceed the value corresponding to saturation at the atmospheric temperature.

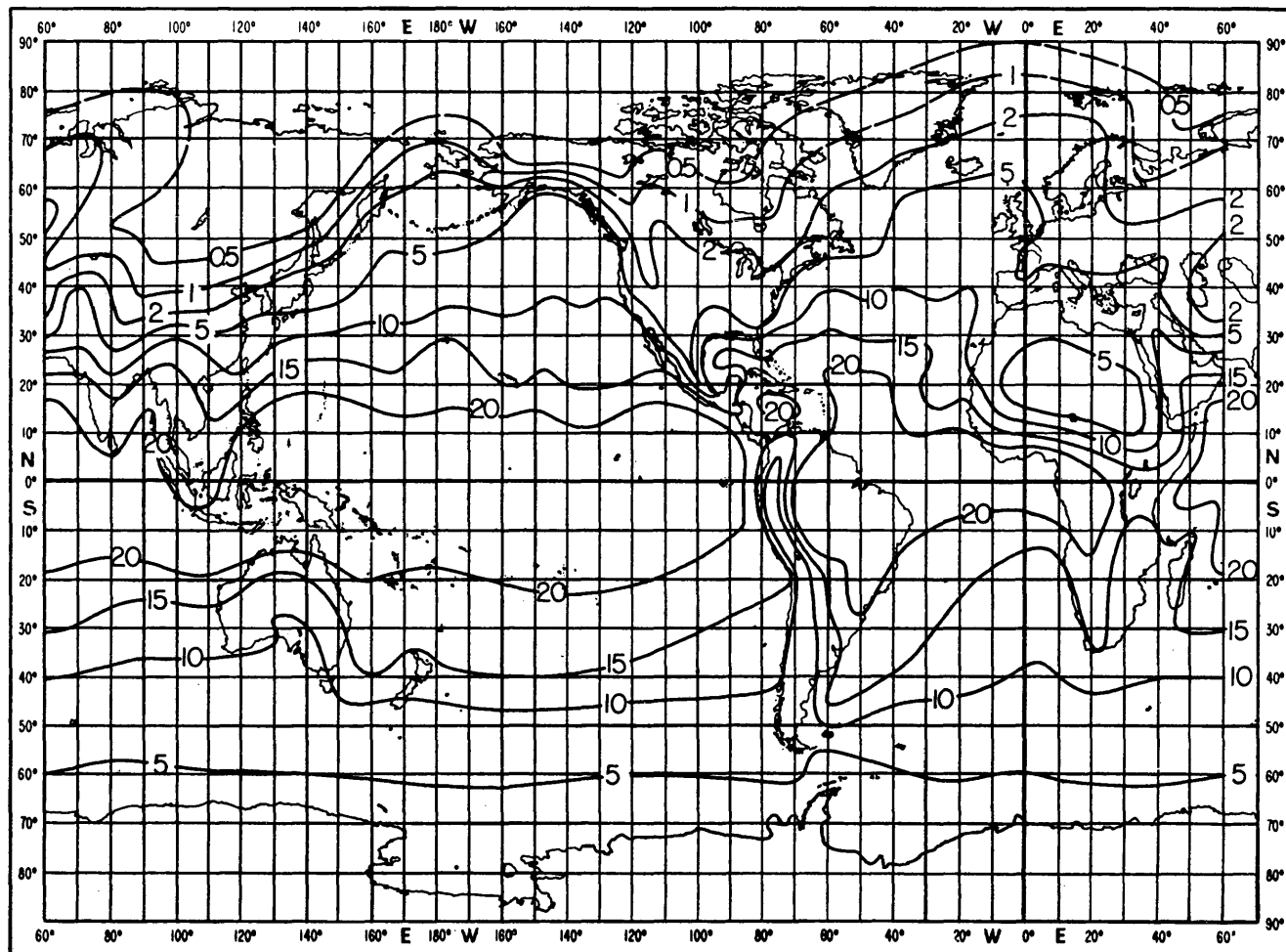
The water vapour concentration increases to a value near saturation in clouds and rainfall. At frequencies above about 15 GHz the correlation between attenuation produced by water vapour absorption and that produced by rain should be taken into account when estimating attenuation statistics or in interference calculations.

In general, rain occurs during the season with the highest average values of water vapour density near the surface and the higher values of rain rate should be correlated with the higher seasonal water vapour density values.

As a first approximation for each location the higher value of water vapour density from Figs. 9 and 10 should be used for rain rates in excess of 25 mm/h and the lower value for lower rain rates.

4. Precipitation characteristics

The following sections provide information on the temporal and spatial characteristics of precipitation. This is presented in terms of the microstructure of rainfall, cumulative distribution of rainfall intensity as measured at a point and of statistical description of the horizontal and vertical variability of precipitation structure.

FIGURE 9 – Water vapour concentration (g/m^3), February

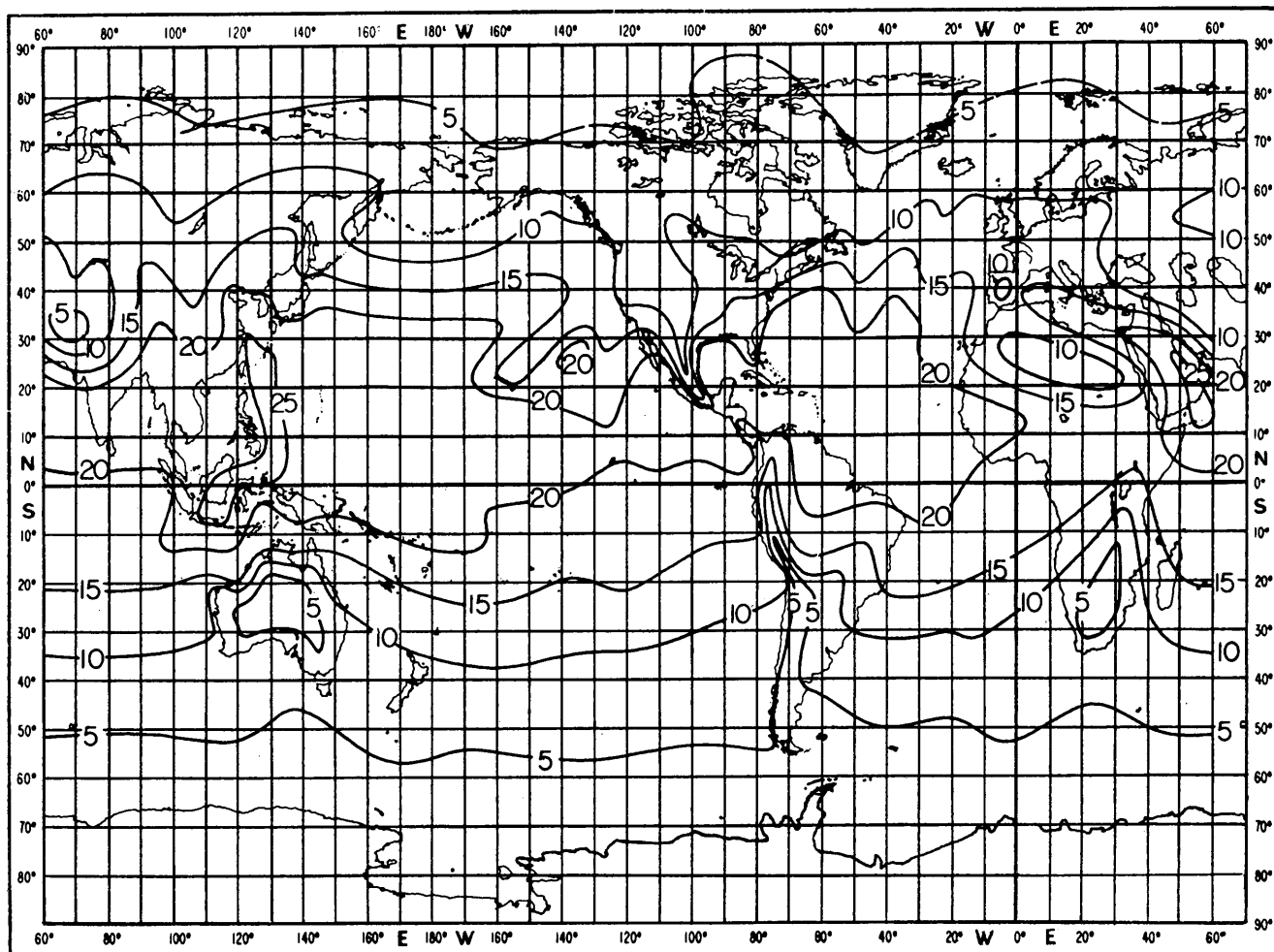


FIGURE 10 – Water vapour concentration (g/m^3), August

4.1 *Microstructure of rainfall*

4.1.1 *Drop size distribution*

The size, shape and orientation distributions of raindrops may vary within a storm. Observations show that on average, the drop size distribution is relatively stable, changing mainly with rain rate. The Laws and Parsons [1943] drop size distribution has been found useful for the estimation of the attenuation and scattering properties of rain at frequencies up to about 40 GHz. The relative concentrations of small drops having diameters less than 0.5 mm, are not well modelled by the Laws and Parsons distribution and use is sometimes made of the Marshall-Palmer [1948] distribution to remedy this defect. The relative concentration of small drops can be highly variable and the use of a single model distribution may not be adequate for all locations.

4.1.2 *Hydrometeor shape and orientation*

Falling drops assume a nearly spheroidal shape when subject only to the effects of gravity and the surface tension of the water. Drop shape has been modelled as a function of drop size by Pruppacher and Pitter [1971]. Observations in the laboratory by Pruppacher and Beard [1970] agree with the shape predictions of Pruppacher and Pitter. Observations in the atmosphere tend to show smaller axial ratios than calculated by the models for the same drop volume.

Snow and ice particles have often been modelled using spheroidal shapes. The bulk density of snow is low (the ice and air mixture has a larger fraction of air within the boundaries of the spheroid) and the snow particles produce little polarization effects. High bulk density ice particles such as ice plates and columns which occur high in the atmosphere produce measurable polarization effects when a significant fraction of the particles have the same orientation.

The force of gravity provides the major orientation force for raindrops. The drops may vibrate and oscillate while falling but the net shape is oblate spheroidal with the symmetry axis close to vertical. Horizontal forces due to vertical wind gradients may cause the mean orientation to be canted by a few degrees. Ice and snow particles are rigid and are apt to tumble while falling. Drag forces tend to force the ice particles to fall with an orientation which maximizes the drag force. Electric fields have also been observed to impose a similar orientation effect on a significant fraction of the particles.

4.1.3 *Terminal velocity*

Gunn and Kinzer [1949] reported the terminal velocities of raindrops as a function of drop size. The measurements were made in quiet conditions in the laboratory but have been assumed to apply in the atmosphere. The velocities of the drops depend on air density and are therefore a function of height. Radar observations show that on average the reflectivity value changes little with height below the rain height. The number and sizes of the drops and the liquid water content of a volume of drops therefore change little with height. Since the terminal velocity is height dependent, the liquid water flux or rain rate is therefore height dependent. Since the specific attenuation depends primarily on liquid water content, the specific attenuation varies little with height below the rain height.

4.1.4 *Drop temperature*

Falling raindrops have a temperature which approximates the wet bulb temperature for the temperature, pressure, and humidity of the surrounding air. Small liquid droplets can exist at temperatures below 0 °C, especially in the updraft regions of convective storms and in supercooled fogs. Ice and water mixtures can also exist in downdraft regions below the height of the 0 °C isotherm. On average, the significant numbers of the larger liquid water drops which contribute to attenuation by rain occur between the height of the 0 ° isotherm and the surface.

4.2 *Statistical characteristics of rainfall intensity at a point*

4.2.1 *Cumulative distribution of rainfall intensity*

Measurements carried out with fast-response rain gauges have indicated that rainfall of high intensity tends to be concentrated in short periods of time, typically a few minutes. Consequently, experimental cumulative distributions of rainfall intensity depend on the integration time employed. The monthly, daily and in some instances hourly rainfall accumulations readily available in the publications of the various meteorological services cannot be utilized directly to obtain cumulative distributions of rainfall intensity down to small percentages of time.

Fine time-resolution rainfall data have been obtained by means of fast-response rain gauges in Europe and from tipping-bucket gauges in Canada. Corresponding rainfall climatic classifications have been proposed on the basis of these data [Fedi, 1979a; Segal, 1979 and 1980a]. Other regions have been categorized by means of rainfall rate distributions generally derived on the basis of somewhat longer integration times, typically five or ten minutes [Lin, 1978; Morita, 1978].

Attempts have been made to provide a statistical relationship between one minute rainfall intensity distributions and those obtained with longer integration times [Rice and Holmberg, 1973; Flavin, 1981] but more information is required to establish a relationship valid in all climate regions.

Whenever appropriate rainfall intensity data exist for a certain location, these data should be used to determine the appropriate cumulative distribution. In the absence of such information the summaries presented in Figs. 11 to 16 and Table I may be used.

The data points in Figs. 11 to 13 and Table I can be easily used and they are suggested for interference and coordination distance calculations (see Reports 569 and 724). Each figure identifies a number of rainfall climatic zones. The mean cumulative distributions presented in Table I are based on the best experimental data presently available. In practice, the transition in rainfall behaviour from one zone to the next will not be abrupt. The cumulative rainfall-rate distributions will vary from one location to another within a given zone and may display considerable variability from year to year [Crane, 1977; Crane, 1980; Segal, 1979].

For availability calculations (see Reports 338 and 564), in the absence of data obtained from local sources, the use of either Figs. 11 to 13 or of Figs. 14 to 16 is suggested, whichever are more convenient for the region and time percentage. In the latter figures, contours of rainfall intensity exceeded for 0.01% of time are shown. Only the rain intensity values at this percentage of time are used for the model calculations of Report 338 and for the model calculations of Report 564 for maritime climate regions:

In order to improve the resolution and accuracy of Figs. 11 to 16 and Table I, and to develop maps giving isopleths of rainfall intensity exceeded for other percentages of time, additional observational data are required. Administrations are asked to provide such data whenever possible, taking into account the fact that reliable statistics require an observation period of many years. Suitably calibrated, continuously-recording rain gauges with adequate sensitivity and time resolution should be used to obtain such information. When tipping-bucket gauges are used, measurement of the time interval between successive tips is recommended for the lower rainfall rates. Unless the gauge and recording system are specifically designed for precise operation at the very highest rainfall rates expected, it may be preferable to integrate over several tips when these occur too rapidly to be resolved on an individual basis.

4.2.2 *Models for the rainfall rate distribution*

Rainfall of high intensity is difficult to record and measure experimentally, as well as being highly variable from year to year. In system design, however, it is the highest rainfall rates which are frequently of great interest and a suitable mathematical model for the "tail" of the distribution is desirable.

At intermediate rainfall rates where accurate measurements are feasible, it appears that the cumulative rainfall rate distribution can be well approximated by a log-normal law. The range over which this relationship may be assumed valid depends somewhat on the climatic region, but typically it extends from 2 mm/h to about 50 mm/h. [Lin, 1975; Morita and Higuti, 1978; Fedi, 1979b; Segal, 1980b]. The standard deviation of this distribution is influenced considerably by the integration time employed in the data sampling and analysis [Barbaliscia and Fedi, 1980].

The gamma function has also been proposed as an approximation to the rainfall rate distribution [Morita and Higuti, 1976] although this function does not appear to be generally applicable in many climatic regions [Fedi, 1979b; Segal, 1979].

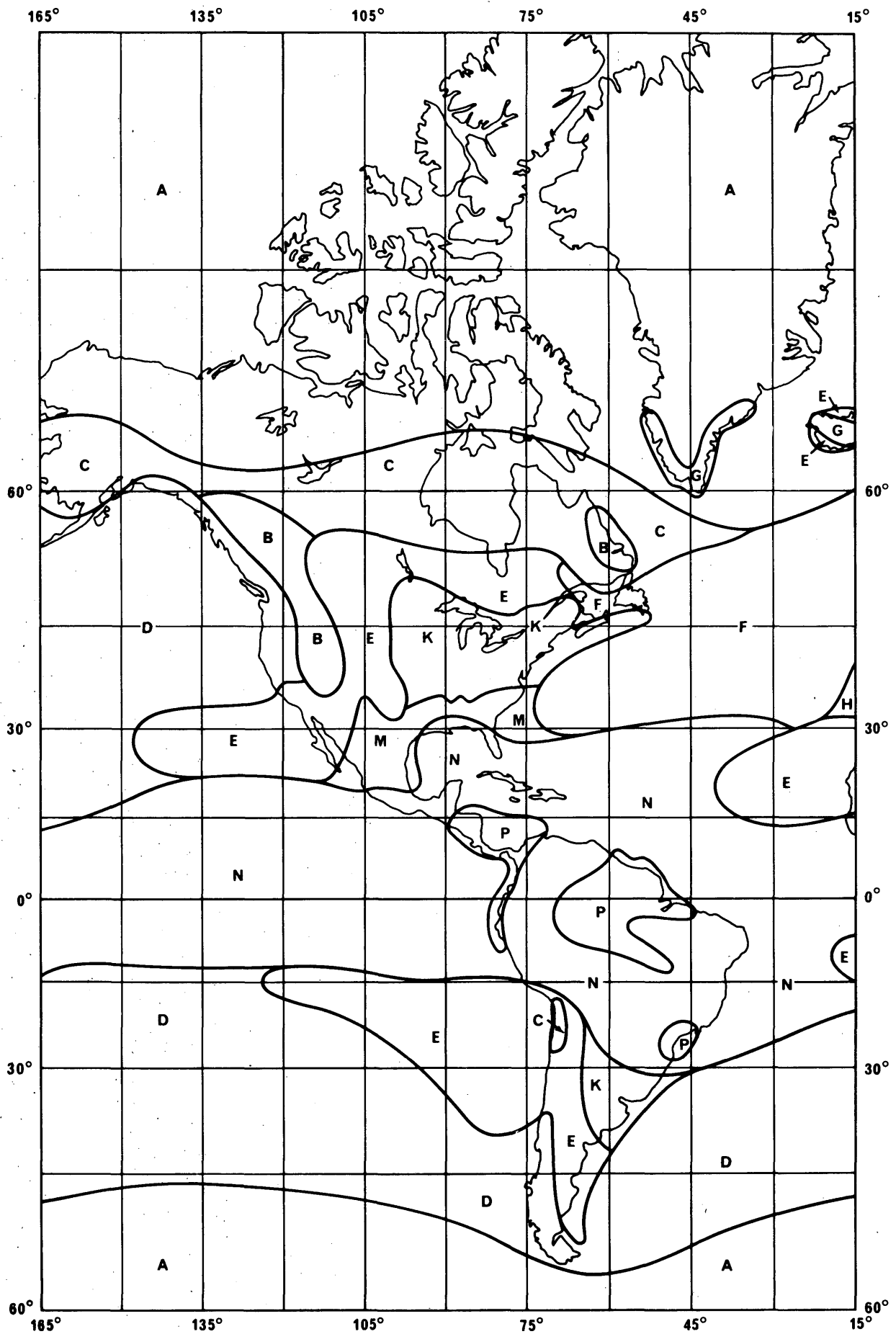


FIGURE 11
(see Table I)

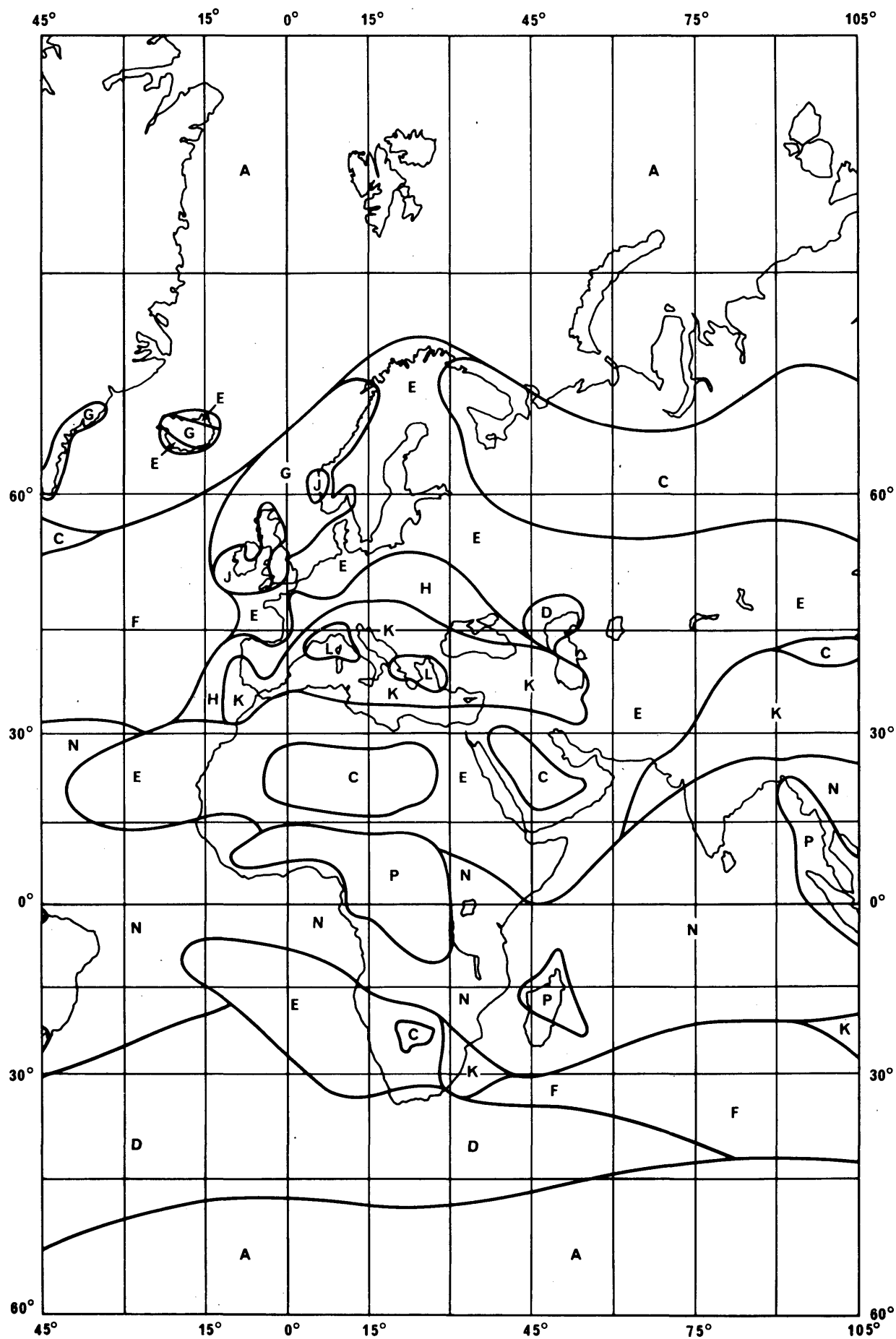


FIGURE 12
(see Table I)

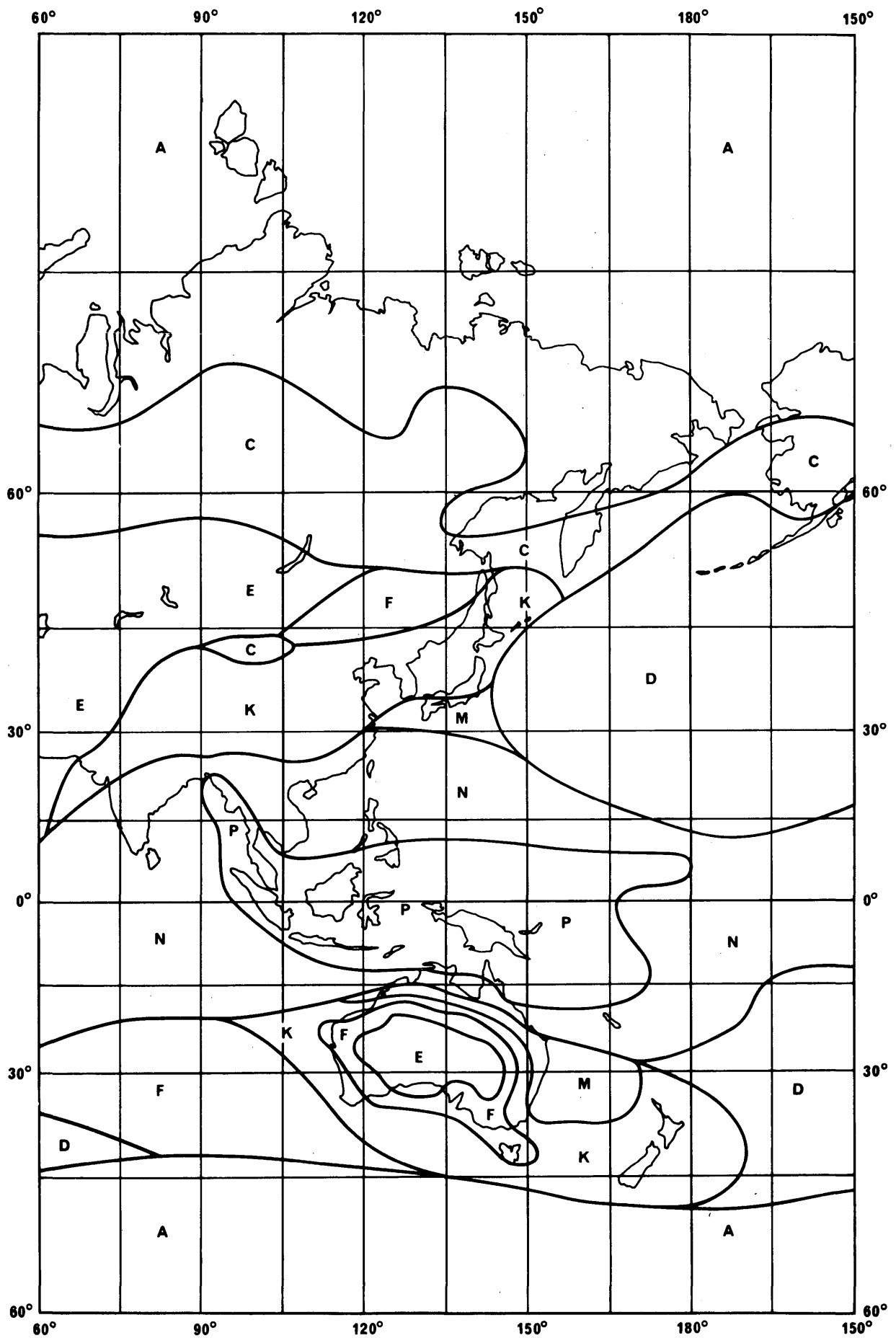


FIGURE 13
(see Table I)

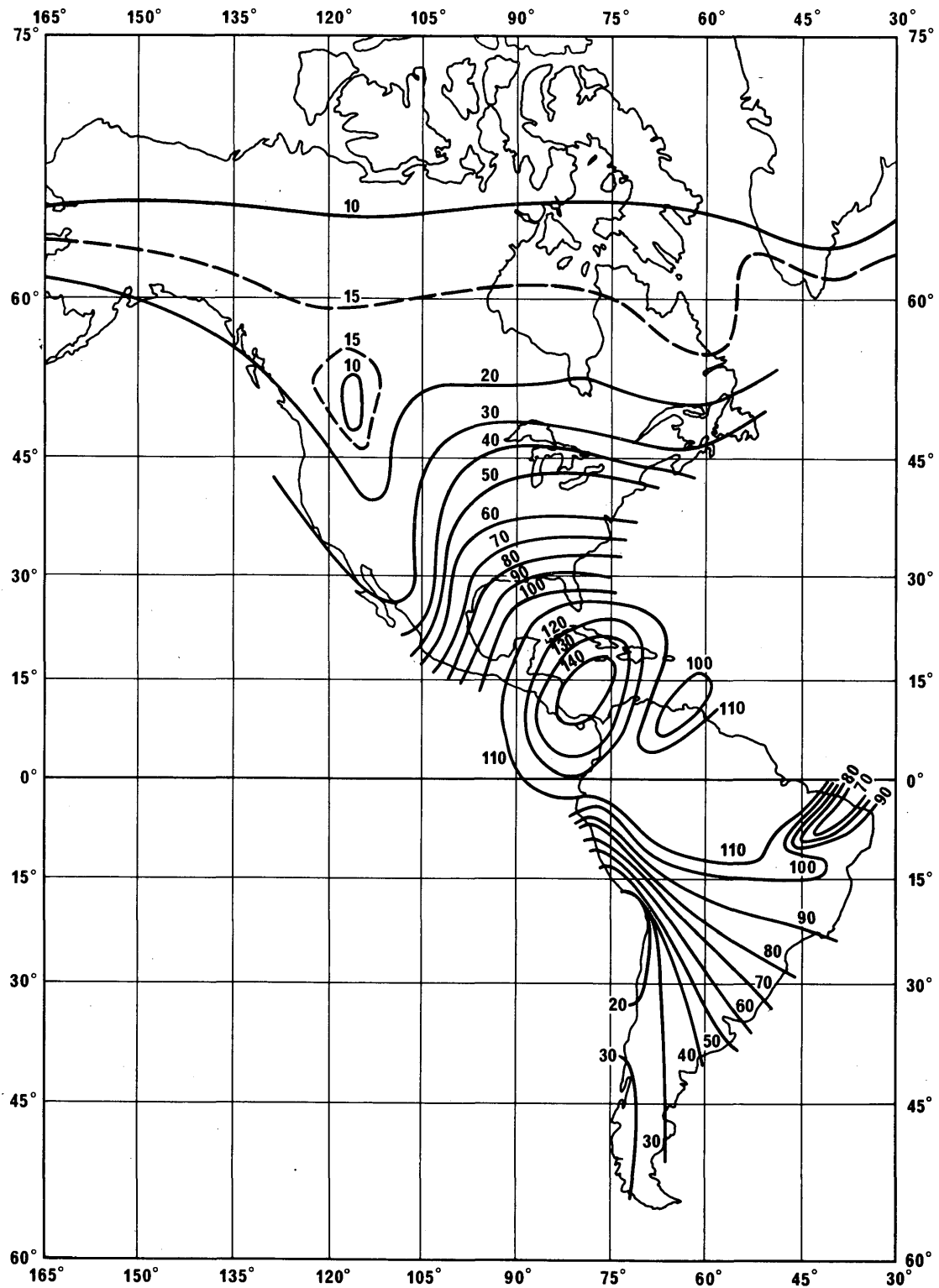


FIGURE 14 - Rainfall contours 0.01 % of the time

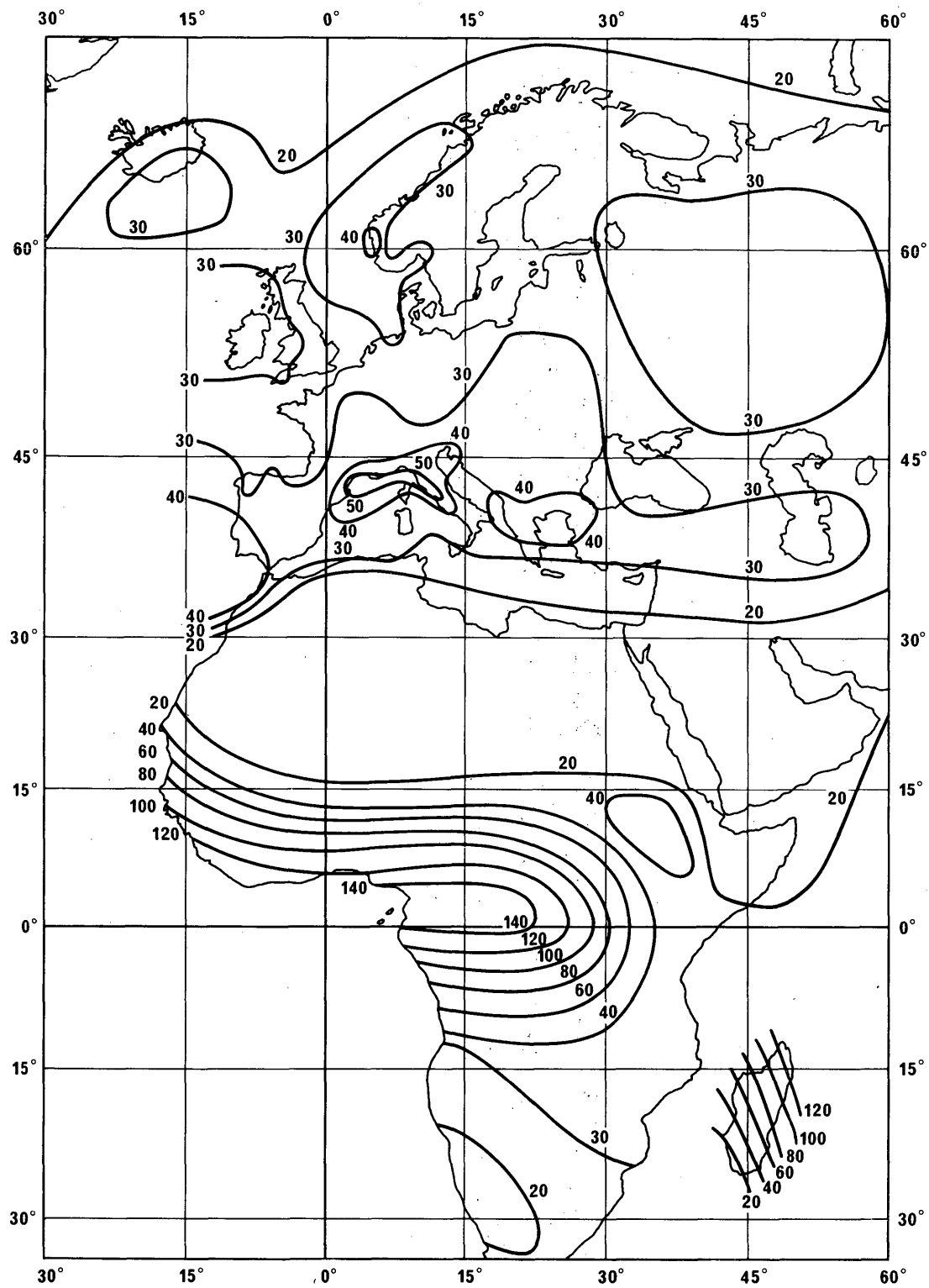


FIGURE 15 - Rainfall contours 0.01 % of the time

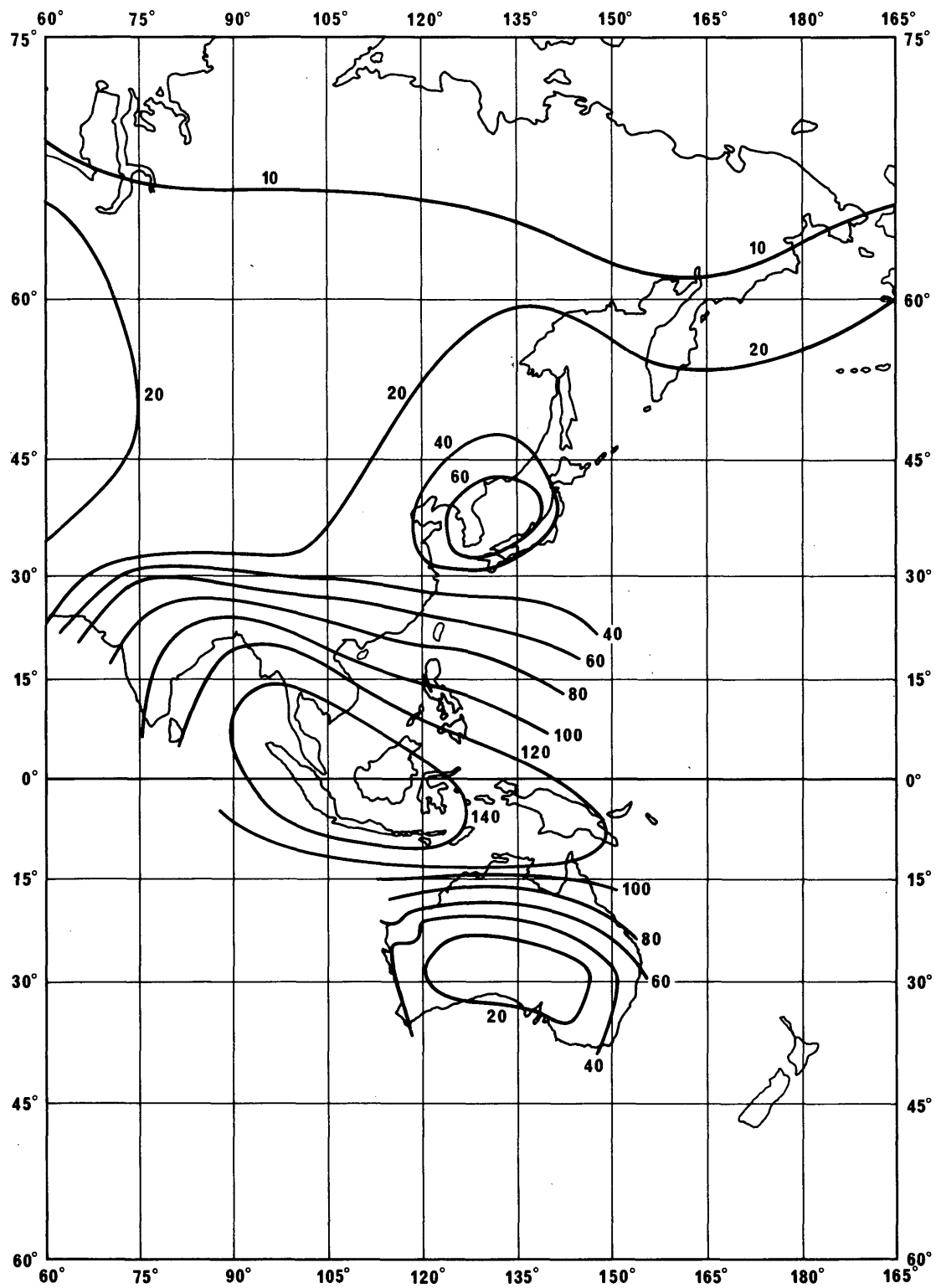


FIGURE 16 - Rainfall contours 0.01 % of the time

TABLE I - Rain climatic zones
Rainfall intensity exceeded (mm/h) (Reference to Figs. 11 to 13)

Percentage of time (%)	A	B	C	D	E	F	G	H	J	K	L	M	N	P
1.0	-	1	-	3	1	2	-	-	-	2	-	4	5	12
0.3	1	2	3	5	3	4	7	4	13	6	7	11	15	34
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200
0.001	22	32	42	42	70	78	65	83	55	100	150	120	180	250

Recent analysis suggests that the rain rate distribution is better described by a model which approximates a log-normal distribution at low rates, and a gamma distribution at high rain rate [Moupfouma, 1981 *; De Reffye, 1982]. The gamma function has been shown to provide a good approximation to the cumulative distribution beyond about 50 mm/h for many different climatic regions [CCIR, 1978-82].

Although the log-normal distribution appeared to provide the best fit for low rainfall rates, studies conducted on measurements taken in Canada suggest that for short integration times a power-law relationship can satisfactorily approximate the entire cumulative distribution beyond about 5 mm/h [Segal, 1980b].

4.2.3 Statistics of rainfall event duration

The statistical distribution of the duration of rainfall events that exceed preselected thresholds is also of interest for the forecast of transmission reliability. Studies made in Japan, France and Italy indicate that this distribution is approximately log-normal [Misme, 1974; Yamada *et al.*, 1977; Barbaliscia and Fedi, 1980]. Measurements in Italy and in Greece indicate that the median durations for rainfall events are approximately inversely proportional to the values of the rainfall intensity threshold [Fedi and Merlo, 1977; Fedi, 1979a].

4.3 Horizontal structure of rainfall

Rainfall is inhomogeneous in the horizontal plane. Measurements carried out with radar systems reveal the existence of larger areas of low precipitation rates with a number of smaller imbedded regions of higher precipitation rates. Localized core regions of higher rain rate called volume cells [Crane, 1979] can usually be identified within larger precipitation regions.

Unfortunately, there does not exist at present an adequate morphology of the structure of precipitation. It is known that the structure should depend upon the rainfall type, the topography and the depth of the potentially unstable layer that produces the convective cells and that such information should be obtained at a number of different latitudes in both maritime and continental regions. Furthermore, for radio propagation applications, the statistical descriptions required for the volume cells and for the spatial variations of rainfall intensity in the larger areas of lighter precipitation depend on the particular application.

* This model may be expressed by the relation:

$$P(R > r) = a_0 \frac{e^{-ur}}{r^b}, r \geq 2$$

where

a_0 , u , b are parameters depending on climate and integration time.

High resolution measurements have been made of the width of the volume cell. The volume cell is defined by a small 3 dimensional volume enclosing the region with reflectivity values larger than half the peak value (3 dB) of reflectivity of the cell. The width values have an exponential distribution for a given intensity. For peak rainfall rates exceeding 10 mm/h, the mean cell diameter is approximately 2.5 to 3.0 km [Debrunner and Liniger, 1975; Crane, 1979]. These mean diameters for the volume cell may be used in defining the common volume responsible for interference scattering by precipitation.

For attenuation predictions the situation is generally more complex. Volume cells are known to cluster frequently within small mesoscale areas [Austin, 1973; Segal, 1979; Crane, 1979]. Terrestrial links exceeding 10 km may therefore traverse more than one volume cell within a mesoscale cluster. In addition, since the attenuating influence of the lower intensity rainfall surrounding the cell must also be taken into account, any model used to calculate attenuation must take these larger rain regions into account. The linear extent of these regions increases with decreasing rain intensity and may be as large as several tens of kilometres. Various precipitation models have been developed in an attempt to deal with these complexities [Druifuca, 1974; Misme and Fimbel, 1975; Morita and Higuti, 1978; Harden *et al.*, 1977 and 1978; Crane, 1980].

Site or path diversity improvement results from the inhomogeneous nature of the precipitation region containing the volume cells. The highest values of attenuation occur when an intense cell lies along the propagation path. The probability of a second intense cell simultaneously occurring along a second path separated from the first by distances of the order of 10 km or more is small, leading to diversity improvement when switched path or site diversity is used. If the attenuation produced by the larger rain areas outside the cells results in system impairment then much larger separation distances are required for significant diversity improvement.

4.4 *Vertical structure of precipitation*

Information on the vertical structure of precipitation is required for the prediction of attenuation on a slant path and for the calculation of interference due to rain scatter. In the former case, the vertical variation of specific attenuation is required, and in the latter case, the vertical structure of reflectivity is important.

Radar observations provide the only direct measurements of the vertical structure of precipitation. On the basis of such observations, two distinct precipitation types have been identified:

- stratiform precipitation characterized by a thin horizontal layer of enhanced reflectivity called a bright band;
- convective precipitation characterized by nearly vertical columnar regions of enhanced reflectivity.

Both types may occur in different regions of the same storm. Seasonal variations of the bright band height have been seen to be correlated with ground temperature. [Fujita *et al.*, 1979].

4.4.1 *Vertical variation of specific attenuation*

Radar measurements show that the reflectivity values do not vary significantly from the surface to the base of the bright band. Aircraft and dual polarization radar measurements [Hall *et al.*, 1980] show that the region below the bright band is composed of liquid drops. The specific attenuation can therefore be assumed to be statistically invariant with height up to the base of the bright band. In the cores of convective showers, the reflectivity profiles generally show a broad vertical region of enhanced reflectivity which forms above the surface then descends to the surface. It has also been found that the region of enhanced reflectivity often contains a mixture of ice and water.

In temperate climates where the ice phase is important to the production of precipitation, a reasonable model for the occurrence of liquid water in a storm is to assume that liquid particles are present below the height of the 0 °C isotherm and snow and ice particles are present above that height. Dual polarization radar observations have confirmed this vertical structure in stratiform rain and have suggested that this structure obtains, on average, in the cores of convective showers.

In tropical climates, especially out over the oceans, showers often occur which do not reach to the height of the 0 °C isotherm. In this region, such showers are all liquid but the specific attenuation cannot be assumed statistically constant to the height of the 0 °C isotherm. In such cases, a vertical path reduction factor will be required for the estimation of attenuation on a slant path. Radar observations however have shown that the ice phase is still important in the most significant precipitation events.

Observations obtained to date, particularly in temperate climate regions, have shown that the reflectivity and therefore the specific attenuation is constant from the surface to the 0 °C isotherm height. Figure 17 presents zonally averaged (averaged over longitude at each latitude) of the 0 °C isotherm height h_R (km) versus latitude ϕ (degrees) to be expected with rainfall occurrences for specified percentages of an average year. The 0.01% curve approximates the average height for the summer season and the 1.0% curve represents a yearly average value. For many maritime climates, most of the significant precipitation events occur in the summer time and the 0.01% curve should be used for attenuation prediction. In continental climates, more variability is evident in the height of the 0 °C isotherm and the curve for the appropriate percentage value should be used for prediction.

For ease of analysis, the 0.01% curve of h_R (km) versus ϕ (degrees) may be represented [Fedi, 1981] by:

$$h_R = 5.1 - 2.15 \log \left(1 + 10^{\frac{\phi - 27}{25}} \right)$$

4.4.2 Vertical variation of reflectivity

Profiles of the radar reflectivity factor Z as a function of height for a given value of Z at the surface display little change below a certain transition height. This is true for both equiprobable profiles [Hall and Goddard, 1978; Yamada *et al.*, 1978; Furuhamma *et al.*, 1980; Ochs, 1981; Rogers *et al.*, 1980] and median profiles based on an analysis of individual rain cells [Goldhirsh and Katz, 1979]. The region below the transition height is predominantly rain and contributes to both attenuation and scattering.

The region above the transition height is a mixture of ice and snow which do not produce significant attenuation at frequencies below about 60 GHz. Ice crystals in cirrus and cirrostratus clouds can produce reflectivity values as high as 100 mm⁶/m³ and occurs for percentages of the year in the 1 and 10% range depending on climate region.

Profiles of Z above the transition height show a decrease with height that appears to depend on climate. The slope just above the transition height varies between about 3 and 9 dB/km [Hall and Goddard, 1978; Olsen and Lammers, 1978; Yamada *et al.*, 1978; Goldhirsh and Katz, 1979; Furuhamma *et al.*, 1980; Rogers *et al.*, 1980; Ochs, 1981]. The slope is expected to become steeper at higher altitudes. Significant numbers of ice particles do not occur above the height of the tropopause.

The transition height is expected to be closely related to the height of the 0° isotherm, which depends on latitude, climate and season, and probability level.

As a provisional model for use in rain scatter calculations the transition height may be identified with the rain height h_R of Fig. 17 for the percentage level in question. Above that height, a constant slope of 6.5 dB/km is suggested. The tropopause may be used as a cut-off height. Figure 18 presents the zonal summer time average tropopause height as a function of latitude.

5. Sand and dust-storms

Sand and dust-storms are dense clouds of suspended sand and dust particles in which, under severe conditions, visibility can be reduced to 10 m or less with the dust rising to more than a thousand metres above the ground and stretching over hundreds of kilometres across the land.

The meteorological aspects of sand and dust-storms have been studied by numerous authors [Lawson, 1971; Farquharson, 1937; Ing, 1972; Bagnold, 1971] and have been reported to occur in the Sudan, Libya, Southern Egypt, Iraq, the Arabian Desert, India, U.S.S.R., Central China, USA and Australia.

Sand and clay particles represent the main constituents of sand and dust-storms with typical sizes of 0.015 cm and 0.008 cm, respectively. Concentration of sand and clay particles may be empirically related to optical visibility.

Further investigations on the characteristics of sand and dust-storms are needed.

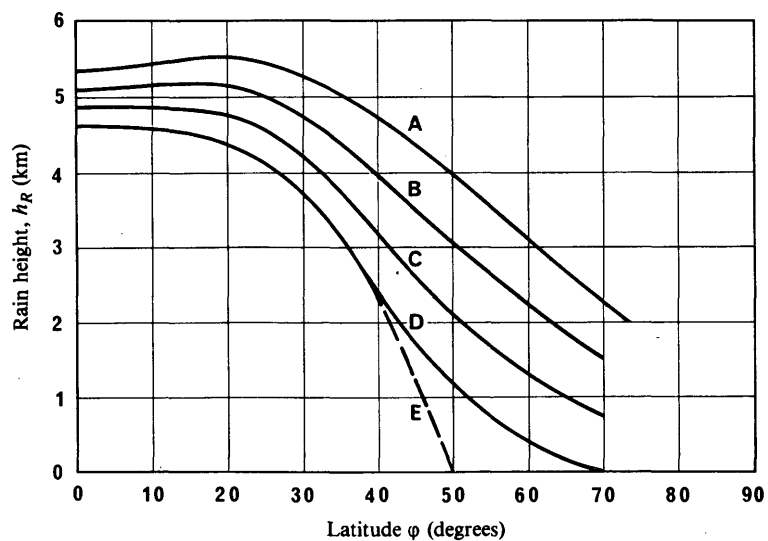


FIGURE 17 – Rain height h_R (km) versus latitude ϕ (degrees)
below which attenuation due to hydrometeors is expected

- Curves A: probability of occurrence of associated rain intensity: 0.001 %
 B: probability of occurrence of associated rain intensity: 0.01 %
 C: probability of occurrence of associated rain intensity: 0.1 %
 D: probability of occurrence of associated rain intensity: 1.0 %
 E: includes rain and snow occurrences

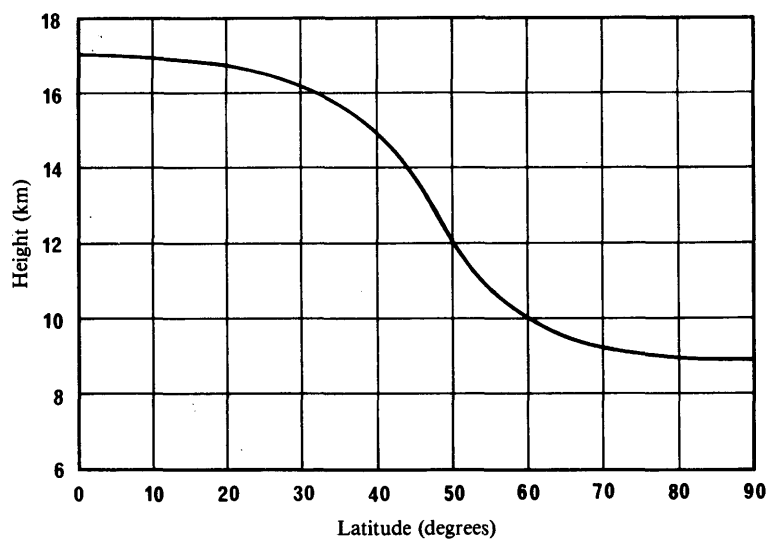


FIGURE 18 – Variation of summer tropopause height with latitude

ANNEX I

TYPES OF PRECIPITATION

Stratiform precipitation

Widespread regions with low rain rates and small embedded showers with rain rates up to 25 mm/h. The precipitation is horizontally stratified with rain up to the height of the bright band, snow to heights of the order of 7 km and ice crystals to heights near 9 km.

Convective precipitation

Localized areas of relatively intense precipitation characterized by strong up- and down-drafts extending through a deep region of the troposphere. The localized regions are columnar in nature sometimes extending to the tropopause. Very intense precipitation may occur with horizontal scales of several kilometres and durations of tens of minutes.

Monsoon precipitation

A sequence of bands of intense convection followed by intervals of stratiform precipitation. The bands are typically 50 km across, hundreds of kilometres in length and produce heavy precipitation lasting for several hours.

Tropical storms

Large organized regions of precipitation extending over hundreds of kilometres. The storms are characterized by several spiral bands terminating in regions of intense precipitation surrounding the central region or eye of the storm. The bands also contain regions of intense convection.

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REPORT 718-1

EFFECTS OF LARGE-SCALE TROPOSPHERIC REFRACTION ON RADIOWAVE PROPAGATION

(Question 2/5)

(1978-1982)

1. Introduction

Refractive index variations are responsible for the following propagation phenomena depending upon the temporal and spatial scales:

- ray-bending, and fluctuations in angle of arrival,
- ducting,
- defocusing,
- fluctuations of amplitude and phase,
- phase delay and its variation,
- tropospheric scatter propagation.

Some of these phenomena connected with the macroscopic characteristics of the atmosphere are discussed in this Report, while others connected with the fine structure of the atmosphere are dealt with in Report 881.

A discussion of the meteorological variations of the radio refractivity, N , is given in Report 563.

2. Propagation in an atmosphere with refractivity gradients near standard

2.1 Ray-bending

A radio ray passing through the lower non-ionized portion of the atmosphere undergoes bending caused by variations in radio refractive index. The effect is largely independent of frequency and its magnitude is greatest at small angles of elevation.

The theory for calculation of refraction is well known [Bean and Dutton, 1966]. The curvature $1/\rho$ of the radio path at a point is given by:

$$\frac{1}{\rho} = \frac{\cos \varphi}{n} \cdot \frac{dn}{dh} \quad (1)$$

where n is the index of refraction, φ the angle of the path with the horizontal at the point considered and dn/dh the vertical gradient of the refractive index. The variability of the gradient determines the variability of the curvature.

If the vertical gradient of radio refractivity in a layer of the atmosphere is equal to -157 N -units/km * the curvature of the paths is equal to the curvature of the Earth. In general, the gradient is above -157 N -units/km. However, for a small percentage of time, which depends on the climate, the vertical gradient is below that value. In that case ducting occurs in the layer of the atmosphere under consideration.

Note. — In this section it is assumed that the index of refraction is effectively constant over layers of the atmosphere of the order of a wavelength in size. It follows that for the lower frequencies about 1 MHz or lower, it is necessary to study this problem with methods that do not use this assumption.

2.2 Effective Earth radius on an approximately horizontal path

The equation given in § 2.1 above is simplified when $\varphi \approx 0$:

$$1/\rho \approx \frac{dn}{dh} \quad (2)$$

A well-known transformation allows propagation to be considered as rectilinear above a hypothetical earth of effective radius ka , where

$$\frac{1}{ka} = \frac{1}{a} + \frac{dn}{dh} \quad (3)$$

By using annual mean figures, an average exponential model atmosphere was introduced, corresponding to an equivalent radius of the Earth equal to the actual radius multiplied by 4/3. Generally speaking, this factor, usually denoted by k , may be derived for any region from either meteorological observations or propagation measurements. In general, k is determined from propagation measurements and represents a spatial average, which could only otherwise be obtained from many simultaneous meteorological soundings along the propagation path. The distribution of k values so determined displays less variability than that derived from single-point meteorological measurements. The variability decreases with increasing distance.

Measurements of angle-of-arrival over a 70 km line-of-sight path in the Federal Republic of Germany carried out at 515 MHz, indicate that, averaged over such a path, the effective k does not exhibit such a wide range of values as would be expected from meteorological observations made at a single point in the path.

Measurements of refraction over a 55 km line-of-sight path in the United Kingdom [Bell, 1967] show that the effective k value exceeds 0.9 for 99.9% of the time. Measurements conducted at 6.7 GHz in Japan on a 112.7 km overseas propagation path with the sea-surface-reflected wave, show that the effective k value exceeds 0.99 for 99.9% of the time.

Measurements made in Italy on a very long (240 km) link over the sea, at 900 MHz and 2164 MHz, show that no value of k less than 1, was measured during a 10-month period of measurement (which included the worst month).

For application to radio-relay links, Report 338 contains an experimental curve showing the minimum effective value of k as a function of path length for a temperate climate [Boithias and Battesti, 1967].

2.3 Bending on slant paths

The decrease in refractive index with height will produce an increase in the apparent elevation angle of an extra-terrestrial source. There will be fluctuations about this apparent angle due to local variations in the refractive-index structure. The ray-bending due to refraction is substantially independent of frequency.

* For definitions of n and N see Recommendation 310.

Published information concerning measurements of ray-bending is not extensive. Measurements using radar techniques have been described [Fannin and Jehn, 1957; Anderson *et al.*, 1960] and measurements using a radiometer are also described [Anway, 1961].

It is observed that a large part of the curvature of a radio ray takes place in the most dense and variable part of the atmosphere closest to the surface of the Earth. In the case of Earth-space propagation, errors in the apparent elevation angle of a satellite due to refraction rapidly decrease as the satellite moves from the horizon to the zenith.

If such a path goes through the atmosphere at altitudes which are always greater than several kilometres, as when the earth terminal is at a high altitude, it avoids the dense variable regions of the atmosphere, the total curvature is less, and the atmospheric models mentioned above are always usable.

The required accuracy for pointing an antenna is greater, the smaller the antenna beamwidth. The atmospheric models mentioned above are at times insufficient to determine the antenna pointing angle and, under these conditions, the measured values of the refractive index as a function of altitude must be used.

Table I presents the average ray-bending values for propagation through the atmosphere. These are equal to the elevation angle errors for an Earth-space path.

TABLE I – Ray bending values.

Elevation angle, θ	Average total ray-bending, $\Delta\theta$	
	Polar continental air	Tropical maritime air
1°	0.45°	0.65°
2°	0.32°	0.47°
4°	0.21°	0.27°
10°	0.10°	0.14°
1° 10°	Day-to-day variation in $\Delta\theta$	
	0.1° r.m.s. 0.007° r.m.s.	

As ray-bending on slant paths is due to an integrated effect over the total atmosphere, a relationship with surface refractivity can be found:

$$\zeta = a + b N_s \quad (4)$$

where ζ is the ray-bending in millidegrees (mdeg).

Table II gives coefficients for this relationship [Crane, 1976].

TABLE II – Regression parameters for estimating bending angle, given surface refractivity

Elevation angle (deg)	a (mdeg)	b (mdeg/ N unit)	Correlation coefficient	r.m.s. error (mdeg)	95% deviation (mdeg)
0.1	– 1112.8	5.778	0.81	89.0	151.0
0.2	– 889.2	4.951	0.85	64.0	119.0
0.5	– 512.3	3.473	0.94	26.0	58.0
1.0	– 268.3	2.372	0.97	12.0	28.0
2.0	– 95.9	1.409	0.99	5.0	11.0
3.0	– 41.0	0.985	0.99	3.1	6.6
5.0	– 10.2	0.610	0.99	1.9	3.8
10.0	– 0.3	0.309	0.99	0.99	1.8
20.0	+ 0.6	0.151	0.99	0.49	0.88
50.0	+ 0.2	0.046	0.99	0.15	0.27

2.4 Defocusing on slant paths

Signal loss may also result from atmospheric defocusing [Crane, 1971; Yokoi *et al.*, 1970] which arises due to spreading of the antenna beam caused by the variation of atmospheric refraction with the elevation angle. This effect should be negligible for all elevation angles above about 3° . Figure 1 [Crane, 1971] shows the focusing losses through the complete atmosphere due to atmospheric refraction effects. At 1° elevation, the focusing losses are about $0.8 \text{ dB} \pm 0.3 \text{ dB}$. At the horizon, the loss becomes greater than 2 dB with uncertainties of the same order as the average loss. These results were obtained by ray tracing through numerous day and night refractive index profiles from Albany, New York over a several-year period. They may be considered typical of effects observed over inland (continental) locations. For sites located near coastal areas, islands, at sea, or in tropical regions, the focusing losses may increase somewhat due to increased surface refractivity and different near-surface refractive index gradients [Yokoi *et al.*, 1970]. Focusing losses should be independent of frequency over the range of 1 to 100 GHz where water vapour is contributing to the refractive profile. The effects due to dry air alone and at higher frequencies have not been estimated but should be smaller.

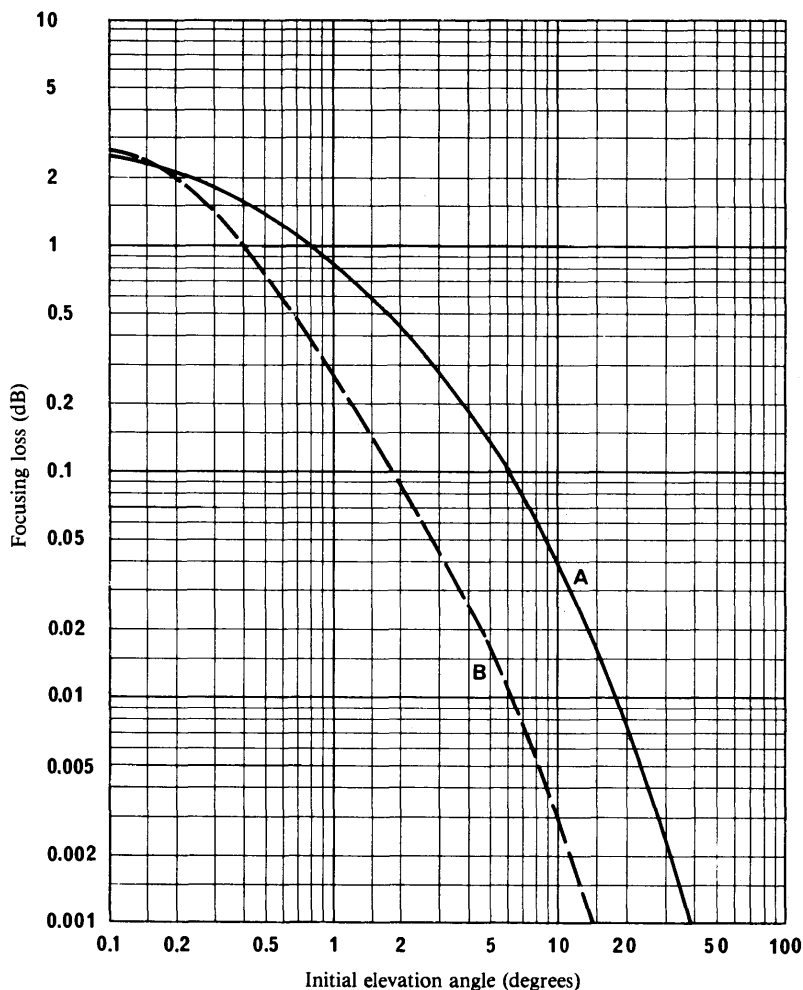


FIGURE 1 – Focusing loss and standard deviation about the average

Curves A: average loss
B: standard deviation

2.5 Phase delay and its variations

Because the troposphere has a refractivity structure which is time varying, a wave propagating along a line-of-sight path suffers a time-varying delay error, relative to the free-space delay. These variations are random and quite small over a period of minutes or hours, but over a longer period they become much larger and more regular due to the daily and seasonal variations in refractivity [Bean and Dutton, 1966].

Several methods are available for estimating the average delay or range errors in propagation over a slant path within or beyond the troposphere [Bean and Dutton, 1966]. A method is also available for estimating the variance of the delay on an Earth-space path, based on the monthly variance of the surface refractivity and semi-empirical estimates of the frequency spectrum of the delay fluctuations [Nuspl *et al.*, 1975]. Some implications of these results are discussed in Report 564.

3. Propagation in the presence of ducting layers

3.1 Effect of ducting layers

Ducting layers have significant effects, both on line-of-sight paths and on paths which would not be line-of-sight under normal conditions of refraction.

3.1.1 Line-of-sight paths

Ducting layers cause the individual rays produced by the transmitting antenna to intersect at certain points. As a result, there are areas of space in which interference occurs between multiple paths and other areas called "radio holes" through which no rays pass and where the signal level is very low. The boundary between two such areas forms a caustic along which the level is very high.

Since refraction conditions vary in time, a given point in space may be located alternatively in one or other of the two types of area described above, with the result that sharp fluctuations occur in the received level.

In addition, the combination of two or more rays which have been subjected to different propagation delays causes selective frequency fading which may result in amplitude and phase variations inside the bandwidth of the transmission channel. For this effect to be characterized with a view to its use by system designers, the complex transfer function during multipath propagation conditions must be obtained (see Report 881).

In many experimental results, there is evidence of relatively fast changes in the propagation conditions during multipath activity, i.e., changes with fractions of a second.

3.1.2 Paths which would be trans-horizon under normal refraction conditions

In the presence of a ducting layer, the concept of horizon no longer has any precise meaning, and very distant points may be "in line-of-sight". The existence of ducting layers is therefore one of the main causes of interference between two services. A general study of interference mechanisms is found in Report 569.

3.2 Characteristics of tropospheric layers

Under the influence of synoptic processes such as subsidence, advection, or surface heating and radiative cooling, there is a tendency for stratification of the lower troposphere to occur. This takes the form of refractivity layering, consisting of layers of very different refractive index gradients. Layers of strong ducting gradients ($dN/dh < -157$ N units/km) of only a few hundred metres and often less in vertical extent occur immersed within super-refractive air ($-157 < dN/dh < -40$ N units/km) or even adjacent to a subrefractive layer ($dN/dh > -40$ N units/km), often bounded by thin turbulent strata. These layers can be horizontally extensive, from tens to hundreds of kilometres in extent.

Whether a ducting layer causes a radio wave that is incident upon the layer from below to be scattered, reflected, or refracted, depends largely upon the refractive index gradient, the small-scale fluctuations in refractive index, the angle of incidence, and the ratio of the radio wavelength to layer thickness. Ducting occurs for grazing angles of incidence θ less than a critical value θ_c :

$$\theta < \theta_c = \arcsin \left(\sqrt{2 |\Delta M| \times 10^{-6}} \right) \quad (5)$$

where the ΔM is the lapse of refractive modulus across a ducting layer of thickness δ [Dougherty and Dutton, 1980]. For efficient duct propagation, the wavelength λ must be less than a critical value, λ_c :

$$\lambda < \lambda_c = 1.9 \times 10^{-4} D^{1.8} \quad (6)$$

For an elevated duct, the duct thickness D (in metres) is given by (Fig. 2):

$$D = \delta \left[1 + \left| \frac{dM}{dh} \right|_{\delta} / \left| \frac{dM}{dh} \right|_s \right] \quad (7)$$

where

$$\left| \frac{dM}{dh} \right|_{\delta} = \frac{\Delta M}{\delta} \quad \text{is the magnitude of the ducting gradient and}$$

$$\left| \frac{dM}{dh} \right|_s \quad \text{is the magnitude of the gradient in the underlying layer (if present). For a ground-based duct with no underlying layer, } D = 2\delta.$$

Reflection will occur when the grazing angle of incidence is below the critical angle. The reflection coefficient for an incident field may be approximated by:

$$| \rho | \simeq \frac{1}{4\pi} \left(\theta_c / \theta \right)^2 \left(\frac{\sigma}{\delta} \right) \quad (8)$$

where $\frac{\sigma}{\delta} = \lambda / 2\delta \sin \theta$ is of the order 1 or less [Hall, 1980]. Efficient specular reflection occurs when the vertical scale $\sigma = \lambda / 2 \sin \theta$ is larger than δ .

A thin turbulent layer will also produce specular reflection when the vertical scale is larger than the vertical outer scale of the turbulence.

$$\sigma > L_{ov} \sim \delta \quad (9)$$

where $\sigma \ll L_{ov}$, the thin layer will produce turbulent volume scattering.

For layer reflection or elevated duct propagation, the requirement is the presence of tropospheric layers of sufficiently strong gradients. These layers are observed to occur bounded by thin turbulent laminae. Depending upon the frequency and incidence angle, the layer will produce ducting, reflection from the entire layer, reflection from the turbulent laminae or volume scatter by turbulence within the laminae.

According to radiosonde data observed at six points in Japan for seven years, the correlation between the refractive modulus gradient in the ducting layer and duct intensity ΔM is comparatively high. Probability density function of these two quantities can be approximated by an exponential function. Their maximum values are -460 M/km and 52 M , respectively [Sasaki and Akiyama, 1979].

3.3 Duct statistics

The existence and extent of tropospheric ducts can be described only in statistical terms. Surface ducts and elevated ducts will be discussed separately.

3.3.1 Surface ducts

The occurrence of refractivity gradients calculated by taking the average over the first 100 metres above the surface has been described from meteorological data on a world-wide basis (Report 563). Recently, additional data have become available for certain areas, notably Canada, the North Sea and India [Segal and Barrington, 1977]. From these data we can take the occurrence of initial gradients $g < -157 \text{ N units/km}$ as direct measures of the occurrence of ground-based ducts that are 100 m thick. The requirement of surface reflections for duct propagation is not always clear, since the strong gradient may have occurred at the surface or slightly above it. On over-water paths, the distinction has sometimes been maintained. Some ocean areas have been extensively mapped for the probability of long-distance propagation via shallow evaporation ducts or via the deeper advection ducts with slightly elevated layers [Dougherty and Hart, 1976].

There are some uncertainties associated with these ground-based ducts, especially those observed at the many recording stations on land. The simultaneous existence, at distant points, of ducts over land does not mean necessarily that these ducts are horizontally extensive (i.e., continuous) unless the terrain is approximately flat. The larger scale irregularities of terrain (hills, cities, etc.) tend to limit the horizontal extent of ducts over land.

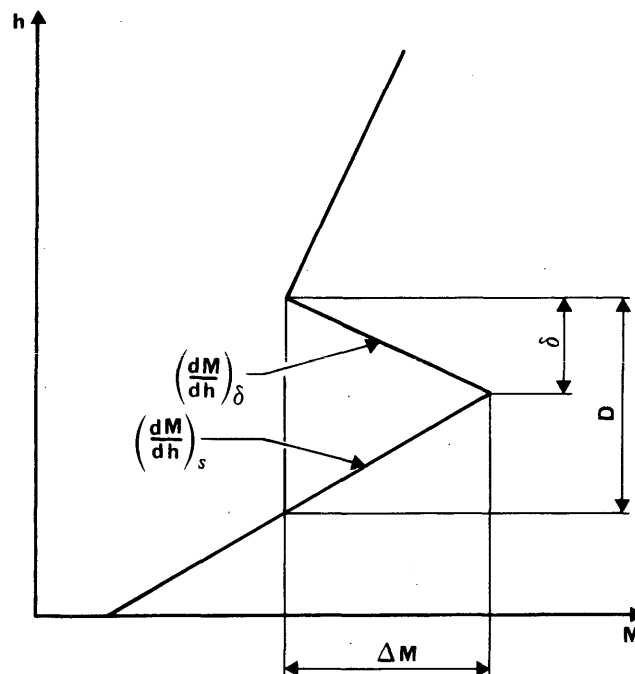


FIGURE 2 – Radiometric characteristics of a ducting layer

δ : ducting layer thickness

D : tropospheric radio duct thickness

The sea-surface ducts tend to be more prevalent and extensive than those over land, although there is some evidence that ocean depth and ocean currents can limit their horizontal extent. It must be emphasized that although individual ducts are of a finite length, there is little physical justification for an abrupt limit to horizontal duct dimensions. This has to be a statistically defined limit for which there is inadequate data at present for both overland and overseas surface ducts.

3.3.2 Elevated ducts

Descriptions of elevated layer statistics are also available world-wide [Segal and Barrington, 1977; Ortenburger *et al.*, 1978] based upon world-wide annual and monthly summaries. These contain statistical descriptions of elevated duct characteristics (dN/dh , ΔM , δ , height of the base of the ducting layer, D).

Since these data are calculations of refractive index gradients deduced from measures of the vertical temperature and humidity structures, they carry some limitations not applicable to the original data. For example, the radio meteorologist is concerned with refractivity structures on a finer scale than of interest to the meteorologists. The instrument response time and the sequential measurements of temperature and humidity, as the meteorological balloon soars vertically, have a tendency to provide an erroneous estimate of the thinness of refractivity layers and to under-estimate their refractivity gradients. Of course, the deduction of a gradient dN/dh more negative than -157 N units/km is direct evidence of at least a duct; the corresponding layer gradient is probably much more negative. Unfortunately, there will be strong gradients unreported because their gradient was computed as less negative than -157 N units/km and therefore not of interest. Crane [1981] reported the observation of ducts by radar surveillance more frequently than those indicated by the radiosonde data. There is another disadvantage of estimating the occurrence of ducts from routine meteorological data. Radiosonde data tend to be collected twice a day (at 1200 and 2400 GMT) which may or may not correspond to the most favourable times of the day for the occurrence of ducts at each location. The data may therefore either over-estimate or underestimate the occurrence of ducts at specific locations. Despite these disadvantages, their corrections can be estimated from additional data so that the large body of data in meteorological records is still applicable.

3.4 Losses in duct propagation

Normally, in free-space propagation the energy spreads out in the two directions orthogonal to the direction of propagation. Hence, the inverse-square distance dependence of free-space transmission. In the case of duct propagation the spread of energy in the vertical direction is eliminated and exhibits the inverse-distance dependency. That is, over a distance d' within the duct, the basic transmission loss L_b is related to that for free space L_{bf} by

$$L_b = L_{bf} - 10 \log d' + A \quad (10)$$

Such low transmission losses have been observed over water. Of course, this significant improvement over free-space propagation is normally off-set by the term A for various attenuation mechanisms including, for example, leakage losses due to duct irregularities or losses due to ground reflection, etc. However, it has been observed that at frequencies between about 0.8 and 3 GHz, the received field after propagation above water is well in excess of the free space value at 370 km and approximately equal to the free-space value at 1000 km. These events are unusual but not rare; they may persist for several hours and at some locations even for several days, corresponding to occurrences of from 0.1% to 0.01% of an average year.

There are also additional losses attributable to duct characteristics and other atmospheric conditions:

- the frequency and time-dependent absorption by the gaseous atmosphere (Report 719);
- the leakage of energy from non-uniform ducts (i.e. ducts whose characteristics vary horizontally).

In addition, there are losses associated with the coupling of radio wave energy into and out of ducts. These are sensitive to the vertical limits of the ducts relative to the positions of radio system terminal antennas. Elevated layers have a horizontally cyclical (wave like) variation in their characteristics that affect the coupling losses into and out of the elevated duct [Crane, 1981; Dougherty and Hart, 1979].

3.5 Ducting studies

The empirical model currently used in Report 569 is based upon the simplified concept that the transmission loss depends upon a coupling constant, a linear range dependence, and an attenuation constant. The coupling and attenuation factors depend upon frequency, type of path (over land or sea), and percentage of time. A coordinated theoretical analysis and experimental observation program is required to evaluate the utility of the model and recommend improvements.

Theoretical simulations of duct propagation in the presence of realistic horizontally non-homogenous layers are required to evaluate the coupling factor for interference paths. Current experiments utilize aperture antennas with main beams directed to maximize coupling. Analyses are required to evaluate the effects of antenna beamwidth and pointing angle. Simulation of sidelobe coupling in a duct is particularly important. The use of site shielding should also be investigated.

The ducted fields of importance in interference problems are now events which may last for hours when they occur. Adequate statistics of such events require many years of observations. Simultaneous, long-term experimental data at several frequencies and with several antennas directed at angles to maximize and to minimize coupling are required to evaluate the factors in the transmission loss equation and to provide theoreticians with the data required to evaluate their models.

The transmission loss values depend critically on the structure of the elevated and surface layers. Meteorological observations are required to obtain information on the range of layer heights, thicknesses, and refractive index gradients to be expected together with data on internal wave fluctuations and the structure of turbulence within the duct. These observations will require the use of radar instrumentation as well as rapid response meteorological probes. The observed refractive index structure should be used for the theoretical simulation of the ducting problem and in the development of meteorological models for the prediction of the occurrence, duration, and horizontal area with ducting conditions.

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REPORT 881

EFFECTS OF SMALL-SCALE SPATIAL OR TEMPORAL VARIATIONS
OF REFRACTION ON RADIOWAVE PROPAGATION

(1982)

1. Introduction

Small-scale variations of the refractivity in the troposphere result in several propagation effects which may be of significance at the higher frequencies. Among these are amplitude and angle-of-arrival variations due to multipath conditions and turbulent fluctuations, and tropospheric scatter. Multipath conditions also give rise to several rays with different amplitude and delay. Where large frequency bandwidths are concerned, vectorial addition of these rays, in the receiving antenna, results in frequency selective fading.

2. Amplitude effects

In addition to the ray-bending produced by variations in the spatial distribution of refractive index, fluctuations in the amplitude of a wave transmitted along a line-of-sight path can be produced. Because of horizontal stratification in the troposphere, the magnitude of these fluctuations is highly dependent on the path elevation angles. The large amplitude fluctuations sometimes occurring on horizontal paths or slant paths of low elevation angles are often referred to as atmospheric multipath fading. The more rapid fluctuation occurring on paths at high elevation angles and super-imposed on the slower multipath fading of low-angle paths is referred to as scintillation.

2.1 Atmospheric scintillation

Amplitude scintillation [Tatarskii, 1967] may be produced by turbulent fluctuations. The variance in the logarithm of the amplitude of the received signal is given by:

$$\sigma_\chi^2 = 42.25 \left(\frac{2\pi}{\lambda} \right)^{7/6} \int C_n^2(\rho) \rho^{5/6} d\rho \quad (1)$$

where

σ_χ : the standard deviation of the logarithm of the received power; (natural logarithm)

λ : wavelength; (m)

C_n^2 : the refractive index structure function (see Report 563); ($\text{m}^{-2/3}$)

and

ρ : distance along the path; (m)

Measurements of the amplitude scintillation variability with satellite observations have been made by Crane [1976a]. The observed data from the Haystack measurements show a range of variability at 7.3 GHz through the seasons as indicated in Fig. 1, showing the r.m.s. fluctuations in log received power σ_χ (dB) versus the apparent satellite elevation angle. Measurements at 0.4 GHz as well as 7.3 GHz produced tropospheric scintillation observations which were in qualitative agreement with predictions of weak scintillation theory for elevation angles above 2 or 3°; at lower elevation angle, atmospheric multipath fading was dominant.

Precise knowledge, therefore, of the amplitude scintillation depends on a knowledge of the refractive index structure function along any given oblique path. Since this is usually unknown in detail, approximations would need to be made to model C_n^2 for a specific location. At 7 GHz and elevation angles above 3°, the signal may fluctuate at levels between 0.1 and about 1.0 dB depending upon elevation angle and conditions (see Fig. 1). At 100 GHz, the levels scale in frequency to lie correspondingly between 0.4 and 3.8 dB.

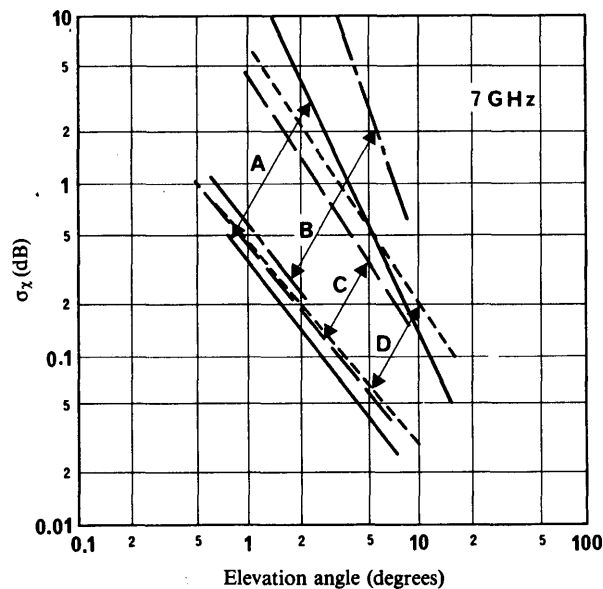


FIGURE 1 – Standard deviation of elevation angle scintillation
(antenna diameter = 37 m)

A: spring
B: summer
C: fall
D: winter

The other effect of significance, antenna aperture degradation, is dependent on the scale sizes of the refractive inhomogeneities relative to the antenna diameter. The effect, sometimes expressed as antenna gain-loss, occurs because the antenna aperture and the propagating medium are coupled. For a propagation path traversing the troposphere to a distant satellite, the Fresnel zone sizes may be defined as:

$$F = \sqrt{n\lambda z} \quad (2)$$

where

n : order of Fresnel zone,

z : the reduced path length = $\frac{\rho(L-\rho)}{L}$,

L : total length of ray path,

ρ : position along ray path, and

λ : operating wavelength.

Turbulent refractive index fluctuations occur over a wide range of scale sizes. At scales small compared to the Fresnel zone size, the scattering can be described as isotropic; at scales larger than the Fresnel zone the scattering is anisotropic and considerable spatial curvature of the incident wavefront can result. The largest amplitude spatial fluctuations observed in the antenna aperture plane are produced by fluctuations on scale sizes of the order of the Fresnel zone size. For antenna apertures larger than the Fresnel zone size, the fluctuations due to the corrugated wavefront are spatially averaged by the antenna. Further, as the elevation angle increases the Fresnel zone size (given by equation 2) for the location where the refractive index fluctuations are strongest decreases due to the rapidly decreasing distance ρ between the turbulent layer and the antenna. The result is therefore a reduction in the fluctuation depth due to aperture averaging and a slight reduction in the effective antennas gain (i.e. gain-loss). Tatarskii [1967] indicated that the r.m.s. fluctuations are reduced by 20% when the diameter of a uniformly weighted circular aperture is one-half the first Fresnel zone size ($D = \sqrt{\lambda z}/2$).

The tropospheric scintillation model presented below is based upon the Haystack measurements and theory. The measurements were made over a period of one year and represent conditions typical of a temperate climate. An assumed average height of 1 km was used for the thin turbulent layer producing the scintillation. The r.m.s. fluctuation level used as a reference point for the model corresponds to the annual median value at a 1° elevation obtained at the Haystack Observatory. As a result of the theory and a cosecant θ power law approximation for a 1 km high layer, the following fluctuation model is obtained:

$$\sigma_x(f, \theta, D) = \sigma_{x, REF} \left(\frac{f}{7.3} \right)^{7/12} \left(\frac{\text{cosec } \theta}{\text{cosec } 1^\circ} \right)^{0.85} \left(\frac{G(R)}{G(R)_{REF}} \right)^{1/2} \text{ dB} \quad (3)$$

where

$\sigma_{x, REF}$: reference r.m.s. fluctuation at 1° , 7.3 GHz, Haystack, $D = 36.6$ m ($\sigma_{x, REF} = 1.883$ dB is used in the model);

f : operating frequency (GHz);

θ : apparent elevation angle;

$G(R)$: antenna aperture averaging factor [Tatarskii, 1967]; and

$G(R)_{REF}$: value for Haystack at 1° , $D = 36.6$ m, ($G(R)_{REF} = 0.572$).

A piecewise linear approximation to Tatarskii's antenna aperture averaging factor, $G(R)$, was made as follows:

$$\left. \begin{aligned} G(R) &= 1.0 - 1.4 \left(\frac{R}{\sqrt{\lambda L}} \right) & \text{for } 0 \leq \frac{R}{\sqrt{\lambda L}} \leq 0.5 \\ &= 0.5 - 0.4 \left(\frac{R}{\sqrt{\lambda L}} \right) & \text{for } 0.5 < \frac{R}{\sqrt{\lambda L}} \leq 1.0 \\ &= 0.1 & \text{for } 1.0 < \frac{R}{\sqrt{\lambda L}} \end{aligned} \right\} \quad (4)$$

where

R : effective radius of circular antenna aperture (m);

$R = \eta^{1/2} (D/2)$ with D : physical diameter of reflector and

η : antenna efficiency factor, $(\eta)^{1/2} = 0.75$ assumed in model);

L : slant distance to height of a horizontal thin turbulent layer;

$$L = \frac{2h}{\sqrt{\sin^2 \theta + \frac{2h}{R_e} + \sin \theta}}$$

h : height of layer ($h = 1000$ m assumed in model);

R_e : effective Earth radius including refraction ($R_e = 8.5 \times 10^6$ m in model); and

λ : operating wavelength (m).

It is noted that Fig. 1 displays a dependence on elevation angle significantly different from the $(\operatorname{cosec} \theta)^{0.85}$ dependence of the model. The difference is produced by the effect of aperture averaging ($G(R)$), which is important for a 37 m antenna.

The model has been tested against experimental observations from the USA and Japan at frequencies between 400 MHz and 20 GHz, exercising the model's frequency, elevation angle and aperture size dependency with very good agreement.

2.2 *Fading and amplitude fluctuations caused by tropospheric multipaths*

Atmospheric multipath fading caused by tropospheric stratification is dependent on the time of day, season and climate. The worst propagation conditions occur as a result of layers with abnormally large vertical gradients in refractive index. On paths in temperate climates these conditions normally occur during the night and early morning hours of summer days. Results of measurements on terrestrial and Earth-space paths are discussed in Reports 338 and 564, respectively.

3. **Fading selectivity**

3.1 *Physical descriptions*

The physical modelling of the atmospheric complex transfer function in multipath propagation conditions has been carefully studied. The function may be characterized by a set of multipath parameters, i.e. the number of separate propagation paths and the amplitude and delay (for normal conditions) associated with each path. The signal received is therefore the geometric sum of the complex signals propagated over separate paths.

The transfer function of the propagation medium and the characteristics of the different paths may be determined by two measuring techniques, one in the time domain and the other in the frequency domain. The first is a pulse measuring technique by which the multipath parameters can be obtained directly; the second is a multifrequency technique consisting of an analysis of the shape of the signals measured by simulation or computer calculation.

Many experiments have been conducted and have given numerous results for the parameters measured. The number of rays deduced from the measurements varies from two to seven, with varied amplitudes and delays.

The results suggest that the relative amplitude of a ray associated with a particular propagation path decreases with the increase in delay. However, no distinct relationship between amplitudes and delays has been established. Major amplitudes normally correspond to delays of less than about 1 ns. The various results and corresponding references have been brought up to date [Stephansen, 1981].

Low amplitudes frequently correspond to delays of several nanoseconds. It is shown, for instance [Martin, 1981], that in 90% of cases where a delay of 6 ns has been observed in attenuation values of more than 12 dB measured at 11 GHz over a 50 km link, the ray amplitude is at least 27 dB below the free-space level.

3.2 *Modelling*

The overall quality of a radio link may be studied only if the complex transfer function is statistically known, which is not generally the case. Simplified statistical models of the transfer function have been proposed, their purpose being not to represent the physical reality but to serve as equivalents to the real model for certain applications. For instance, the validity of a two-ray model for determining the percentage of time which corresponds to an error rate on a digital link [Rooryck, 1979a], has been demonstrated. In this model, the delay distribution of one ray in relation to the other is not dependent on the distribution of the amplitude ratio. The delay is generally below 1 ns. This model has been used for quality calculations at 11 GHz on digital links of 50 to 60 km [Rooryck, 1979b].

Again on the basis of a two-ray model, it has been possible to calculate digital link quality at 11 GHz and the variation in the time percentage for a certain error rate has been given in terms of the length of the link [Andreucci *et al.*, 1980].

The two-ray propagation model has also been used in other studies of digital link performance [Emshwiller, 1978; Jakes, 1979], and for interpreting different results obtained on analogue systems [Fehlhaber, 1973; Azoulay, 1976].

A three-ray statistical model containing certain simplifications has been proposed. The transfer function of the transmission channel is expressed by:

$$H(\omega) = a (1 - b e^{\pm j(\omega - \omega_M) \tau}) \quad (5)$$

in which a and b are statistically determined parameters, τ is fixed, and f_M , where $\omega_M = 2\pi f_M$, is the frequency of maximum attenuation. For a τ value of 6.31 ns, this model accords well with the experimental results obtained on a 42.5 km link at 6 GHz [Rummler, 1979].

4. Angle-of-arrival fluctuations

The angle-of-arrival effects produce a slight angular variation of the received signal about the apparent angular position (affected by refractive bending, Report 718) of the rays. The elevation angle variations are typically 10 times larger than the azimuthal variations at elevation angles below 3° . Data obtained from satellite observations made using a large aperture tracking antenna at Haystack Observatory, Westford, (Massachusetts) (at 7.3 GHz), suggest that angle scintillations are not likely to be important for antenna beamwidths larger than 0.3° at all elevation angles or for beamwidths larger than 0.01° at elevation angles higher than 10° . The elevation angle fluctuations are of the same order of magnitude as the expected uncertainty in refraction correction using surface refractivity values [Crane, 1976b]. Figure 2 [Crane, 1976a] indicates the range of extremes in the r.m.s. fluctuations in elevation angle versus elevation on the 36.6 m (120 foot) antenna at 7.3 GHz. A seasonal dependence was identified, as shown, throughout a year of observations sampled at different times of day, seasons, and meteorological conditions. It is anticipated that these magnitudes of angle-of-arrival effects may be expected over a variety of operating conditions relatively independent of frequency. For reference also, the median r.m.s. fluctuations by season are shown in Fig. 3 [Crane, 1976a]. These data, ranging in initial elevation angles from the horizon to 43° , represent the median elevation angle measurement uncertainties (within a five-minute observation period) to be expected due to the troposphere. Single antenna radar or communication systems probably will not achieve better measurement accuracies or lower angular position uncertainties, respectively, than these for paths traversing the complete troposphere.

The Haystack observations were made over the period of a year and were representative of values to be expected in a temperate climate. Angle-of-arrival fluctuations due to atmospheric turbulence are not frequency dependent and the values in Figs. 2 and 3 may be used throughout the 1 to 30 GHz range. At lower frequencies, angle-of-arrival scintillation produced by the ionosphere can be important (see Report 236).

5. Tropospheric scatter propagation

This mode of trans-horizon propagation depends on small-scale fluctuations in refractive index.

5.1 Correlation with ΔN

In a number of instances, theory and practice agree in showing the existence of a correlation between the variations in the field strength observed on paths beyond the horizon and the quantity ΔN , the difference between the refractivity at a height of one kilometre and the refractivity on the ground. This correlation has been clearly demonstrated in temperate countries only, when the comparison is made on the basis of monthly, or at least weekly, medians [Troitsky, 1958].

5.2 Correlation with refractive index gradient at the base of the common volume

Attempts have been made to improve the correlation by taking into account atmospheric conditions in the neighbourhood of common volume. The influence of stability and air motion has been studied [Bolgiano, 1960; Misme, 1958; Fukushima, 1967]. However, these parameters do not seem to play a comparable role in all climates. The thickness of the layer between 500 and 1000 mb has been found to be correlated with field-strength variations on some UHF links. However, this correlation is probably not valid on a world-wide basis and it is not applicable to frequencies much below 1 GHz or to path lengths much below 300 km.

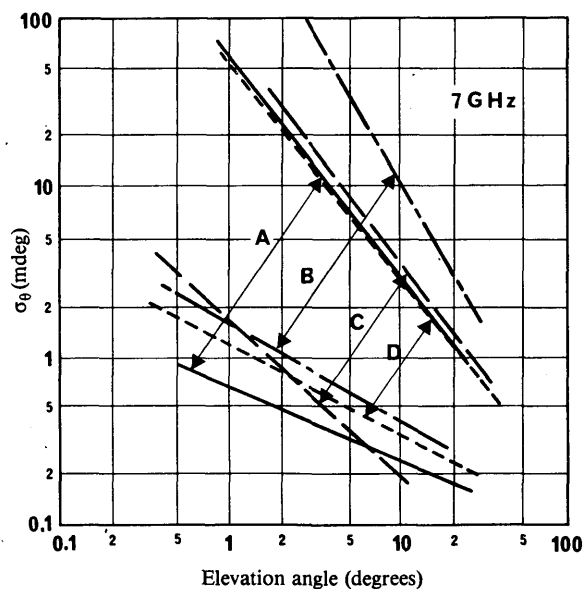


FIGURE 2 – *Standard deviation of elevation angle scintillation*
(antenna diameter = 37 m)

A: spring
B: summer
C: fall
D: winter

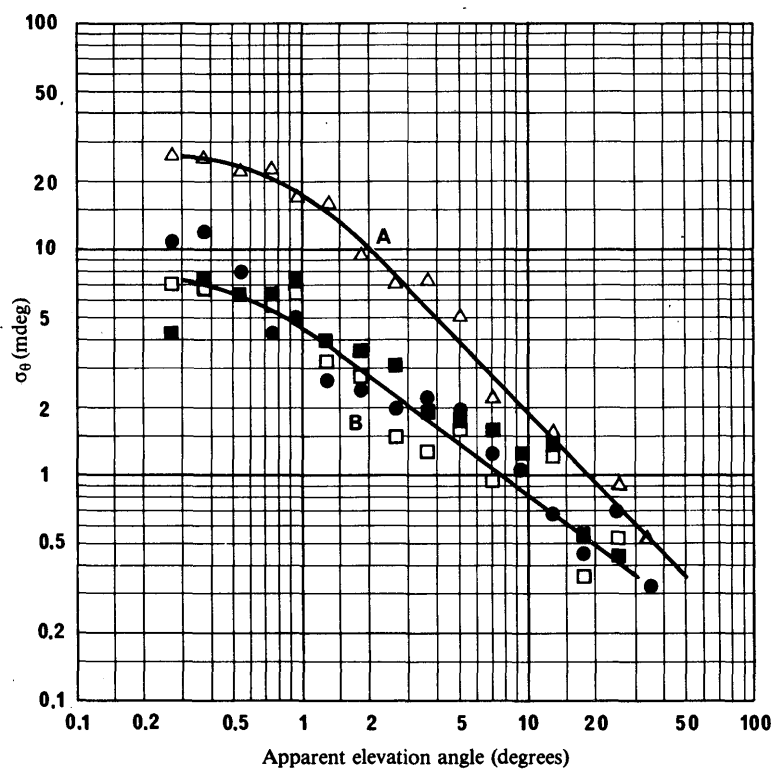


FIGURE 3 – *Median standard deviation in elevation angle scintillation*

● - spring
△ - summer
□ - fall
■ - winter
A : summer
B : rest of year
 $f = 7.3$ GHz
 $D = 36.6$ m

Taking into account the refractive index gradient near the base of the common volume of antenna beams greatly improves correlation. This is attributable to the fact that this is the region of space in which the bulk of the radio energy is propagated, and also that the number and size of the inhomogeneities of the refractive index greatly depend on the mean gradient of this index [Battesti *et al.*, 1968]. A method of predicting trans-horizon loss has been based on this result; it is described in Report 238.

5.3 Correlation with surface refractive index

The refractive index at the surface is easier to determine from the existing statistical meteorological data than is the gradient of the index; the latter requires radiosonde measurements, which are usually performed only at specific hours each day in the meteorological observatories of the world. A detailed study of the correlation between transmission loss and the value of the refractive index at the surface has been carried out in the United States for distances far beyond the horizon.

Correlation has been noted between observed transmission loss and the values of refractive index at the surface [Pickard and Stetson, 1974; Bean and Dutton, 1966]. However, this is apparently true only when a good correlation has been established between the vertical gradient of the refractive index and the value of this index at the surface [Lane, 1961]. In temperate climates, the month corresponding to the highest transmission loss has been found to be the same corresponding to the lowest values of N_s , where N_s is the value of N at ground level.

If, in these regions, the yearly variation of the monthly mean values of N_s is small (less than 10 to 15 N), good correlation between the propagation loss variation and the monthly mean value of N_s is not necessarily to be expected.

In other climates, the available evidence of correlation is inconclusive. Some measurements give good correlation [Gray, 1959]; others give poor correlation [Boithias and Misme, 1964]. In the latter cases, the correlation appears to be good except at that time of the year when N_s is larger than approximately 350. Caution should be used in applying this value as a world-wide criterion, however. It would appear that the cause of the breakdown in correlation noted in other areas of the world is too complex to be represented by such a simple parameter as N_s , and probably lies in vertical air-mass characteristics (e.g. atmospheric subsidence).

It has been found that N_s is often useful for predicting regional, seasonal and daily variations in transmission loss, but it is of limited value for predicting them in tropical and equatorial regions.

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REPORT 719-1 *

ATTENUATION BY ATMOSPHERIC GASES

(Question 2/5)

(1978-1982)

1. General aspects

Molecular absorption experienced during radio-wave propagation through the atmosphere at centimetre or millimetre wavelengths is due primarily to atmospheric water vapour and oxygen. Figure 1 shows the specific attenuation (dB/km) for paths near the ground as a function of frequency from 1 GHz to 10^4 GHz. However, this Report is mainly concerned with frequencies below 350 GHz.

Oxygen has an isolated absorption line at 118.74 GHz and a series of very close lines between about 50 and 70 GHz. These act in the lower layers of the atmosphere as a continuous absorption band. The magnetic moment of the oxygen molecule also produces a line at zero frequency in the absorption spectrum.

Water vapour has three absorption lines, at the frequencies 22.3 GHz, 183.3 GHz and 323.8 GHz. Moreover, at the sub-EHF and infra-red frequencies, it has a very large number of lines, some of which are very intense. The result is that the sum of the wings of these lines makes a substantial contribution to the absorption at SHF and EHF. To provide a model for the calculation of specific attenuation in the window regions, an empirical correction term [Waters, 1976; Liebe, 1975] must be added to the resonant line calculations. The correction term is proportional to the square of the frequency.

For very low water vapour concentrations, we may assume that the attenuation is proportional to the concentration. However, it must be borne in mind that this relation is only approximate and may lead to an under-estimation of the attenuation at high relative humidity [Gibbins *et al.*, 1975; Emery *et al.*, 1975; DeLogne *et al.*, 1981].

* This Report is brought to the attention of Study Groups 2, 4, 7, 8, 9, 10 and 11.

The total gaseous absorption in the atmosphere, A_a (dB), over a path length r_0 (km), is given by:

$$A_a = \int_0^{r_0} \gamma_a(r) dr \quad \text{dB} \quad (1a)$$

where

$$\gamma_a(r) = \gamma_o(r) + \gamma_w(r) \quad (1b)$$

In the last formula γ_a is the specific attenuation (in dB/km) and γ_o , γ_w are the oxygen and water vapour contributions respectively.

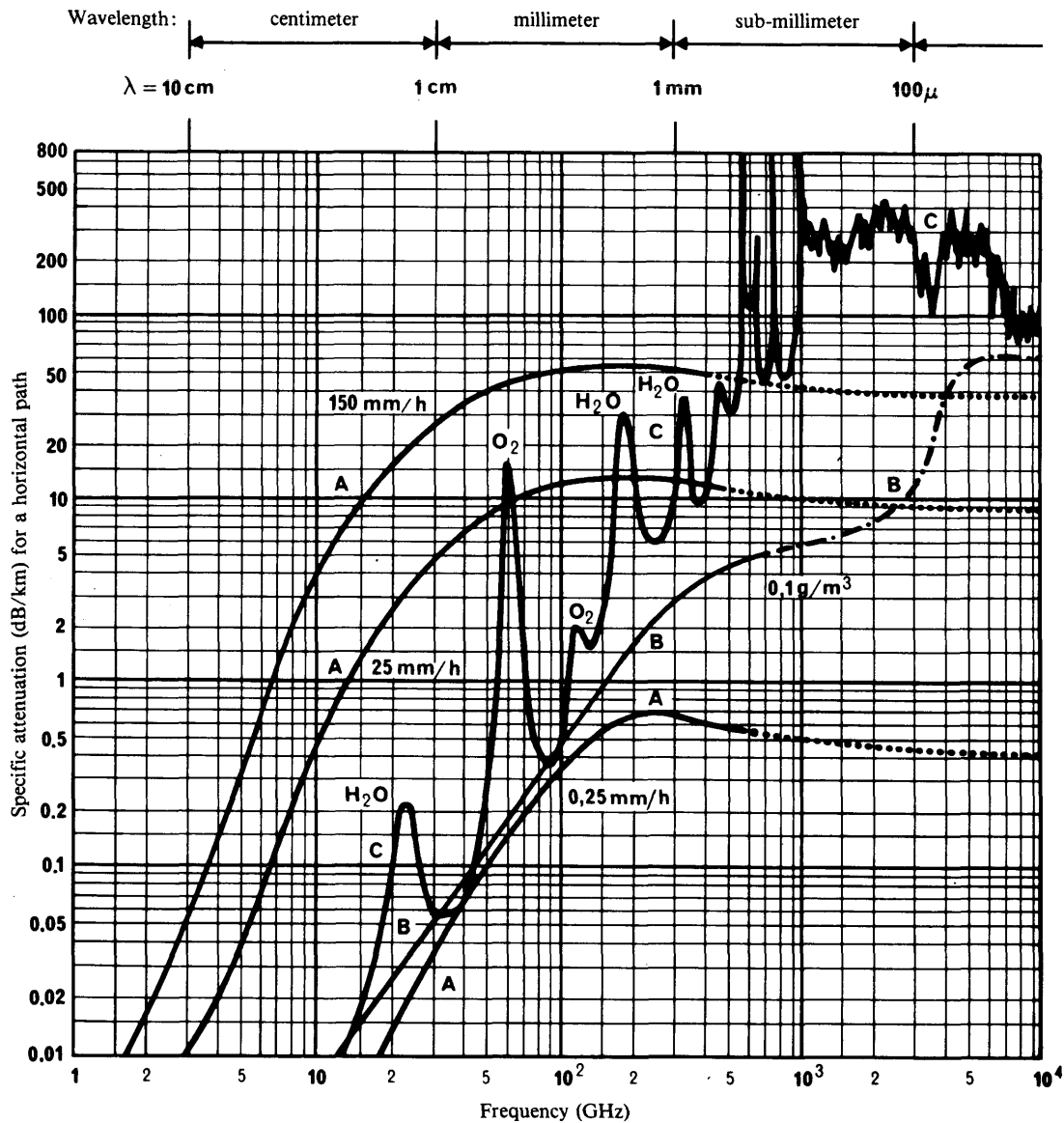


FIGURE 1 – Attenuation due to gaseous constituents and precipitation for transmissions through the atmosphere

Temperature: 20° C
Pressure: sea level: 1 atm
Water vapour: 7.5 g/m³

A: rain
B: fog
C: gaseous

2. Specific attenuation

2.1 The calculation of the specific absorption produced by either the oxygen or water vapour components of the gaseous atmosphere is complex, requiring computer evaluation for each value of temperature, pressure and water vapour concentration. Approximate techniques can however be employed for practical application.

One technique is to employ an approximation based on the use of the Van Vleck-Weisskopf line shape profile with coefficients adjusted to fit the computer calculations. This led to the following formulae, valid at a temperature of 20 °C at ground level:

$$\gamma_o = \left[\frac{6.6}{f^2 + 0.33} + \frac{9}{(f-57)^2 + 1.96} \right] f^2 10^{-3} \quad \text{dB/km} \quad (2a)$$

for $f < 57$ GHz

$$\gamma_o = 14.9 \quad \text{dB/km} \quad \text{for } 57 < f < 63 \text{ GHz} \quad (2b)$$

$$\gamma_o = \left[\frac{4.13}{(f-63)^2 + 1.1} + \frac{0.19}{(f-118.7)^2 + 2} \right] f^2 10^{-3} \quad \text{dB/km} \quad (2c)$$

for $63 < f < 350$ GHz

It should be noted that the formula (2b) is very approximate, due to the many oxygen lines in this spectrum region.

$$\gamma_w = \left[0.067 + \frac{2.4}{(f-22.3)^2 + 6.6} + \frac{7.33}{(f-183.5)^2 + 5} + \frac{4.4}{(f-323.8)^2 + 10} \right] f^2 \rho 10^{-4} \quad \text{dB/km} \quad (3)$$

for $f < 350$ GHz

where f is the frequency expressed in GHz, and ρ is the water vapour density expressed in g/m^3 .

The attenuation values obtained by using formulae (2) and (3) have been included in Fig. 2. For water vapour, a value of 7.5 g/m^3 was selected, which represents 1% of water vapour molecules mixed with 99% of dry air molecules. It may be noted that this value corresponds, for example, to ground level, at 50% humidity with a temperature of 16.5° or 75% humidity for a temperature of 10° .

For more accurate computation, the effect of temperature may be taken into account by a negative correction of the formulae of 1% per °C (attenuation rising with decreasing temperature).

2.2 Alternatively, the combined specific attenuation γ_a at the surface of the Earth (1000 mb pressure) can be statistically related to water vapour concentration and temperature by a multiple regression analysis. The results of such an analysis performed on a selected global sample of 220 radiosonde profiles [Crane, 1976] representing a large data base spanning all seasons and geographic locations, may be summarized by the relationship:

$$\gamma_a = a + b\rho - ct \quad \text{dB/km} \quad (4)$$

where

ρ : surface water vapour concentration, g/m^3 ;

t : surface air temperature, °C; and

a, b, c : empirical coefficients derived by multiple regression analysis which vary with operating frequency f .

The global mean value of specific attenuation at the surface is shown as a function of frequency in Fig. 3. The average values correspond to a surface air temperature of 14.6°C and mean water vapour concentration of 11.1 g/m^3 . Shown also is the standard deviation (σ) of the specific attenuation values about the mean value and the standard deviation about the multiple regression equation estimate.

The variation in specific attenuation to be expected at a single location may be estimated from

$$\sigma_a^2 = b^2\sigma_\rho^2 + c^2\sigma_t^2 + \sigma_m^2$$

where σ_a is the standard deviation at a single location, σ_ρ , σ_t are the standard deviations of water vapour density and temperature, respectively, for that location, and σ_m is the standard deviation about the estimate from the regression analysis (Fig. 3).

Two curves are displayed for standard deviation, one for the standard deviation to be expected in moving from one location to another, and the second for the standard deviation to be expected between the computer calculations and the model predictions (equation (4)) when the surface values for ρ and t are used.

The coefficients a , b and c of the multiple regression analysis are tabulated in Annex I. Interpolation between points in the table should be accomplished using a power law relationship. It will be noted in Fig. 3 that the use of known local conditions reduces considerably the uncertainty in obtaining the specific attenuation by equation (4). To realize the reduced standard deviation, however, the user must employ the average surface conditions for the locality concerned.

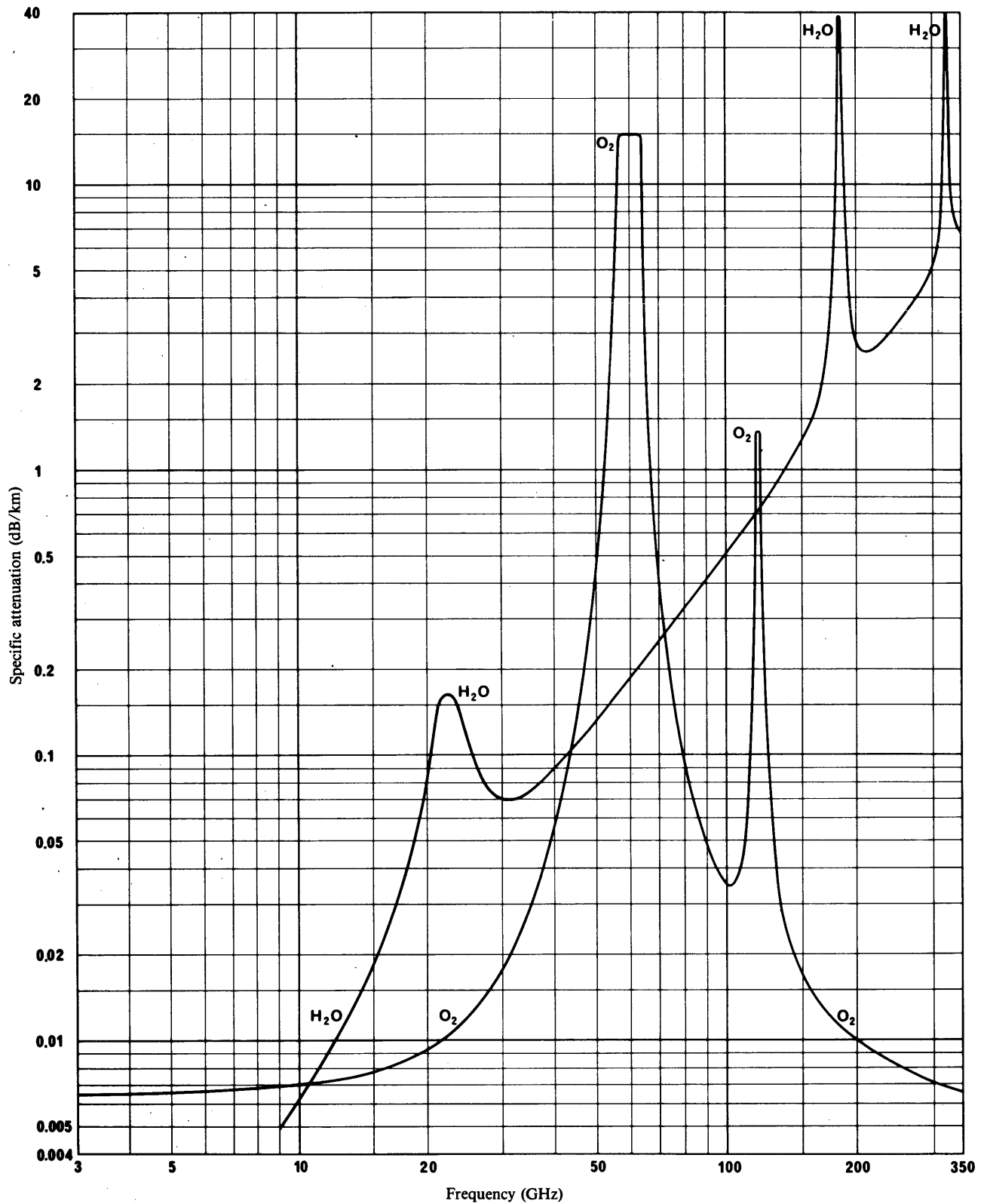


FIGURE 2 - Specific attenuation due to atmospheric gases

Pressure: 1 atm
Temperature: 20° C
Water vapour: 7.5 g/m³

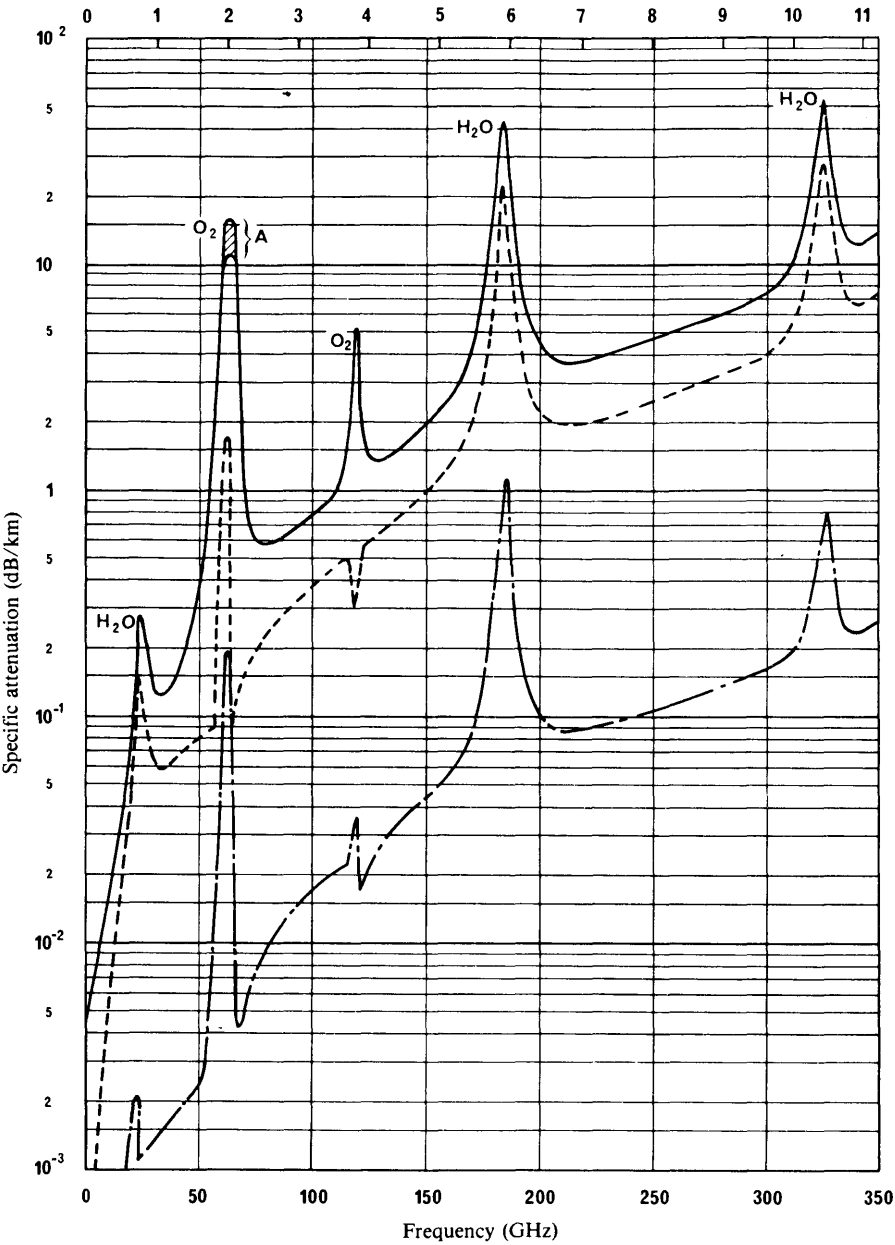


FIGURE 3 – Specific attenuation (dB/km) at the surface of the atmosphere and standard deviations to be expected from the model

Surface values:
— mean specific attenuation
- - - standard deviation
- · - standard deviation about estimate from regression analysis
A: range of values
 $t = 14.6^\circ\text{C}$, $\rho = 11.1\text{ g/m}^3$

3. Path attenuation

3.1 Terrestrial paths

For a terrestrial path, or for slightly inclined paths close to the ground, the path attenuation may be written as:

$$A_a = \gamma_a r_0 \quad (5)$$

where

r_0 : path length in km.

For a very long path above varied terrain types and surfaces of liquid water (sea or lakes), allowance must sometimes be made for humidity variations.

3.2 Slant paths

3.2.1 For an inclined path or an Earth-space path, the expression (1a) must be integrated through the atmosphere to obtain the total path attenuation.

A first order approximation is to use the concept of equivalent heights for oxygen and water vapour components. In Europe these equivalent heights may be approximated by 8 km for oxygen and 2 km for water vapour. Moreover, we can adopt a "cosecant law" for elevation angles θ greater than 10° . Hence the total attenuation A_a is given by the relation:

$$A_a = \frac{8\gamma_o + 2\gamma_w}{\sin \theta} \quad \text{dB} \quad (6a)$$

For elevation angles less than 10° , the cosecant law must be replaced by a more accurate formula allowing for the real length of the atmospheric path. This leads to the following relation:

$$A_a = \frac{16\gamma_o}{\sqrt{\sin^2 \theta + \frac{16}{R}} + \sin \theta} + \frac{4\gamma_w}{\sqrt{\sin^2 \theta + \frac{4}{R}} + \sin \theta} \quad (6b)$$

R being the effective earth radius including refraction, given in Report 718, expressed in km (a value of 8500 km is generally acceptable).

3.2.2 Alternatively, the total zenith attenuation from the ground at any geographic location can be obtained similarly to the model for specific attenuation (§ 2) based on local surface humidity and temperature. A multiple regression analysis based on the global data set yields a computation of the total zenith attenuation (τ_{90}) using the following relationship:

$$\tau_{90} = \alpha + \beta \rho - \xi t \quad \text{dB} \quad (7)$$

where

τ_{90} : total zenith attenuation from the surface to the top of the atmosphere at a given frequency, (dB)

ρ : water vapour concentration at the surface, g/m³;

t : air temperature at the surface, °C; and

α, β, ξ : empirical coefficients derived by multiple regression which vary with operating frequency f .

The total one-way zenith attenuation mean values for standard surface conditions, 20 °C and 7.5 g/m³ water vapour density are presented in Fig. 4. The global average conditions and standard deviations, as described for Fig. 3, are presented in Fig. 5. The coefficients obtained from the multiple regression analysis, which may be used in equation (7) together with surface conditions, are shown in Figs. 6 and 7 as a function of frequency, and tabulated in Annex II. For inclined paths the atmospheric attenuation may then be assumed proportional to the effective distance through the attenuation medium as approximated by:

$$\tau(\theta) = \tau_{90} \cdot \frac{r_a}{H_a} = \gamma_a r_a \quad (8)$$

where

r_a : effective slant path (km)

$$r_a = \frac{2H_a}{\sqrt{\sin^2 \theta + 2 \frac{H_a}{R}} + \sin \theta} \quad (9a)$$

For θ greater than 10° , the cosecant approximation may be valid in place of equation (9a).

$$r_a = \frac{H_a}{\sin \theta} \quad (9b)$$

where

H_a : scale height of combined atmospheric attenuating H_2O and O_2 layer;

The scale height H_a for absorption can be obtained from the values of specific attenuations (equation (4)) and zenith attenuation (equation (7)).

$$H_a = \tau_{90} / \gamma_a \quad (10)$$

The attenuation on a slant path at an elevation angle θ from the surface to a height h is given by:

$$A_a = \gamma_a r_a \left[1 - \exp(-h/H_a) \right] \quad (11)$$

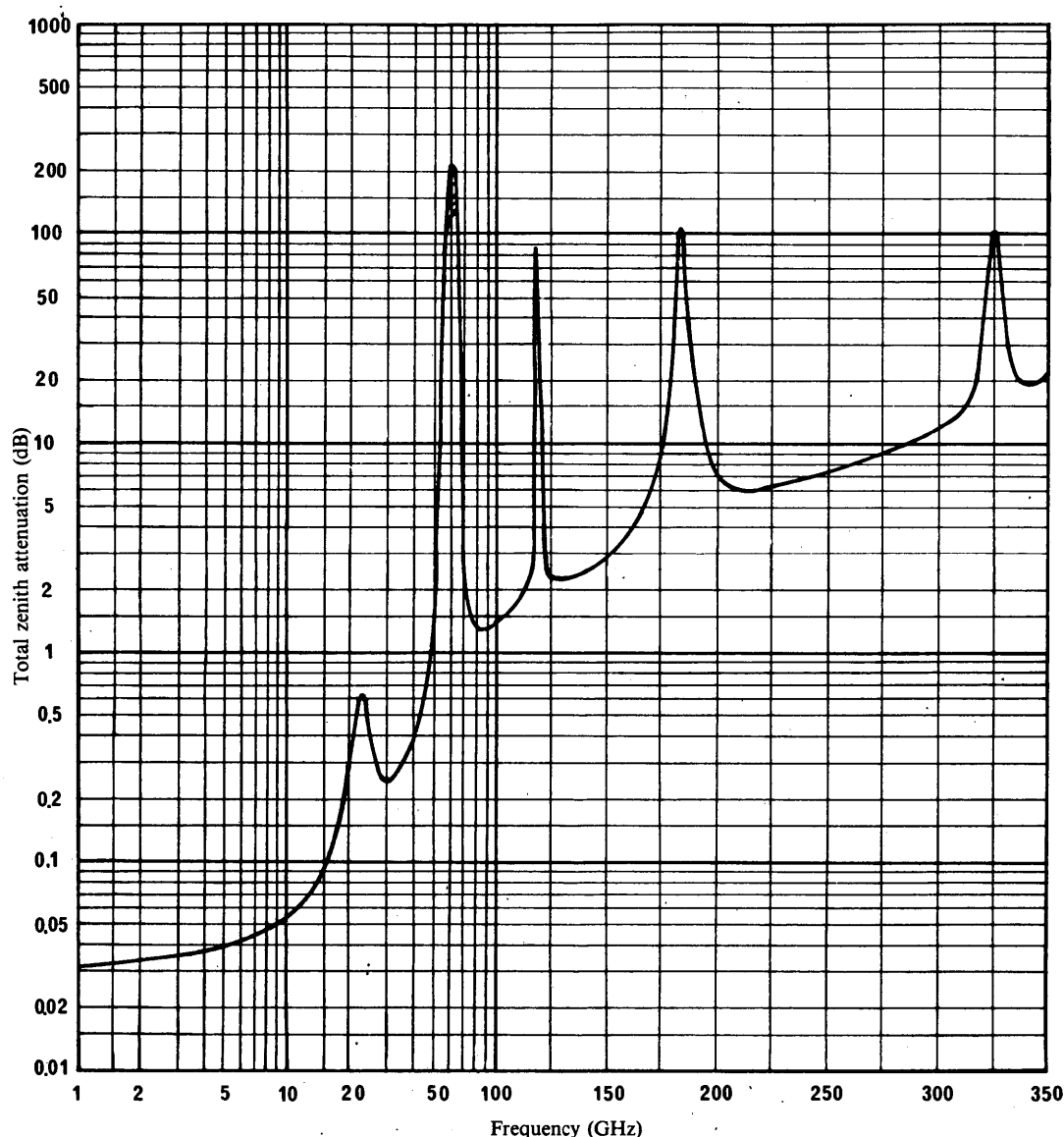


FIGURE 4 - Total zenith attenuation

Pressure : 1 atm
 Temperature : 20°C
 Water vapour : 7.5 g/m^3 } at ground level

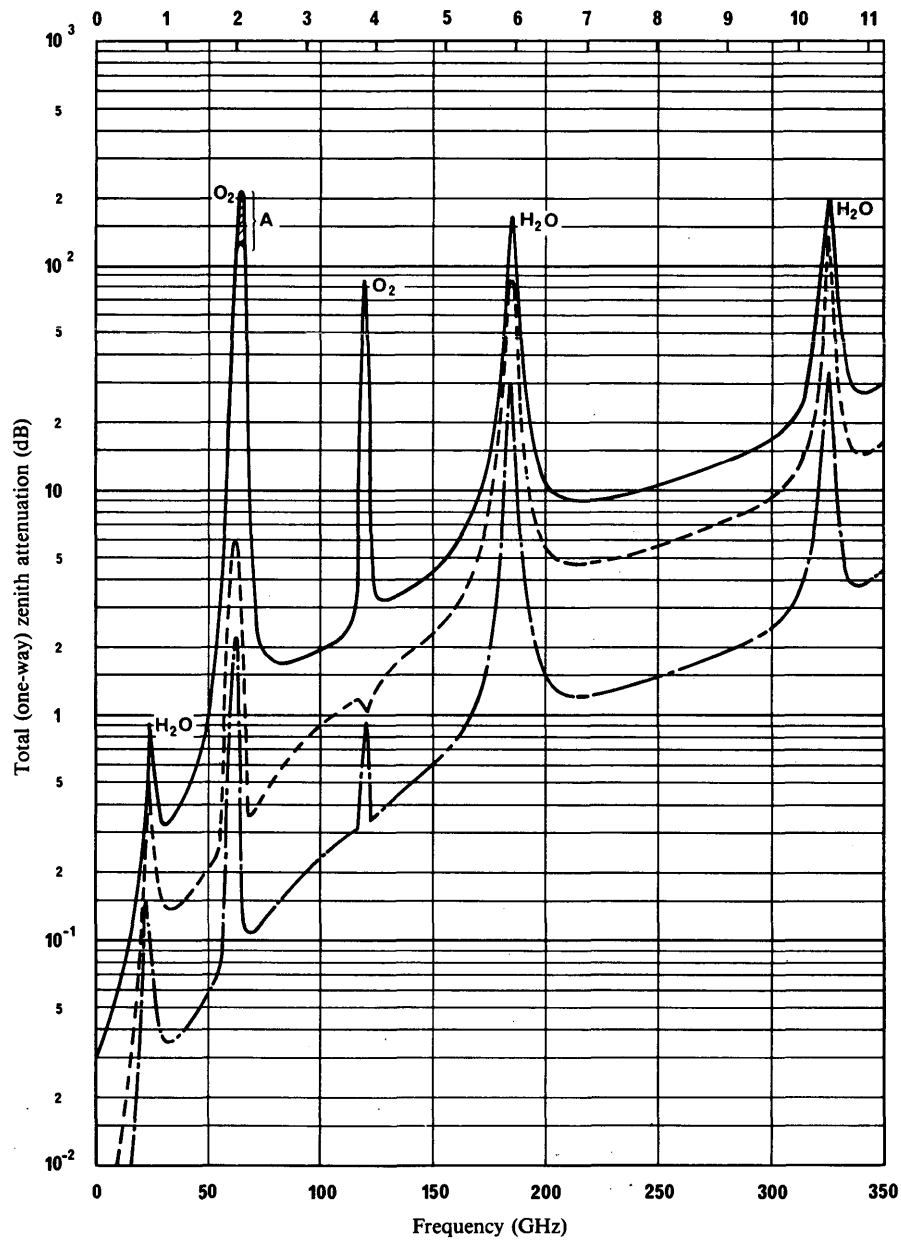


FIGURE 5 – Total one-way zenith attenuation (dB) from the surface to the top of the atmosphere and standard deviations to be expected from model

————— mean total attenuation
 - - - - - standard deviation
 - . - . - standard deviation about estimate from regression analysis
 A: range of values
 $t = 14.6^{\circ}\text{C}$, $\rho = 11.1\text{ g/m}^3$

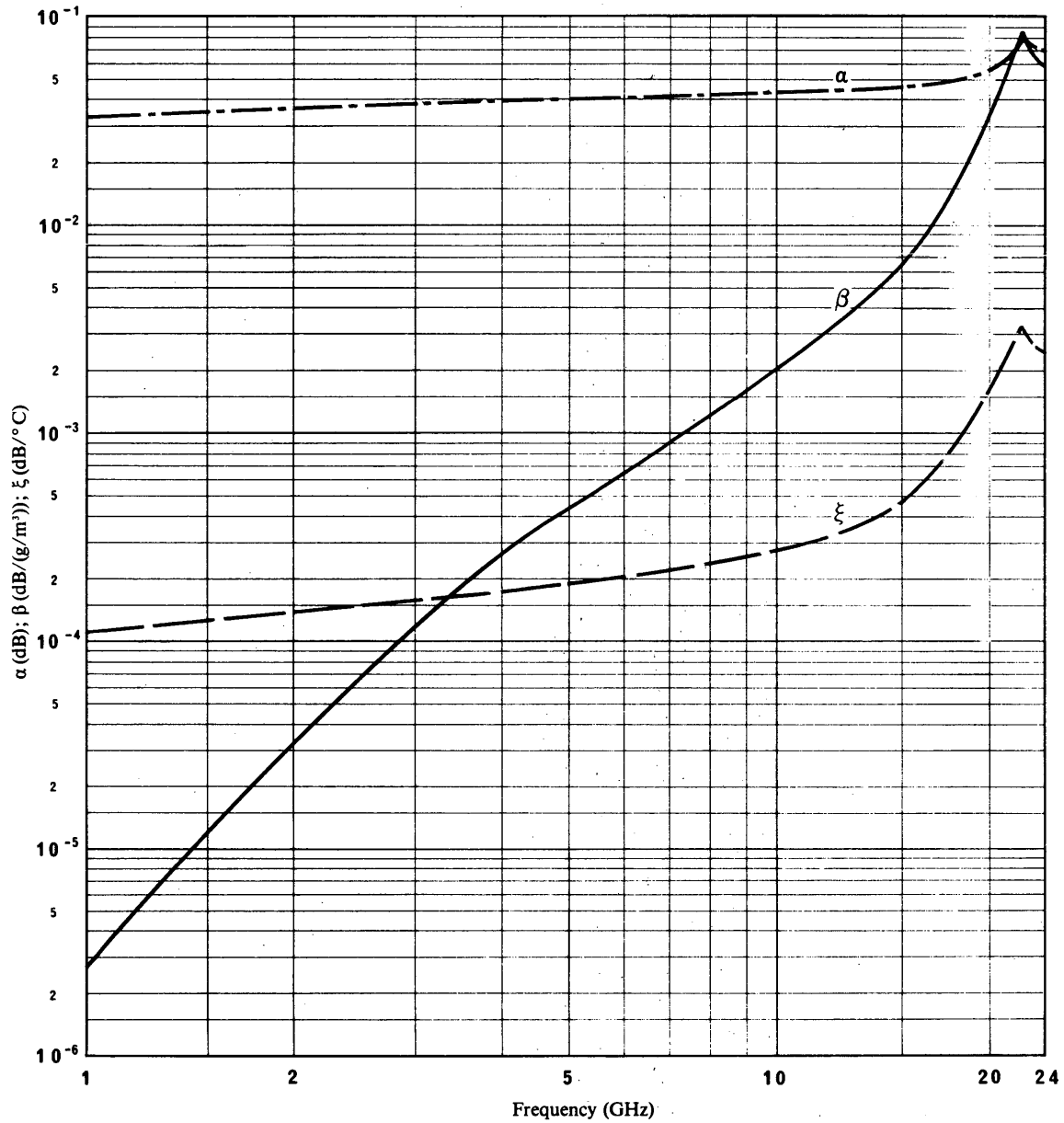


FIGURE 7 - Coefficients for computing total one-way zenith attenuation
from surface to top of atmosphere given surface conditions
(1 to 24 GHz)

Zenith attenuation: $\tau_{90} = \alpha + \beta\rho - \xi t$ (dB)
 ρ (g/m³), t (°C)

— — — α coefficient
— — — β coefficient
- - - ξ coefficient

4. Application to remote sensing

The variation with frequency of the total zenith attenuation from the top of the atmosphere to a specified height, may be used to sense remotely the variation of atmospheric temperature with height. The effective noise temperature (see Report 720) depends upon the temperature of the medium and the rate of change of the total zenith attenuation with height (which is the weighting function, $d(\exp(-23A_o))/dh$). The weighting functions for specific frequencies in the oxygen absorption are given in Fig. 8.

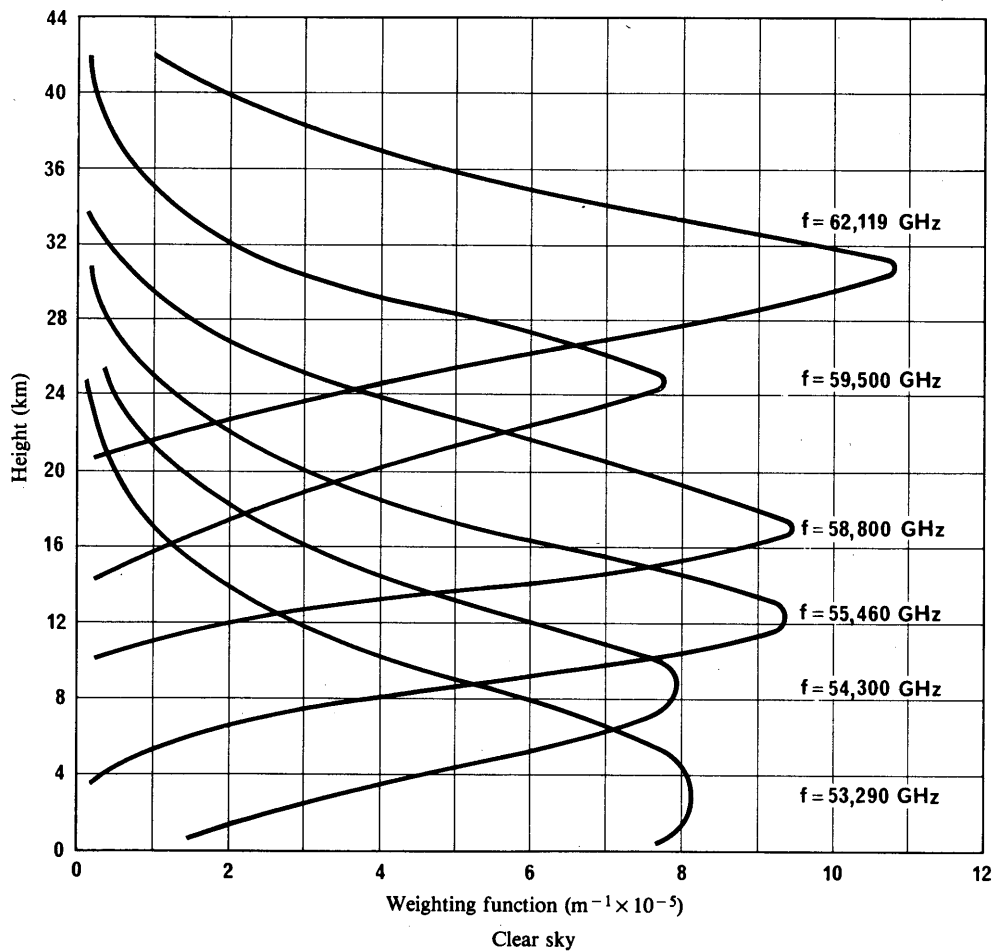


FIGURE 8 - Temperature weighting functions ($\theta = 40^\circ$, polarization = 90°) of frequencies indicated, f

ANNEX I

COEFFICIENTS FOR COMPUTING SPECIFIC ATTENUATION
AT THE SURFACE DUE TO GASEOUS CONTRIBUTIONS

$$\gamma_a = a + b\rho \text{ (g/m}^3\text{)} - ct \text{ (}^\circ\text{C)} \quad (\text{dB/km})$$

Frequency f (GHz)	Coefficients		
	$a(f)$	$b(f)$	$c(f)$
1	0.00588	0.0000178	0.0000517
4	0.00802	0.000141	0.0000850
6	0.00824	0.000300	0.0000895
12	0.00898	0.00137	0.000108
15	0.00953	0.00269	0.000125
16	0.00976	0.00345	0.000133
20	0.0125	0.0125	0.000101
22	0.0181	0.0221	0.000129
24	0.0162	0.0203	0.0000563
30	0.0179	0.0100	0.000280
35	0.0264	0.0101	0.000369
41	0.0499	0.0121	0.000620
45	0.0892	0.0140	0.00102
50	0.267	0.0171	0.00251
55	3.93	0.0220	0.0158
70	0.449	0.0319	0.00443
80	0.160	0.0391	0.00130
90	0.113	0.0495	0.000744
94	0.106	0.0540	0.000641
110	0.116	0.0749	0.000644
115	0.206	0.0826	0.00185
120	0.985	0.0931	0.0115
140	0.123	0.129	0.000372
160	0.153	0.206	0.000784
180	1.13	1.79	-0.00237
200	0.226	0.366	0.00167
220	0.227	0.316	0.000174
240	0.258	0.356	-0.000119
280	0.336	0.497	-0.0000664
300	0.379	0.629	0.000808
310	0.397	0.812	0.00286
320	0.732	2.36	0.00467
330	0.488	1.61	0.00945
340	0.475	1.06	0.00519
350	0.528	1.23	0.00722

ANNEX II

COEFFICIENTS FOR COMPUTING TOTAL ZENITH ATTENUATION

$$\tau_{90} = \alpha + \beta\rho \text{ (g/m}^3\text{)} - \xi t \text{ (}^\circ\text{C)} \quad (\text{dB})$$

Frequency f (GHz)	Coefficients		
	$\alpha(f)$	$\beta(f)$	$\xi(f)$
1	0.0334	0.00000276	0.000112
4	0.0397	0.000276	0.000176
6	0.0404	0.000651	0.000196
12	0.0436	0.00318	0.000315
15	0.0461	0.00634	0.000455
16	0.0472	0.00821	0.000536
20	0.0560	0.0346	0.00155
22	0.0760	0.0783	0.00310
24	0.0691	0.0591	0.00250
30	0.0850	0.0237	0.00133
35	0.123	0.0237	0.00149
41	0.237	0.0284	0.00211
45	0.426	0.0328	0.00299
50	1.27	0.0392	0.00572
55	24.5	0.0490	-0.00121
70	2.14	0.0732	0.0104
80	0.705	0.0959	0.00586
90	0.458	0.122	0.00574
94	0.417	0.133	0.00594
110	0.431	0.185	0.00785
115	0.893	0.203	0.0113
120	5.35	0.221	0.0363
140	0.368	0.319	0.0119
160	0.414	0.506	0.0191
180	2.81	5.04	0.192
200	0.562	0.897	0.0339
220	0.543	0.777	0.0276
240	0.601	0.879	0.0307
280	0.760	1.22	0.0428
300	0.853	1.54	0.0551
310	0.905	1.97	0.0735
320	1.66	6.13	0.238
330	1.13	3.94	0.155
340	1.07	2.56	0.0969
350	1.20	2.96	0.114

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REPORT 720-1 *

RADIO EMISSION FROM NATURAL SOURCES ABOVE ABOUT 50 MHz

(Study Programme 5C/5)

(1978-1982)

1. Introduction

Radio noise emitted by all matter is used as a source of information in radioastronomy and in remote sensing. Noise of thermal origin has a continuous spectrum, but other radiation mechanisms cause the emission to have a different frequency dependence or a spectral line structure. Different gaseous constituents are distinguished by their different spectral lines (see Report 719 for a discussion of O_2 and H_2O).

For other services, received noise is a limiting factor for the receiving system, as generally it is inappropriate to use receiving systems with noise temperatures much less than those specified by the median external noise.

Extra-terrestrial noise is of solar, planetary, galactic and cosmic origin. Information concerning the intensities of galactic noise between 50 kHz and 100 MHz is contained in Report 322. The Report gives mean galactic noise powers in the absence of ionospheric screening and monthly median values of mean atmospheric noise power as a function of location, season and time of day. Other parameters defining the short-term amplitude distribution (or structure) of atmospheric noise and the day-to-day variations are also quoted. Data on man-made noise for the frequency range 300 kHz-250 MHz are also contained in Report 258 for receiving sites in business, residential, rural and quiet rural areas (see Recommendation 372). The likely intensities of noise on a particular system need to be assessed taking into account knowledge of the distributions of sources of noise and the directional properties of the receiving antenna.

From about 30 MHz to about 1 GHz, galactic noise predominates over atmospheric noise but will generally be exceeded by man-made noise in populated areas. Above 1 GHz, the absorptive constituents of the atmosphere (water vapour, oxygen, hydrometeors) also act as noise sources. Minimum levels of radio noise are given in Report 670. Spectroscopic information about other gaseous constituents and pollutants may be found in Poynter and Pickett [1980].

In the bands of strong gaseous absorption, the noise temperature reaches maximum values of some 290 K. At times, precipitation and clouds will also increase the noise temperature at frequencies above about 5 GHz. Evaluation of radio emission from atmospheric gases and precipitation is given in § 2.

The Sun is a strong variable noise source with a noise temperature of about 10^6 K at 30 MHz and of at least 10^4 K at 10 GHz under quiet Sun conditions. Large increases occur when the Sun is disturbed. The noise temperature of the Earth as seen from space is 140 to 290 K depending on the percentage of land versus sea in the antenna beam, the degree of cloud cover, the frequency, wave polarization and angle of incidence.

The radio noise temperature observed with an antenna having an infinitely narrow beam, pointed towards the zenith but away from any localized noise source, is about 5 K for frequencies from about 2 GHz to about 10 GHz. For decreasing elevation angles, the noise temperature increases, reaching about 80 K when the antenna is pointed horizontally in clear-air conditions. For a more realistic antenna, noise contributions through both the main beam and the side lobes (including the contribution from the ground) must be considered, as shown in Report 390.

* This Report is brought to the attention of Study Groups 1, 2, 4, 6, 7, 8, 10 and 11.

1.1 General aspects

The Earth's surface and the non-ionized region of the atmosphere are sources of noise radiation. The effective brightness temperature or noise temperature for a given direction (see Fig. 1) for a microwave receiver or radiometer in a space station (T_{SS}) or earth station (T_{ES}) can be approximated from the equation for radiative transfer at frequencies of 1 to 50 GHz [Staelin, 1969; Crane, 1971; Tomiyasu, 1974; Waters, 1976] (see Report 693). The expressions, if scatter from atmospheric particles can be neglected, are:

Space-Earth down-link (or uplooking radiometer; Fig. 1a)

$$T_{ES} = T_A + T_{sky} e^{-\tau_0} \quad (1)$$

Earth-space up-link (or downlooking spaceborne radiometer; Fig. 1b)

$$T_{SS} = T'_A + (\epsilon T_{surf} + \rho T_B) e^{-\tau_0} + \rho T_{sky} e^{-2\tau_0} \quad (2)$$

where

$$T_A = \int_{surf}^{\infty} T(r) \times \alpha(r) e^{-\tau_1(r)} dr \quad (\text{downward emission from atmosphere})$$

$$T_B = T_A$$

$$T'_A = \int_{surf}^{\infty} T(r) \times \alpha(r) e^{-\tau_2(r)} dr \quad (\text{upward emission from atmosphere})$$

$$\tau_0 = \int_0^{\infty} \alpha(r) dr \quad (\text{optical depth through the atmosphere along } r \text{ for path A or B (see Note)})$$

$$\tau_1 = \int_0^r \alpha(r) dr \quad (\text{optical depth from earth station to point } r \text{ along A (see Note)})$$

$$\tau_2 = \int_r^{observer} \alpha(r) dr \quad (\text{optical depth from point } r \text{ to spacecraft along path A') (see Note)}$$

T_{surf} : temperature (K) of the Earth's surface

$T(r)$: temperature (K) of the medium at point r

$\alpha(r)$: specific absorption per metre of the medium at r

$\epsilon = 1 - \rho$: emissivity of the surface ($0 \leq \epsilon \leq 1$)

ρ : surface reflection coefficient (power); ($0 \leq \rho \leq 1$)

α : absorption coefficient of the medium at r (per metre)

T_{SS} : observed brightness temperature at space station (K) and received noise power is $p_r = k T_{SS} B \eta$

T_{ES} : observed brightness temperature at earth station (K)

p_r : noise power (W)

k : Boltzmann's constant = 1.38×10^{-23} joule/K

B : receiver bandwidth (Hz)

η : antenna efficiency ($0 < \eta < 1$)

T_{sky} : extraterrestrial noise temperature: generally 2.7 K for 2 to 50 GHz (unless pointing near the Sun); see § 4 for lower frequencies.

Note. — The unit for optical depth (a measure of attenuation) is the neper where 1 neper = 4.34 dB (e.g. Report 693). This differs from traditional electrical engineering usage where 1 neper = 8.68 dB [Fink, 1975].

The model in Fig. 1b is shown for a reflecting surface ($\rho = 1$, $\epsilon = 0$) which is not a realistic case. In practice it provides reasonable values in most cases (e.g., sea surface for $0 \leq \theta_i \leq 60^\circ$). For a truly diffuse surface such as thick vegetation a good approximation to the temperature derived from integrating the atmospheric emissions over a hemisphere is given by King [1970]:

$$T_B|_{diffuse} \approx T_B|_{\theta_i = 55^\circ} \quad (3)$$

Equation (1) treats the brightness temperature in a direction whereas an antenna accepts a solid angle with its main lobe and may pick up significant amounts of thermal noise with its sidelobes (as in earth stations). If the earth does not fill the spacecraft antenna beam then the contribution (ΔT_{SS}) of the Earth (T_E) to the observed brightness temperature in the spacecraft (T_{SS}) is given by:

$$\Delta T_{SS} = T_E \frac{\Omega_E}{\Omega_{SS}} \quad (4)$$

where Ω_E is the solid angle subtended by the Earth and Ω_{SS} is the equivalent solid angle for the space station antenna. Similarly an antenna intercepting 1/3 land and 2/3 sea has a brightness temperature:

$$T_{SS} = \frac{1}{3} \left\{ T_{SS|land} \right\} + \frac{2}{3} \left\{ T_{SS|sea} \right\} \quad (5)$$

where the first term on the right-hand side of equation (5) is calculated from equation (2) using a value of T_{surf} appropriate to land and the second term a value of T_{surf} appropriate to sea.

If atmospheric absorption and emission could be totally ignored (not normally a realistic case) then the spaceborne radiometer or up-link Earth-space transmission of equation (2) case can be approximated by:

$$T_{SS} \approx \epsilon T_{surf} + \rho T_{sky} \quad (6)$$

If the temperature $T(r)$ can be replaced by a mean radiating temperature, T_m , expression (1) simplifies to

$$T_{ES} \approx T_m \left(1 - \frac{1}{L} \right) + \frac{T_{sky}}{L} = T_m \left(1 - 10^{-\frac{A}{10}} \right) + \frac{T_{sky}}{L} \quad (7)$$

where

$$L = e^{\tau_0} = e^{\frac{A \text{ (dB)}}{4.34}} = \text{loss factor due to the absorbing medium}$$

A : one way attenuation through the atmosphere along r (dB).

Furthermore, in the case of a horizontally stratified atmosphere, the sky temperature in equation (1) at a zenith angle θ is given by:

$$T_{ES}(\theta) = T_m (1 - \beta_0^{\sec \theta}) \quad (8)$$

where $\beta_0 = 1/L_0$ and relates to the atmosphere in the zenith direction. For zenith angles less than 70° , the error in replacing $1/L$ by $\beta_0^{\sec \theta}$ is less than 1% [Waters, 1976].

The approximation to equation (2) corresponding to equation (7) is unwieldy but a useful approach is contained in Report 693.

In the estimation of antenna temperature, the antenna pattern and particularly radiation from the surface of the Earth into antenna side lobes must be considered.

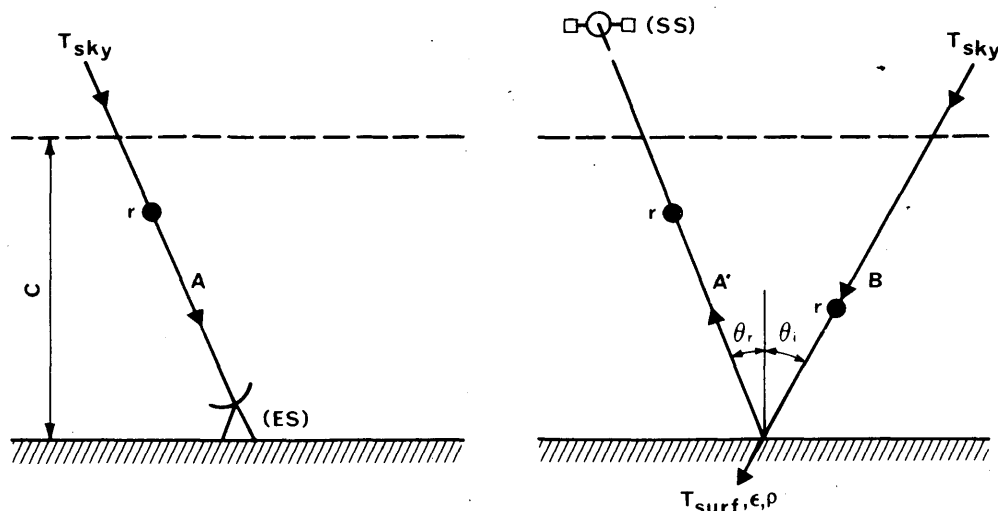


FIGURE 1 – Sketches of noise source

- (a) Earth station (ES), or ground based radiometer, showing path, A, through the atmosphere, point r on that path, and extraterrestrial noise (T_{sky});
- (b) Space station (SS), or spacecraft based radiometer, showing emission and reflection from ground surface ($\epsilon T_{surf}, \rho$) as well as atmospheric contributions along paths B and A' and extraterrestrial contribution T_{sky} .

2. Sky-noise temperature due to atmospheric gases

Figures 2 to 5 show the sky-noise temperature due to atmospheric gases for an infinitely narrow beam at various angles of elevation, and for frequencies between 1 and 340 GHz [Smith and Waters, 1981]. The 2.7 K background cosmic noise contribution has not been included. The three cases are chosen to represent a fairly dry atmosphere (3 grams per cubic metre of water vapour), an average atmosphere (7.5 g/m³ water vapour) and a moist atmosphere (17 g/m³ of water vapour). The temperature profile for the first two cases is from the 1976 US Standard Atmosphere [NOAA, NASA and USAF, 1976] (15 °C surface temperature) while for the moist atmosphere the temperature profile is that of the Tropical Atmosphere for 15° N latitude [US Standard Atmosphere Supplements, 1966], surface temperature 29.44 °C. Figure 5 offers an expanded version of Fig. 3 (7.5 g/m³) for use with frequencies below 60 GHz.

For all the calculations, the model assumed is one of a horizontally stratified atmosphere, corrected for Earth curvature. The total pressure is that for the standard atmosphere (1013 mb) with the water vapour added to it (1017 mb, 1023 mb, and 1037 mb for 3 g/m³, 7.5 g/m³, and 17 g/m³ water vapour respectively). An exponential decrease of water vapour with height is assumed, with a scale height of 2 km up to the level of the tropopause, above which the water vapour profile given by Harries [1976] is used.

Figures 2 to 5 are in reasonable agreement with the limited amount of experimental data available. However, they should be used with caution, especially at very high relative humidities, pending further experimental observations in the millimetre region.

If one assumes a law governing the decrease of water vapour content with altitude, it can be shown [Damosso and De Padova, 1976] that in the 10 to 20 GHz frequency range, zenith noise temperature may be evaluated from surface humidity data. Hence, sky noise temperature at various elevation angles may be obtained for a given locality taking into account its climatic characteristics. This method is not recommended for equatorial regions (see Report 563).

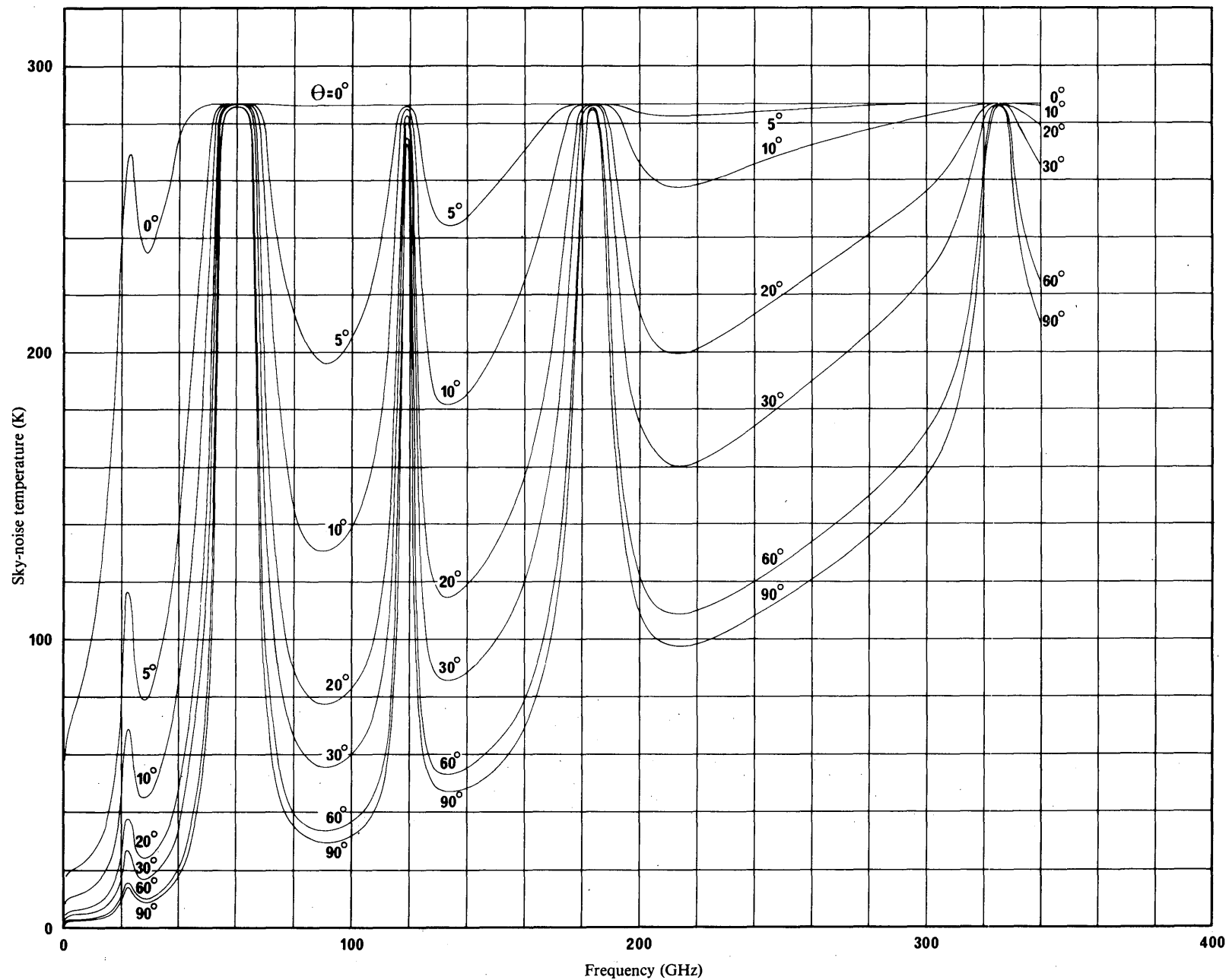


FIGURE 2 – Sky-noise temperature (clear air) for a surface pressure of 1017 mb and temperature of 15°C for a surface water vapour concentration of 3 g/m³; θ is the elevation angle

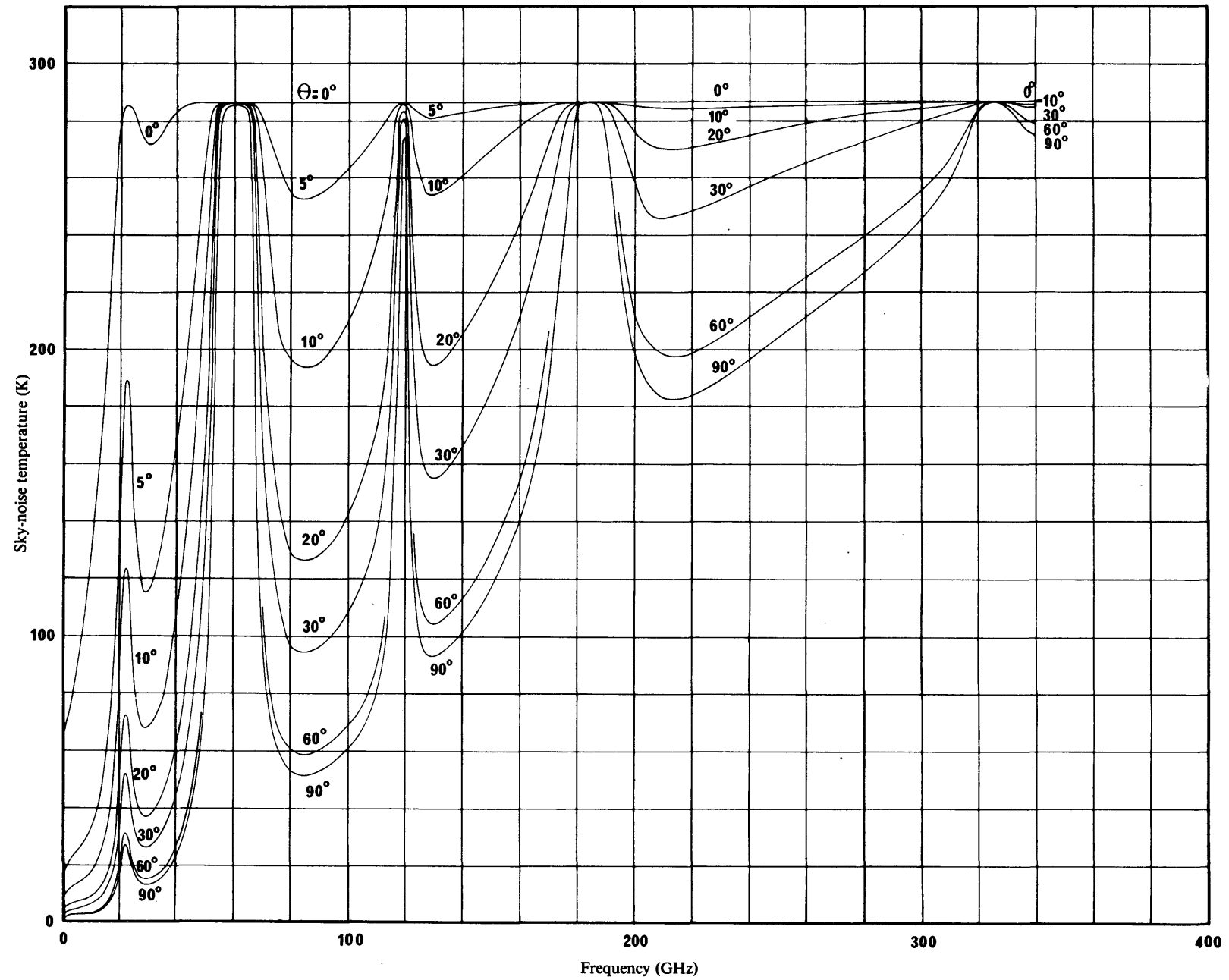


FIGURE 3 – Sky-noise temperature (clear air) for 7.5 g/m³ water vapour concentration (surface temperature and pressure equal to 15°C and 1023 mb); θ is the elevation angle

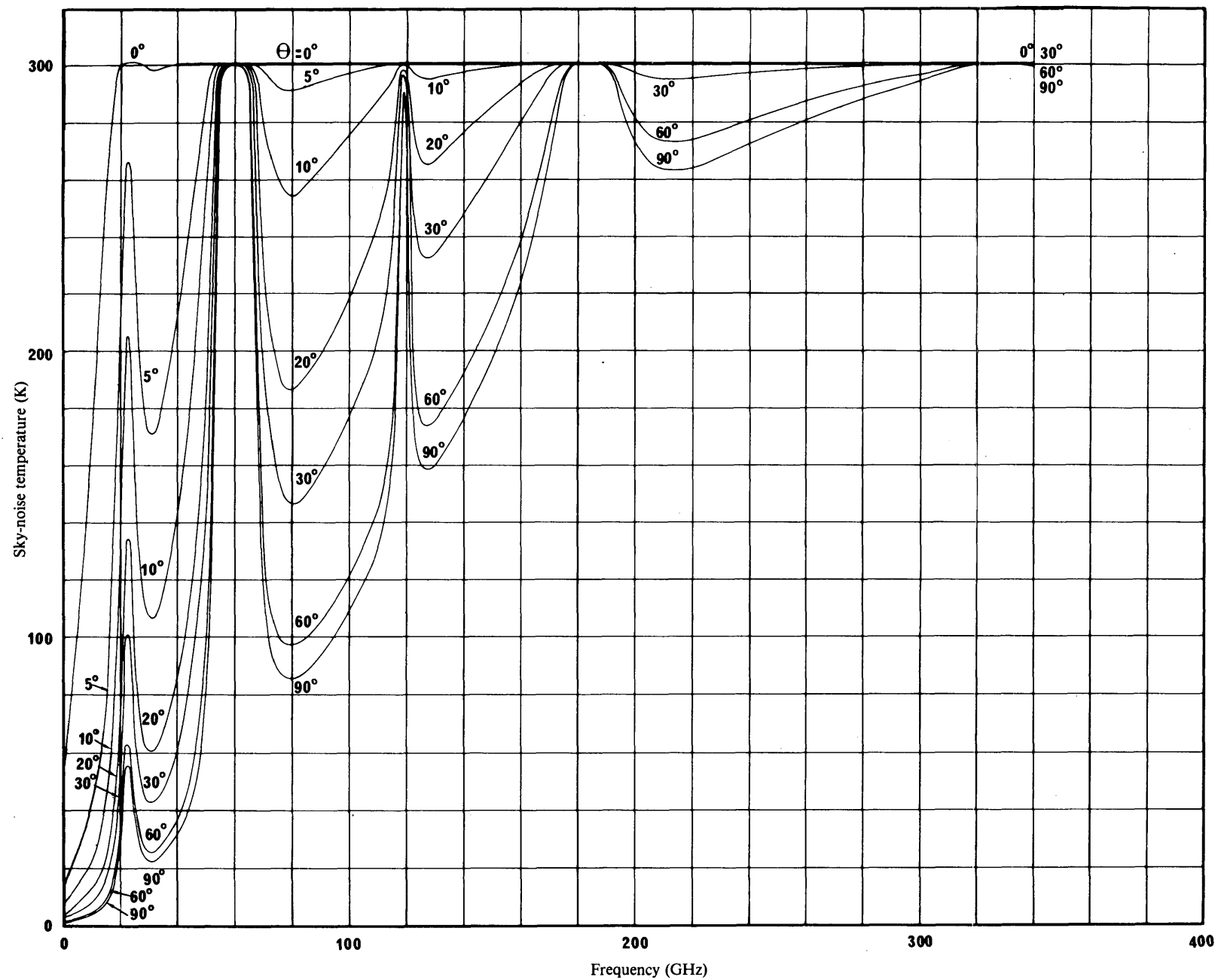


FIGURE 4 – Sky-noise temperature (clear air) for 17 g/m³ water vapour concentration (surface temperature and pressure equal to 29.4°C and 1037 mb); θ is the elevation angle

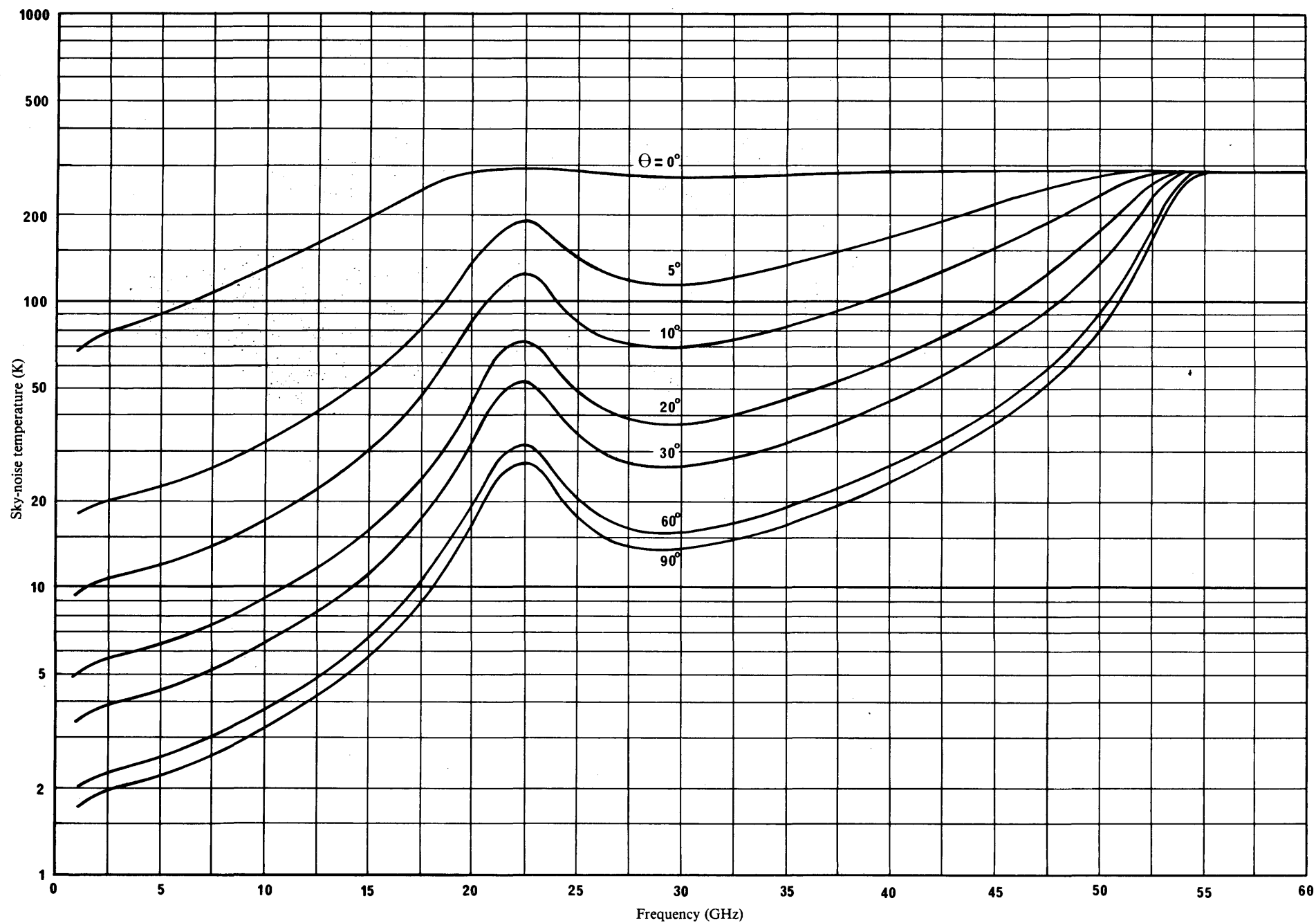


FIGURE 5 — Sky-noise temperature for clear air for 7.5 g/m^3 of water vapour concentration (expansion of abscissa scale of Fig. 3); θ is the elevation angle

3. Sky-noise temperature due to rain and cloud

The noise due to absorption in rain and cloud can also be calculated from the expressions given above, provided the temperature and specific attenuation and their variation along the path are known. At frequencies above 10 GHz both absorption and scattering may contribute to the attenuation and the full radiative transfer equation may be required. The frequencies at which rain (12 mm/h) and cloud (0.8 g/m³ water) produce significant scattering can be judged from Fig. 6 [Tsang *et al.*, 1977; Crane, 1971; Závody, 1974].

Studies carried out in the U.S.S.R. have shown that, at an elevation angle of 10°, for 1% of the time, a contribution to the antenna noise temperature of about 40 K due to rain and cloud, can be expected at 10 GHz, and of about 140 K at 20 GHz. The corresponding values for 0.1% of the time are 90 K and 260 K respectively.

A radiative transfer study of cloud effects has been carried out by Slobin [1981]. A possible configuration involving two cloud banks of equal thickness (1 km), the first between heights of 1 and 2 km, the second between 3 and 4 km above the earth station, is shown in Fig. 7a. The effect of adding first the lower cloud and then both on the sky-noise temperature is shown in Fig. 7b. The dashed line illustrates the displacement of the centre of the "window" to lower frequencies as cloud content increases. The cloud density is 0.5 g/m³ of water for both cloud banks.

4. Sky-noise temperature due to extraterrestrial sources

As a general rule, for communications below 2 GHz one needs to be concerned only with the Sun and the Milky Way, while above 2 GHz this reduces to the Sun and the cosmic background (2.7 K) [Kraus, 1966] and a few non-thermal sources such as Cassiopeia A, Cygnus A, and X and the Crab nebula. If concern is restricted to satellites in geostationary orbit then these latter three sources are not of concern from any location on the Earth's surface as can be seen in Fig. 8 where the radio sky at 250 MHz [Ko and Kraus, 1957] is shown in equatorial (or celestial) coordinates. When plotted on the celestial sphere a geostationary satellite as seen from the Earth appears as a horizontal line of declination between $\pm 8.7^\circ$. The ecliptic appears between $\pm 23.5^\circ$, so that if one is observing a spacecraft in interplanetary space one normally does view regions of the celestial sphere closer to the galactic nucleus than if one observes only geostationary satellites.

The contours of Fig. 8 are in units of 6 K above 80 K, the values corresponding to the coldest parts of the sky. For example, at 1800 h and 0° declination, the contour value would be 37. The brightness temperature at $f_0 = 250$ MHz is then $T_b = 6 \times 37 + 80 = 302$ K. To obtain the brightness temperature for another frequency, f_i , for the galactic background use:

$$T_b(f_i) = T_b(f_0) \left(\frac{f_i}{f_0} \right)^{-2.75} + 2.7\text{K} \quad (9)$$

Thus for the example above at frequencies of:

$$f_i = 1 \text{ GHz: } T_b = 302 \left(\frac{1}{0.25} \right)^{-2.75} + 2.7 = 9.4\text{K}$$

$$f_i = 4 \text{ GHz: } T_b = 302 \left(\frac{4}{0.25} \right)^{-2.75} + 2.7 = 2.8\text{K}$$

More detailed information is given at 408 MHz by Haslum *et al.* [1974].

The strongest discrete radio sources between declinations $\pm 8.7^\circ$ are shown in Fig. 9 along with the radio sources recommended for system calibration (data from Wielebinski [1976]).

If still more detail on sky background and sources is desired, it is available in great abundance in the Astrophysical Journal Supplements. The Ohio State Dixon Catalogue is a standard resource of surveys and sources.

The Sun is a strong variable noise source with a noise temperature of about 10^6 K at 50 to 200 MHz and at least 10^4 K at 10 GHz under quiet Sun conditions. Large increases occur when the Sun is disturbed. Detailed information on the Sun at radio frequencies is given in Krüger [1979].

The noise temperature of the planets is a function of frequency. Values for UHF are tabulated in Wielebinski, [1976].

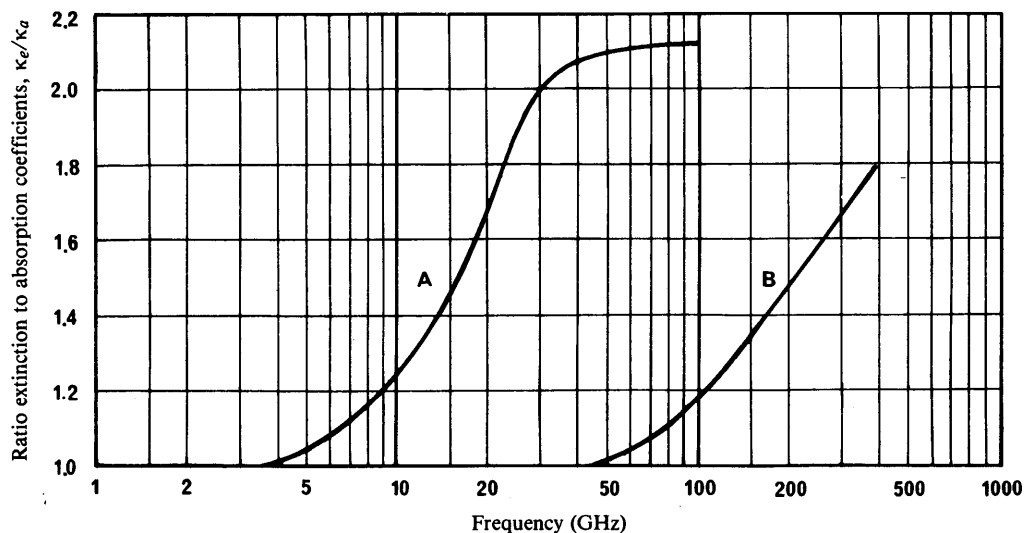


FIGURE 6 – Frequency for which scattering becomes important illustrated by ratio of extinction to absorption coefficients for the rain model (A) and cloud model (B) (Horizontal polarization)

Rain model: 12 m/h, 400 μm mean drop size
 Cloud model: 0.8 g/m³, 20 μm mean drop size
 Percentage energy scattered = $100 \left[\frac{\kappa_e - \kappa_a}{\kappa_e} \right]$

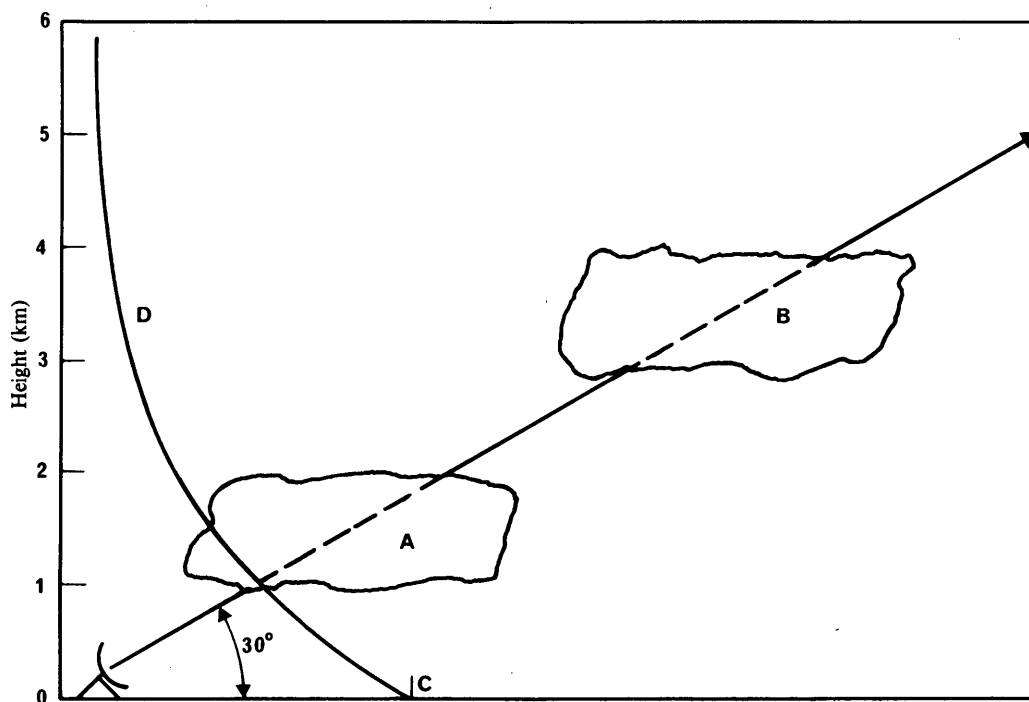


FIGURE 7a – Example of the effect of cloud layers on sky-noise temperature

Clouds A and B are each 1 km thick with 0.5 g/m³ liquid water content.
 C: Water vapour is 7.5 g/m³ at the surface and decreases with height with a scale height of 2 km.

Curve D: water vapour profile = $e^{-h/2.0}$

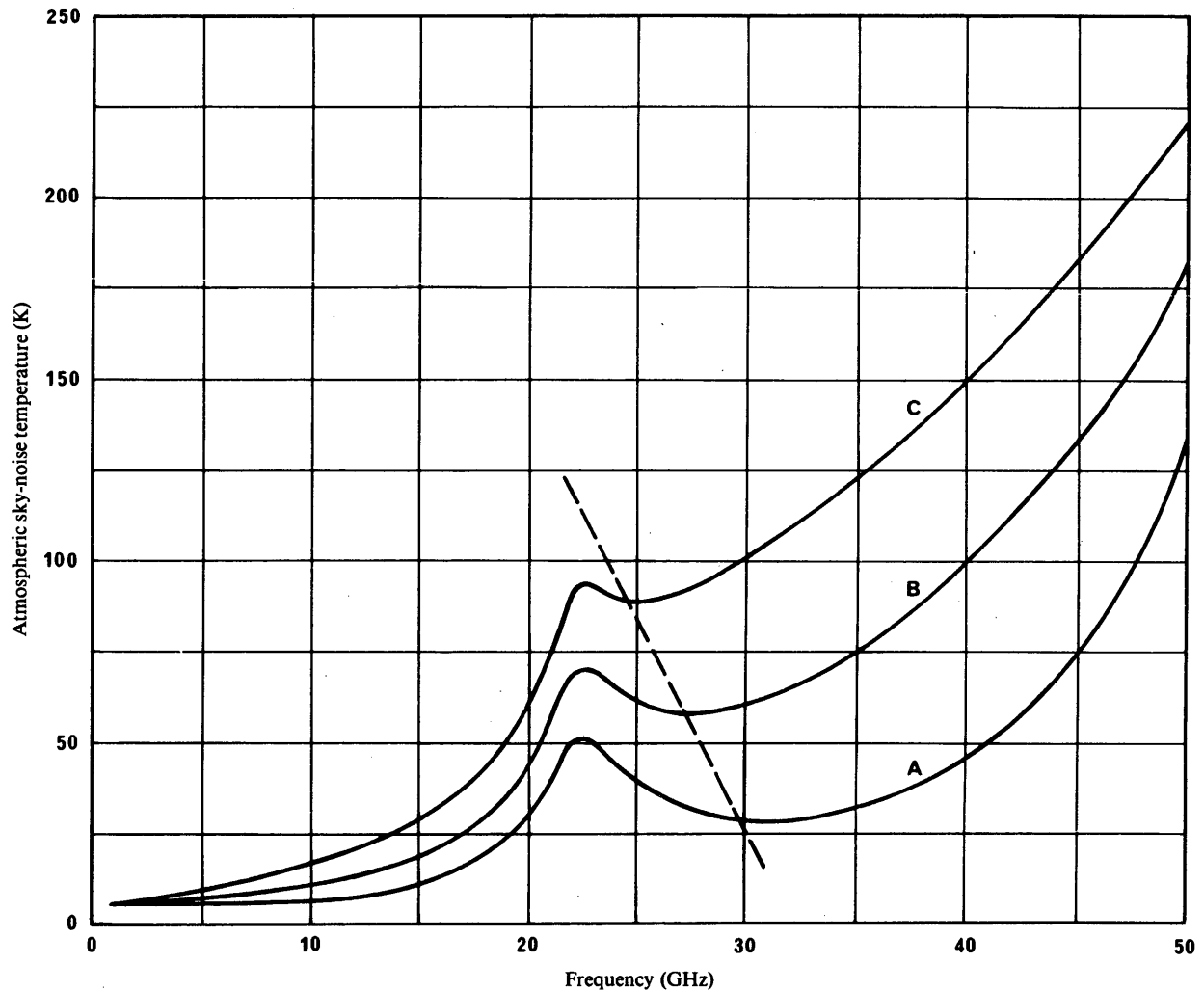
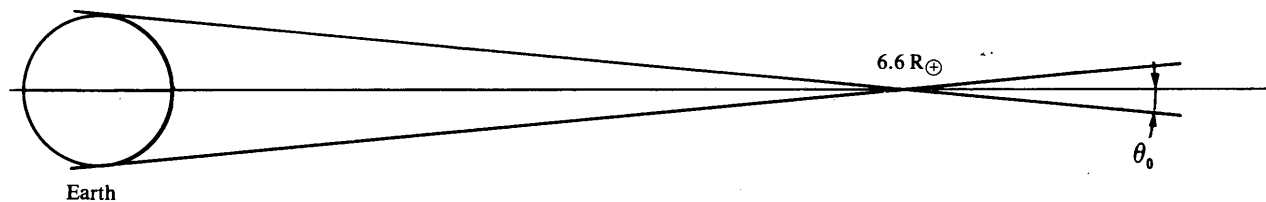


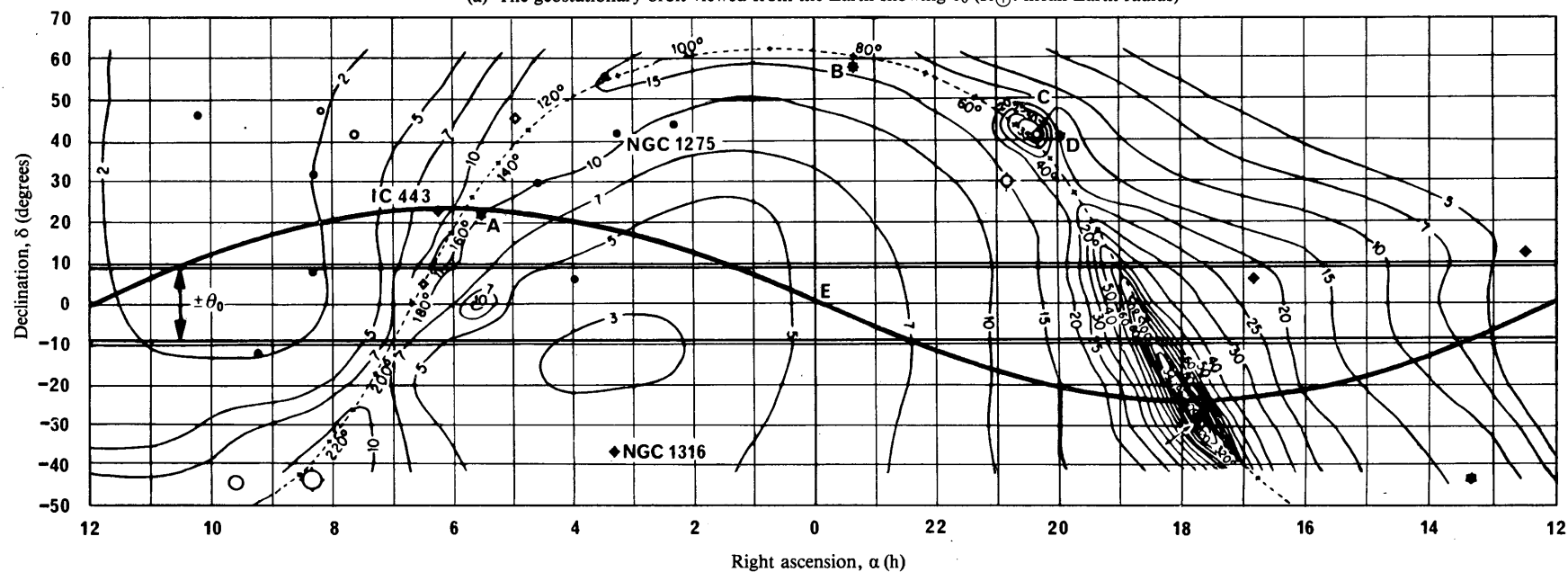
FIGURE 7b – Example of the effect of cloud layers on sky-noise temperature

Parameters: Elevation angle: = 30°
 clear air: 7.5 g/m^3 of water vapour
 cloud banks: 0.5 g/m^3 of *liquide* water

Curves A: clear air only
 B: clear air plus one cloud layer 1 km thick centered on 1.5 km altitude
 C: as above plus a second cloud layer 1 km thick centered on 3.5 km altitude
 — — — — centre of "window"



(a) The geostationary orbit viewed from the Earth showing θ_0 ($R_{\oplus}$: mean Earth radius)



(b) The celestial sphere at 250 MHz [Ko and Kraus, 1957] with $\pm \theta_0$ and the ecliptic indicated

FIGURE 8 – Radio sky at 250 MHz as a background for that part of the celestial sphere of interest in earth-satellite telecommunications using the geostationary-satellite orbit

Magnitude
(angular size)

$<1^\circ$	$\geq 1^\circ$	
1-2	•	◐
3-4	•	◐
5-6	•	◐
7-8	•	◐

A: Crab
B: Cassiopeia A
C: Cygnus X
D: Cygnus A
E: Ecliptic

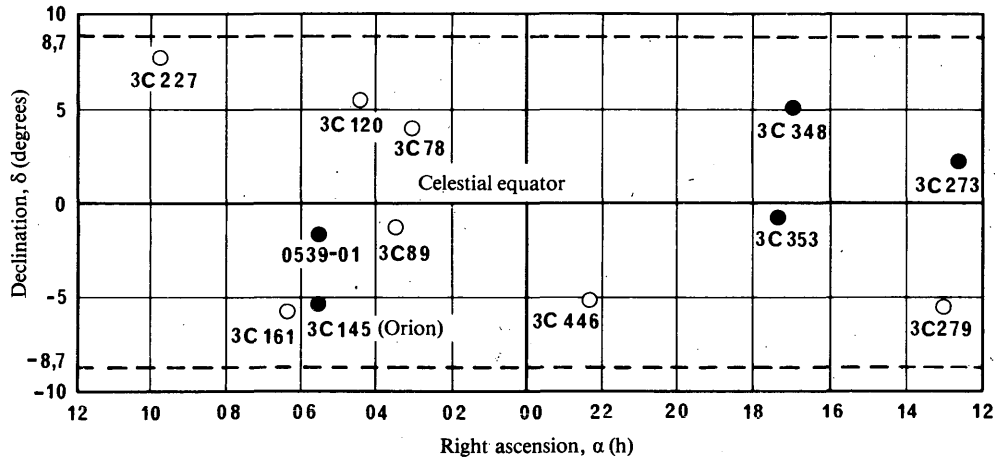


FIGURE 9 – Locations of strongest radio sources (●) and calibration sources (○) for a band of $\pm 8.7^\circ$ about the celestial equator. The numbers refer to catalogue designations, e.g. 3C indicates third Cambridge. [Wielebinski, 1976]

5. Sky-noise temperature due to the surface of the Earth

Energy incident at some angle to the surface of the Earth of power p_i will be partially specularly reflected (p_r), partly transmitted and absorbed (p_t) and, if the surface is rough, partly scattered (p_s). If we define a reflection coefficient (power), ρ , such that:

$$\rho = \frac{p_r + p_s}{p_i} \quad (10)$$

Then, quite generally, the emissivity, ϵ , is:

$$\epsilon = 1 - \rho \quad (11)$$

and the apparent (or brightness) temperature of the surface at the angle of interest, $T_a(\theta)$, is:

$$T_a = \epsilon T_{surf} = (1 - \rho) T_{surf} \quad (12)$$

For smooth surfaces ($p_s \ll p_r$) we have $\rho = p_r/p_i$ and normal analytical approaches may be used. A rather different approach is required for rough surfaces where scattering is important.

5.1 Smooth surfaces

The reflection coefficients for surfaces which are smooth in terms of Rayleigh's criterion are treated as follows: the brightness temperature will be a function of frequency, polarization, incidence angle, and the dielectric constant and conductivity of the surface. Rayleigh's criterion is given by:

$$h \leq \lambda / (8 \cos \theta) \quad (13)$$

where

h : obstacle height (m)

λ : wavelength (m)

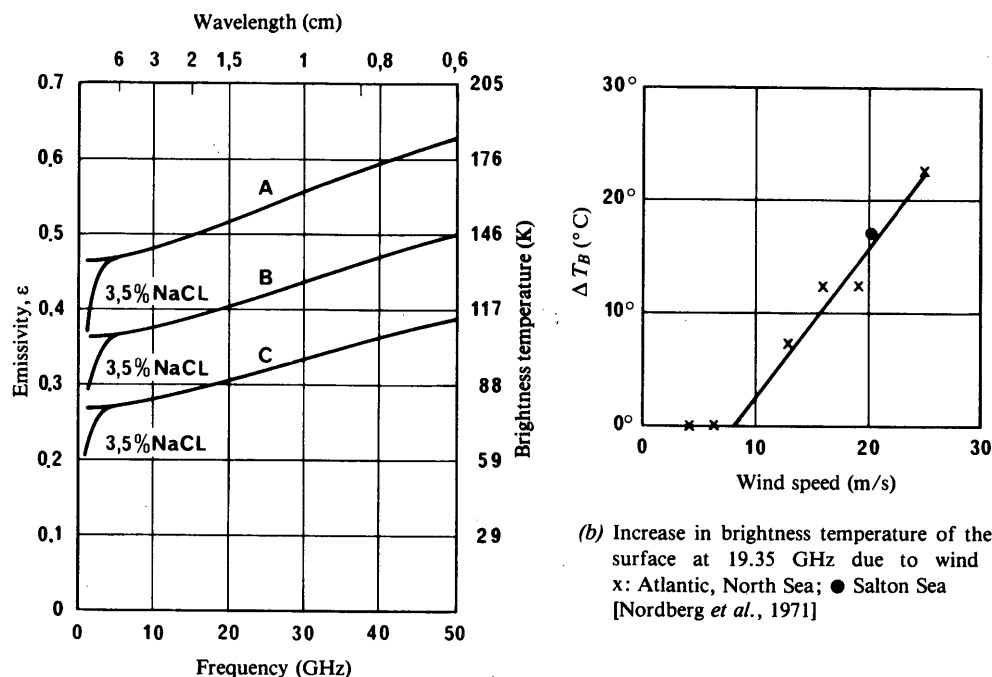
θ : angle of incidence (zenith angle).

5.2 Diffuse surfaces

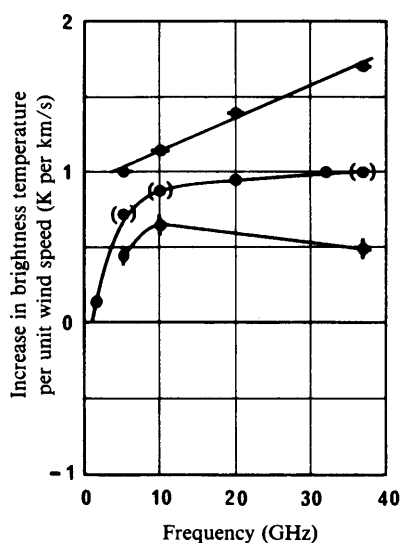
When surfaces appear rough by Rayleigh's criterion (equation (13)), i.e., if the obstacle height, $h > \lambda / (8 \cos \theta)$, more energy shows up in the scattered power (p_s) as compared to specularly reflected power (p_r) in (equation (11)) but the reflectivity, ρ , is approximately unchanged unless the character of the surface changes (e.g., foam from breaking ocean waves, vegetation over land surfaces). The shape of the Fresnel coefficients with incident angle is generally still discernible but the Brewster angle may be shifted to higher frequencies [Reeves *et al.*, 1975].

5.3 Ocean surface

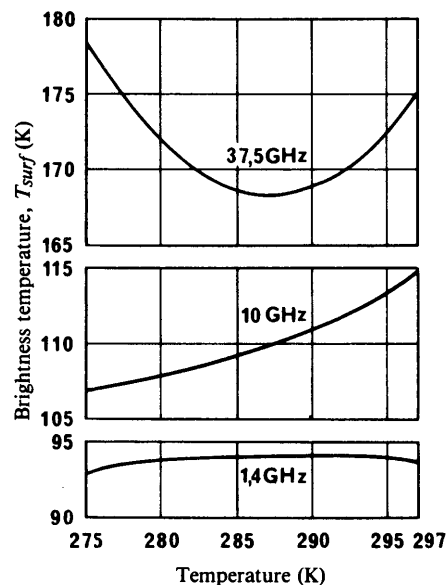
The dielectric constant of both fresh water and sea water is very high up to 10 GHz ($\epsilon_1 > 50$) but drops to only moderately high values ($\epsilon_1 \approx 8$) by 100 GHz (Fig. 1 of Recommendation 527, [Saxton and Lane, 1952; Lane and Saxton, 1952]). The result is that the reflection coefficient ρ is generally high and the emissivity ϵ low; and water appears radiometrically cold at low microwave frequencies and cool at millimetre wave frequencies as shown in Figs. 10(a) and 10(d) [Wilheit and Chang, 1979; Reeves *et al.*, 1975]. The increase in brightness temperature with wind speed (Figs. 10(b) and 10(c)) provides a very useful tool for storm detection [Nordberg *et al.*, 1971; Wilheit and Chang, 1979; Njoku *et al.*, 1980].



(a) Emissivity of a smooth water surface for vertical (A) and horizontal (C) polarization for incidence angles of 0° (B) and 45°. Fresh and salt water are indistinguishable for frequencies greater than 5 GHz [Wilheit and Chang, 1979]



(c) Spectrum of increase in brightness temperature caused by wind at the ocean surface: ● nadir, ◆ vertical (38°), ◐ horizontal (38°), (●) inferred [Wilheit and Chang, 1978]



(d) Brightness temperature of the sea surface as a function of sea surface temperature (nadir) for a salinity of 36 parts per thousand

FIGURE 10 – Emissivity and brightness temperature variations of the sea surface

5.4 Land surfaces

The emissivities (and hence the brightness temperature) of land surfaces are higher than those of water surfaces due to the lower dielectric constants. This feature is illustrated in Fig. 11. The effect of moisture in soil is also seen to decrease the emissivity.

The degree of roughness scales with frequency. At the low end of the microwave band, near 1 GHz, only deep vegetation such as dense woods provides a rough surface deep enough to eliminate all specular reflection from the underlying ground. At 10 GHz, shrubbery suffices, and at 35 GHz even short grass acts as a rough surface [King, 1970].

The penetration of microwaves may extend to appreciable depths. A measure of depth of penetration is the skin depth, δ , which represents an attenuation of 1 neper or 8.68 dB (note that in this case the neper is used in its traditional sense, rather than that of Report 693 where 1 neper = 4.34 dB when associated with optical depth). Skin depths of various materials as a function of frequency are given in Fig. 2 of Recommendation 527. A case in point is that of snow which is normally penetrated to its underlying surface at microwave frequencies.

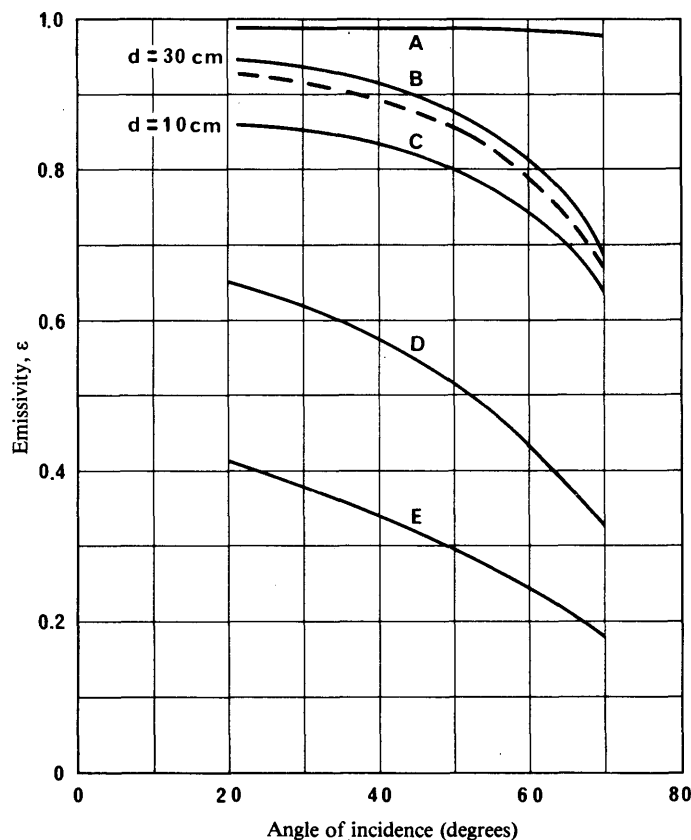


FIGURE 11 - Calculated soil emissivities: $\lambda = 1.8$ cm;
 d = depth of dry soil on moist soil

The dashed curve represents measured data

Other curves are:

- A: rough soil;
- B and C: dry soil (specular) over rock;
- D: moist soil (specular) 15 % by volume;
- E: water [King, 1970]

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REPORT 721-1 *

ATTENUATION BY HYDROMETEORS, IN PARTICULAR PRECIPITATION, AND OTHER
ATMOSPHERIC PARTICLES

(Question 2/5)

(1978-1982)

1. Introduction

Precipitation, especially rain, causes absorption and scattering of a radio wave. These effects combine to produce attenuation.

Although all frequencies are subject to these effects, attenuation is of practical importance only for frequencies above several gigahertz and for percentages of time for which there is intense precipitation.

Sand and dust particles appear to be of minor importance at frequencies as low as 12 GHz. Significant propagation effects have not been reported up to the present time.

2. Attenuation by rain

2.1 Attenuation by rain may be approximately evaluated on the basis of the classical Mie scattering theory. Assuming spherical drops, the attenuation coefficient due to rain γ_R (dB/km) at a given frequency, may be related to the rainfall rate R (mm/h) from a knowledge of the complex index of refraction of water at the temperature of the raindrops and the terminal velocity and the size distribution of the raindrops [Ryde and Ryde, 1945; Medhurst, 1965; Setzer, 1970].

The behaviour of the attenuation coefficient versus frequency for various values of rainfall rate is shown in Fig. 1 [Rogers and Olsen, 1976]. For frequencies up to 40 GHz values of specific attenuation have been extrapolated in Fig. 2, for rainfall rates up to 250 mm/h. These Figures have been obtained on the basis of experimental data on the microstructure of rainfall (see Report 563).

For all rainfall rates the specific attenuation increases quite rapidly up to frequencies of about 100 GHz. Above 100 GHz, the specific attenuation does not increase appreciably as a function of frequency except for very low rainfall rates. Above about 200 GHz, depending on the rain rate, the specific attenuation decreases slightly with increasing frequency, until at 1000 GHz it has nearly reached its optical limit.

2.2 Particular attention has been given to the validity of the hypotheses and of the experimental data on the microstructure of rainfall used to calculate the specific attenuation due to rainfall; and to the applicability of these calculations to real rainfall situations [Medhurst, 1965; Crane, 1971; Crane, 1975; Waldeufel, 1973; Fedi and Mandarini, 1973]. Measurements carried out at millimetre wavelengths in natural rain [Norbury and White, 1972; Sander, 1975], and in simulated rain [Crane, 1974] are in satisfactory agreement with the theoretical calculations. Many of the measurements at longer wavelengths differ from theory mainly because of limitations in the rain rate sampling techniques employed [Fedi *et al.*, 1974].

2.3 The results shown in Figs. 1 and 2 apply generally for an incident plane wave, an isotropic spherical wave, or a spherical wave with a finite beam. Their applicability for rain in the near field of the antennas has been investigated recently [Haworth, 1980]. The calculations apply to the attenuation of the coherent wave and therefore can strictly be used only for coherent communications systems [Crane, 1971]. However, since the raindrop pattern is broad (at least at microwave frequencies), only a small amount of power due to incoherent scattering will enter a narrow beam receiving antenna [Hogg and Chu, 1975]. Thus, with caution, the calculations can also be used for incoherent transmission systems.

* This Report is brought to the attention of Study Groups 2, 4, 7, 8, 9, 10 and 11.

Although commonly thought to include only the effects of single scattering, the theory [Van de Hulst, 1957] also includes the effects of the forward multiple scattering processes (i.e., those processes in which the multiple scattering paths between the scatterers all have components in the forward direction). Because of the limited raindrop population in even the heaviest rains, these are the only multiple scattering processes which give a significant contribution to the average (or coherent) field transmitted through the rain [Rogers and Olsen, 1976].

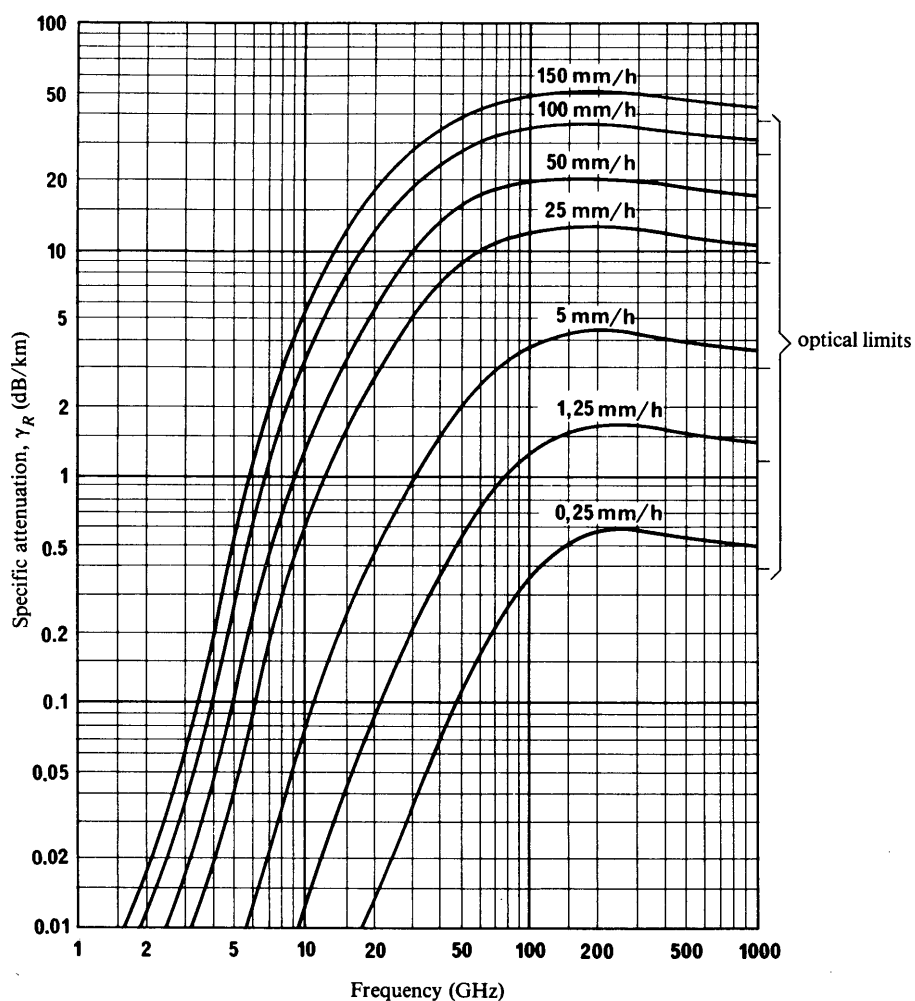


FIGURE 1 — Specific attenuation γ_R due to rain

Raindrop size distribution [Laws and Parsons, 1943]
 Terminal velocity of raindrops [Gunn and Kinzer, 1949]
 Index of refraction of water at 20° C [Ray, 1972]
 Spherical drops

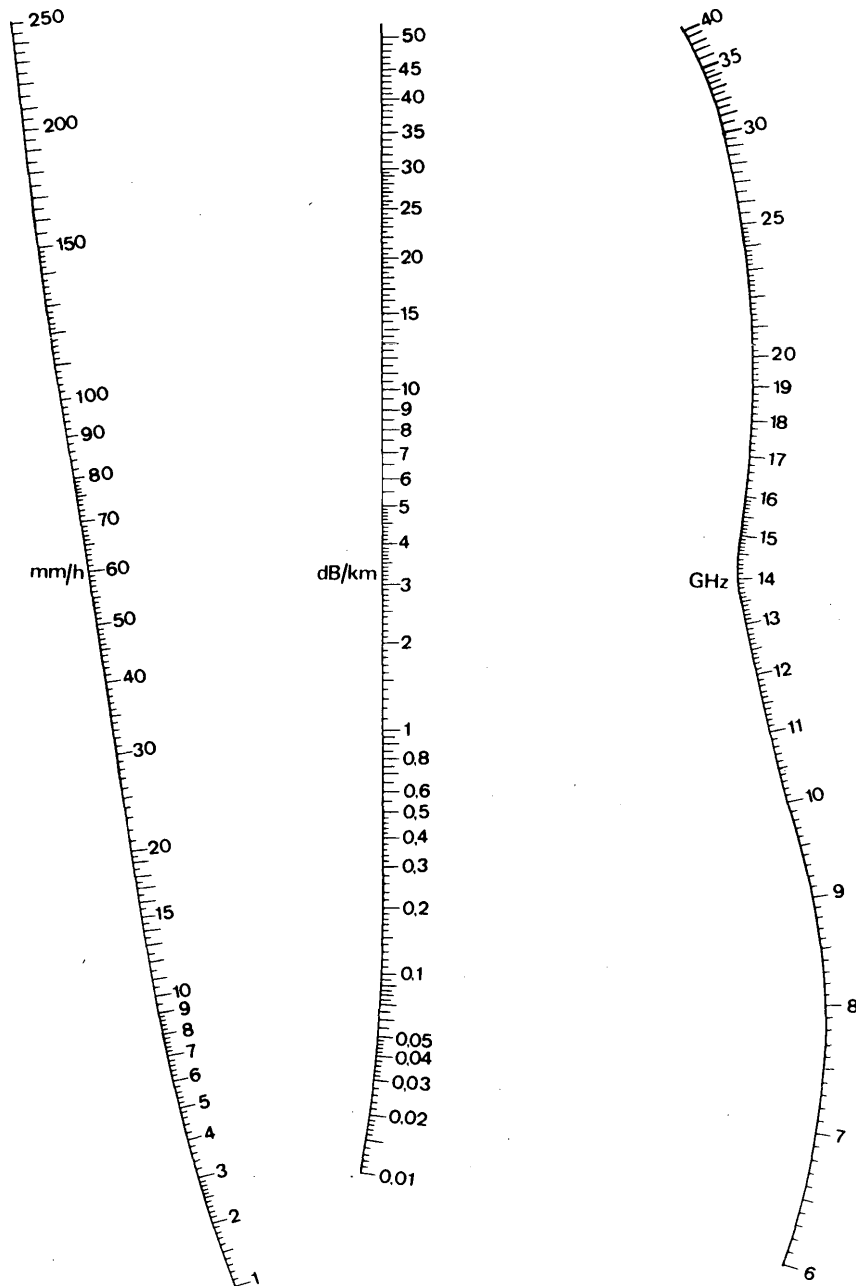


FIGURE 2 – Specific attenuation γ_R due to rain

Raindrop size distribution [Laws and Parsons, 1943]
 Terminal velocity of raindrops [Gunn and Kinzer, 1949]
 Index of refraction of water at 18° C [Ray, 1972]
 Spherical drops

2.4 Calculations of the specific attenuation at a given frequency versus rainfall intensity strongly depend on the assumed microstructure of rainfall (size distribution, temperature, terminal velocity and shape of the raindrops) (see Report 563).

The Laws and Parsons raindrop size distribution is the most commonly used to calculate specific attenuation. It is based on measurements for rain rates up to 50 mm/h, but may be extrapolated beyond this. Other drop size distributions represented by a negative-exponential function [Marshall and Palmer, 1948; Joss *et al.*, 1968] have also been used for calculations of specific attenuation. The distribution of Joss *et al.* differs from the others in that it is specified for three rain types; thunderstorm or convective rain, widespread rain, and drizzle. At the high rain rates of most importance in the design of communications systems and at frequencies above 10 GHz, the Laws and Parsons distribution gives higher specific attenuations than does the thunderstorm distribution of Joss *et al.* This difference is particularly large at frequencies above 100 GHz. On the other hand, the drizzle distribution of Joss *et al.* gives larger specific attenuations at low rain rates for these high frequencies [Olsen *et al.*, 1978]. Caution should be exercised in the application of attenuation estimates at frequencies above 100 GHz, since the devices used to obtain raindrop size distribution data tend to underestimate the number of small drops which provide a significant contribution to the attenuation at these frequencies.

Changes of the drop temperature from the assumed values are only important at frequencies below 20 GHz and may cause departures of up to 20% from the curves in Figs. 1 and 2.

Experimental data on terminal velocity of the raindrops in still air are generally in good agreement with those assumed to derive the curves in Figs. 1 and 2.

A greater limitation of the results in Figs. 1 and 2 is the assumption that the raindrops are spherical. Because of the non-spherical shape of the raindrops horizontally polarized waves suffer greater attenuation than vertically polarized waves [Morita *et al.*, 1974; Chu, 1974]. In some climates the difference in attenuation may reach values as high as 35% [Fedi *et al.*, 1977; Fimbel and Juy, 1977]. Specific attenuations for vertical and horizontal polarizations, and frequencies up to 100 GHz, may be obtained from the extensive calculations that take into account the non-spherical shape of the raindrops [Oguchi and Hosoya, 1974; Chu, 1974; Oguchi, 1977].

2.5 For practical applications the relationship between attenuation γ_R (dB/km) and rain rate R (mm/h) can be approximated by the power-law [Olsen *et al.*, 1978]:

$$\gamma_R = kR^\alpha \quad (1)$$

Based on the assumption of spherical drops, values of k and α have been calculated at a number of frequencies between 1 and 1000 GHz for several drop temperatures and drop size distributions [Olsen *et al.*, 1978].

Values of k and α for a Laws and Parsons drop size distribution and a drop temperature of 20 °C have also been calculated by assuming oblate spheroidal drops aligned with a vertical rotation axis and with dimensions related to the equivolumic spherical drops [Fedi, 1979; Maggiori, 1981]. These values, which are appropriate for horizontal and vertical polarizations, are presented in Table I (denoted k_H , α_H and k_V , α_V). Values of k and α at other frequencies than those in Table I can be obtained by interpolation using a logarithmic scale for frequency and k and a linear scale for α .

For linear and circular polarization, the coefficients in equation (1) can be calculated from the values in Table I using the approximate equations (2) and (3) below [Nowland *et al.*, 1977].

$$k = [k_H + k_V + (k_H - k_V) \cos^2 \theta \cos 2\tau]/2 \quad (2)$$

$$\alpha = [k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2 \theta \cos 2\tau]/2k \quad (3)$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal ($\tau = 45^\circ$ for circular polarization).

It is recommended that equations (1), (2), (3) and the coefficients k and α in Table I be used for evaluating the statistical characteristics of rain attenuation. However, in view of the complexity of real rain structure, caution should be exercised in applying this relationship to individual rain events [Fedi *et al.*, 1977], particularly at frequencies above about 40 GHz.

TABLE I - Regression coefficients for estimating specific attenuations in equation (1)*

Frequency (GHz)	k_H	k_V	α_H	α_V
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
4	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0335	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	0.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

*Raindrop size distribution [Laws and Parsons, 1943].
Terminal velocity of raindrops [Gunn and Kinzer, 1949].
Index of refraction of water at 20°C [Ray, 1972].

Values of k_H , k_V , α_H and α_V for spheroidal drops [Fedi, 1979; Maggiori, 1981] based on regression for the range 1 to 150 mm/h.

3. Predictions of attenuation by rain on terrestrial paths from rainfall rate data

3.1 Single path statistics

Attenuation due to rain over a path may be calculated by integrating the specific attenuation over the path length if the rainfall rate variation along the path is known. Due to the considerable variability of attenuation statistics in different years and among different localities the possibility of deriving these statistics from the long-term meteorological data appears very desirable.

Several methods have been proposed for predicting rain-induced, path-attenuation statistics from rainfall rate measurements near the path. These methods all make use of the relationship between the specific attenuation and rain rate, which as discussed in the previous section, depends on the rainfall microstructure. The main difference in the methods is in the models used to describe the time-space structure of rainfall rate (see Report 563) [Fedi, 1981].

The "synthetic storm method" generates attenuation statistics by converting rain rate/time profiles recorded at a point, to rain rate/distance profiles, using the translation velocity of the rain pattern; a good estimate of which seems to be the wind speed derived at the 700 mb level from a conventional radiosonde [Drufuca, 1974; Bertok *et al.*, 1977; Segal, 1982]. Although this method requires a very detailed data base, it represents a technique with a high degree of physical realism. It is therefore possible to utilize this technique to investigate other attenuation characteristics such as duration statistics, frequency scaling methods and effective path length conversion. All other methods [Fedi, 1981] make use of the cumulative distribution of rainfall rate measured at a point. One method [Misme and Fimbel, 1975] derives the statistical profile of rain along the path by assuming a single rain cell of suitable shape. This method has been tested thoroughly with European data [Fedi, 1979] and shown to give good results. In a recent extension of this method [Rue, 1981] the single cell concept has been replaced by a statistical distribution of rain cell sizes which appeared to remove the sensitivity of the model to the log-normal approximation for rainfall intensity distribution [Damosso *et al.*, 1980].

Other methods characterize the statistical rain profile simply by a reduction coefficient which may be derived from the spatial autocorrelation function of rainfall [Morita and Higuti, 1976] or from measurements using rapid-response rain gauges actually spaced along a line [Harden *et al.*, 1978a; Crane, 1980] or from a semi-empirical law [Battesti and Boithias, 1978]. Multiplying point rain rate by this reduction coefficient gives the equivalent path-averaged rain rate.

An alternative procedure is to apply the reduction coefficient to the actual path length which yields an equivalent path length over which the rain intensity may be assumed to be constant [Kalinin, 1974; Lin, 1975]. One method in this category [Fedi, 1981] assumes a constant slope for the attenuation distribution and requires only the reduction coefficient for 0.01% of the time. Strictly speaking, this reduction coefficient, in whichever way applied, is a function of rain rate, probability, frequency, path length and climate. The various models mentioned above assume a simple dependence on one or two parameters only.

In general, in order to be widely used, a prediction method should:

- be easy to apply;
- give good agreement with experimental results in different regions;
- not be too critically dependent on the technique used for obtaining the rainfall intensity data;
- preferably have a physical significance.

The semi-empirical approach defined in Report 338 uses very simple relations only, as these suffice to describe the limited data available and is considered to have practical applicability in system planning. More elaborate methods that are based on an analysis of the physical structure of rain should be used for the refinement and further development of such simple, but generally applicable methods, in particular regarding the characterization of climate dependence and extreme events.

3.2 *Path-diversity statistics*

Path diversity appears to be an effective means for increasing the maximum length of a link while still meeting previously determined availability objectives. Because of the complexity of the problem, however, techniques for predicting the joint attenuation statistics of paths in tandem are still at an early stage of development. The synthetic-storm technique discussed in the previous section has been used when the necessary time histories of rain rate at a point are available. More information on the statistical structure of rain intensity over an area is required to develop models for predicting path diversity improvement from statistics of rain rate measured at a point.

4. **Prediction of attenuation by rain on Earth-space paths from rainfall rate data**

4.1 *Single-site statistics*

As in the case of terrestrial paths, the possibility of deriving path attenuation statistics from long-term meteorological data appears very desirable. However, because the vertical structure of precipitation is involved in addition to the horizontal structure (see Report 563), the problem is somewhat more complicated.

In order to take the vertical structure into account various techniques have been proposed [Brussaard, 1981]. A number of these techniques [Kalinin, 1976; Morita and Higuti, 1978; Misme and Waldeufel, 1980; Crane, 1980; Fedi, 1980] are extensions of those developed for terrestrial paths. Others, derived strictly for Earth-space paths, assume statistical models for the vertical profiles of liquid water content [Dutton and Dougherty, 1977] or rain rate [Goldhirsh and Robison, 1975]. An estimate of the rain height is included in all these methods, usually based on the height of the 0° isotherm. In one of the methods [Crane, 1980] the rain height was described by a dependence on latitude and probability of occurrence (see Fig. 17 in Report 563). In this and one other method [Fedi, 1980], the rainfall structure was assumed to be constant from the surface to the rain height.

In one method proposed to estimate attenuation statistics exceeded for 1% of the time, the rain rate statistics for this percentage of time are estimated from an empirical relation in terms of the total annual rainfall and the rain height from an empirical relation with the surface temperature [CCIR, 1978-82a].

The requirements placed on attenuation prediction methods for Earth-space paths in order to be widely used are identical to those discussed in the previous section for terrestrial paths.

The method given in Report 564 is an extension of the method of Report 338 assuming rain structure to be independent of height up to the rain height h_R (see Report 563).

In the same way as discussed in § 3.1 above, this simple approach should be updated and modified as more data become available, in particular, from radar equipment that allow a thorough investigation of the physical structure of rain aloft. Also, long-term statistical data in all regions of the world are required to test and further develop this model.

4.2 *Site-diversity statistics*

Because of the non-homogeneous structure of rain in the horizontal and vertical directions and the additional complexity added by a second Earth-space path parallel with the first, attenuation prediction techniques for site-diversity configurations of Earth stations are at an early stage of development [Allnutt, 1978].

4.3 *Differential attenuation along two paths to an earth station*

The joint effects of rain attenuation along two paths to an earth station, one path from an intended space station and the other from an interfering space station, have been investigated [Rogers *et al.*, 1980]. Of importance to this problem are the statistics of the differential attenuation under the condition that the wanted signal attenuation is less than the fade margin.

The technique given in Report 885 on interference along Earth-space paths for predicting the differential attenuation distribution is based on a combination of point rain rate data for calculating the single-path attenuation distribution and radar data for calculating the conditional probability that the wanted-signal attenuation is less than the fade margin but greater than a small threshold attenuation. Application of the radar data from a single location to provide estimates for a variety of locations is based on the assumption that the horizontal and vertical structure of rain is relatively constant from one location to another. Additional data are requested to assess the general applicability of this technique.

5. **Frequency scaling of rain attenuation statistics**

Scaling of attenuation statistics in frequency is a useful technique if radio data for a desired locality are available. The methods may be classified in two main groups as follows:

5.1 *Single-frequency scaling*

With these techniques attenuation statistics at one frequency are used to predict statistics at a second frequency.

5.1.1 The following empirical formula may be applied for frequency scaling at a given polarization [CCIR, 1978-82b]:

$$\frac{A_1}{A_2} = \frac{g(f_1)}{g(f_2)} \quad (4)$$

where

$$g(f) = \frac{f^{1.72}}{1 + 3 \times 10^{-7} (f^{1.72})^2} \quad (5)$$

A_1 and A_2 are the values of attenuation (in dB) at frequencies f_1 and f_2 (in GHz), respectively, and are exceeded with equal probability.

This formula does not require any *a priori* assumption of microstructure or intensity profile of rainfall. It implies a constant ratio of the attenuations at the two frequencies, whereas the actual ratio will vary with rainfall rate. However, it gives reasonable results over a frequency range of about 7 to 30 GHz and for attenuation values of practical interest. In regions of low rainfall rate (< 50 mm/h) it may be used up to 50 GHz.

5.1.2 For frequency and polarization scaling and better accuracy, more sophisticated methods based on models for the microstructure and intensity profile of rainfall are available [Hodge, 1977; Rue 1980; Kheirallah *et al.*, 1980; Barbaliscia *et al.*, 1980].

5.2 *Multi-frequency scaling*

In this second group of methods, attenuation statistics at two frequencies are used to predict statistics at another frequency [Hogg, 1973; Matricciani, 1980; Capsoni *et al.*, 1980; Kheirallah and Olsen, 1981]. Three other methods use experimental data at three different frequencies to derive parameters of statistical models for rainfall intensity profile [Harris and Hyde, 1977; Muller, 1977] or of path-averaged raindrop-size distribution [Ihara and Furuhashi, 1981; Furuhashi and Ihara, 1981] and hence predict attenuation at another frequency.

Caution should be exercised in deriving information on the physical spatial structure of rainfall intensity from purely radio measurements due to the considerable variability of the microstructure of rainfall [Fedi *et al.*, 1977; Harden *et al.*, 1978b; Debrunner, 1980].

6. Path length scaling of rain attenuation statistics

Scaling of measured attenuation statistics for different path lengths is also a useful technique within a limited region. Asymptotic path length scaling techniques have been suggested [Rogers, 1976].

For example, if the attenuation statistics are determined either by the occurrence of relatively small cells of heavy rainfall or by the events of widespread precipitations, then their dependence on path length can be described by simple formulae. In the first case, the probability $P_2(A)$ that the attenuation A is exceeded on a path of length D_2 is proportional to the probability $P_1(A)$ on the path D_1 and we can write:

$$P_2\{A\} = (D_2/D_1) \cdot P_1\{A\} \quad (6)$$

Assuming widespread precipitations, the attenuation A exceeded with a given probability P is proportional to the path length, thus

$$P_2\{A_2\} = P_1\{(D_1/D_2) \cdot A_2\} \quad (7)$$

where $P\{A\}$ denotes the functional relationship between the probability P and the attenuation A . Equation (6) is employed in some techniques for predicting attenuation statistics [Crane, 1980].

The asymptotic scaling relation in (6) must be used with caution for short paths, and that in (7) for long paths. A more general method of scaling attenuation statistics in path, with equations (6) and (7) applying in the asymptotic limits, has been tested in Switzerland.

7. Variability of attenuation statistics

The highest values of attenuation are produced by rare events which happen, on average, only once in a number of years. An adequate statistical description of these rare events requires measurements over a number of years to allow for the observation of an event.

Little data are available on the long-term variability of the attenuation in the higher rain rate régime corresponding to less than 0.003% of the year (16 minutes per year) and only a modest number of observations may be used to assay variability in the 0.1% to 0.01% of the year range.

Observations of the long-term variability of the annual rain rate distribution values suggest that the variations at a point at 0.001 and 1.0% of the year are of the order of 25%. The variability at 0.1 and 0.01% of the year has been estimated at 20% [Harden *et al.*, 1978a; Crane, 1980]. Crane [1977] found that more than 16 years of observations were required to estimate the rain rate expected to be exceeded five minutes per year with an uncertainty of 10%.

Variations are to be expected among long-term statistics of point rainfall rate over an area. These variations are also important in the estimation of path averaged rain rate and of attenuation. Observations to date suggest that the variability in the conversion from point to path rain rate is of the order of 15%. It is therefore expected that attenuation predictions may differ from observations by about 20%.

8. Method for testing attenuation predictions

Attenuation predictions are generally made for a number of transmission paths at a fixed set of probability levels. Data for prediction method comparison are to be tabulated at fixed probability levels, e.g. 0.001, 0.01 and 0.1% of the year. The ratio of predicted to measured attenuation is calculated for each path. The logarithm of the ratio is used as a test variable. To suppress the effect of measurement inaccuracy, the ratio is taken to be unity if the predicted and measured values differ by 1 dB. The mean and standard deviation of the test variable is then calculated to provide the statistics for prediction method comparison.

Procedure

- For each percentage of time, calculate the ratio of predicted attenuation A_p (dB) to measured attenuation A_m (dB) for each radio link:

$$S_i = A_p / A_m \quad (8)$$

where S_i is the above ratio calculated for the i radio link.

- If $|A_p - A_m| \leq 1$ dB set $S_i = 1$.
- Calculate the test variable:

$$V_i = \log S_i \quad (9)$$

- Calculate the mean μ_V and standard deviation σ_V of the V_i values.
- Calculate the deviation D (%):

$$D = \left(10^{\sqrt{\mu_V^2 + \sigma_V^2}} - 1 \right) \times 100 \quad (10)$$

- Repeat the procedure and calculate D for each percentage of time.

In the comparison of prediction methods, the best prediction method produces the smallest D values.

The overall evaluation of a prediction procedure should include the calculation of the deviation for at least 3 percentages of the year, e.g. 0.001, 0.01 and 0.1%. Experience with the testing of the methods proposed in Reports 338 and 564 suggests that the deviations should be within 20% at these probability levels when the point rainfall rate distributions are obtained from local data sources and within 30% if the rainfall rate distributions are estimated from the maps of Report 563.

9. Attenuation by hydrometeors other than rain

Although rain is the most important type of hydrometeor affecting wave propagation, mention must also be made of the influence of clouds, fog, snow and hail. Attenuations caused by clouds and fog are relatively small but may occur during high percentages of time.

For clouds or fog consisting entirely of small droplets, generally less than 0.01 cm, the Rayleigh approximation is valid and it is possible to express the attenuation in terms of the total water content per unit volume [Ryde and Ryde, 1945]. Thus, the specific attenuation within such a cloud or fog can be written as:

$$\gamma_c = K_l M \quad (11)$$

where γ_c is the specific attenuation (dB/km) within the cloud, K_l is the specific attenuation coefficient (dB/km)/(g/m³) and M is the liquid water content of the cloud (g/m³).

At frequencies of the order of 100 GHz and above, attenuation in fog may become significant. The liquid water content of fog is typically about 0.05 g/m³ for medium fog (visibility of the order of 300 m) and 0.5 g/m³ for thick fog (visibility of the order of 50 m). The corresponding specific attenuation would be, for example, about 0.4 dB/km and 4 dB/km, respectively, at a frequency of 140 GHz. In practice, the values will depend on the type of fog and may also be influenced by anomalies in water vapour absorption.

Studies of the additional attenuation caused by clouds on Earth-space paths have been carried out in the USA and UK at frequencies up to 150 GHz, [Lai-Iun Lo *et al.*, 1975; CCIR, 1974-78]. Table II shows the range of values likely to be experienced at frequencies of 95 and 150 GHz. For widespread cloud the attenuation may be expected to vary approximately as cosec θ , where θ is the elevation angle. Figure 3 shows theoretical values of the specific attenuation coefficient, as a function of frequency, for temperatures between -8°C and 20°C .

Because of the difference in dielectric properties, ice clouds give attenuations about two orders of magnitude smaller than water clouds of the same water content up to 35 GHz, [Crane, 1977]. At higher frequencies the contribution of ice clouds to attenuation may be significant.

For frequencies less than about 50 GHz dry snow has little effect. By contrast, for higher frequencies, several measurements have shown the importance of attenuation by dry snow [Misme, 1966]. Attenuation by hail may be significant at frequencies as low as 2 GHz. Hail seems to be of importance only for less than 0.001% of the time in most climate regions.

Although wet snow fall can cause larger attenuation than the equivalent rainfall rate the results of propagation tests carried out in Japan [Takada and Nakamura, 1966], the U.S.S.R. [Nadenenko and Sviatogor, 1974], France [Battesti, 1979], and Switzerland [Debrunner, 1980] show that these events do not dominate attenuation statistics. The degradation of antenna characteristics due to accumulations of snow and ice may be of greater importance than snow along the path.

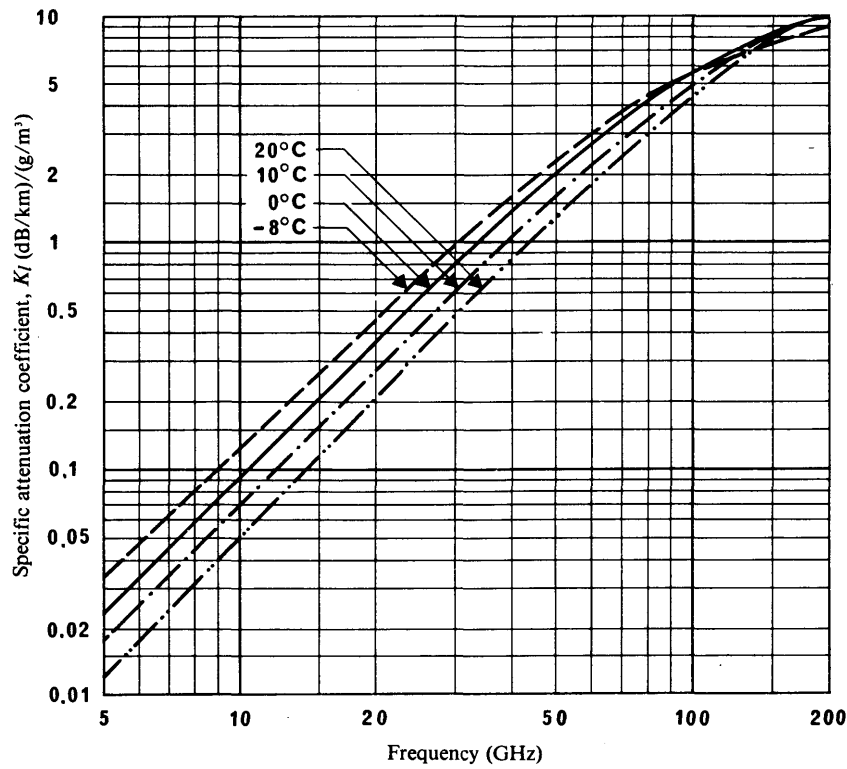


FIGURE 3 – Theoretical attenuation by water cloud at various temperatures as a function of frequency

TABLE II – Atmospheric attenuation in the vertical direction for 95 and 150 GHz
Slough, United Kingdom; October 1975 – May 1976

Frequency	95 GHz	150 GHz
Attenuation (dB) in clear air; water vapour content at ground-level 4 – 11 g/m ³	0.7 – 1	1 – 3
Additional attenuation (dB) due to clouds:		
Strato-cumulus	0.5 – 1	0.5 – 1
Small, fine weather cumulus	0.5	0.5
Large cumulus	1.5	2
Cumulo-nimbus	2 – 7	3 – 8
Nimbo-stratus (rain cloud)	2 – 4	5 – 7

10. Attenuation by sand and dust-storms

Sand and dust particles (see Report 563) may attenuate electromagnetic waves and their effects may be evaluated on the basis of the Mie scattering theory.

Measurements carried out in the laboratory at 10 GHz on simulated dust and sand conditions have shown that, for concentrations of less than 10^{-5} g/cm³, the attenuation coefficient would be less than 0.1 dB/km for sand and 0.4 dB/km for clay [Ahmed and Auchterlonie, 1976]. For severe storms, and for links operating under grazing conditions, attenuation of microwave signals might be expected to be higher than these values. In the case of satellite broadcasting — where the path length through dust-storms is expected to vary between 0.5 and 3 km — attenuation of microwave signals is expected to be less than 1 dB under severe conditions.

Further investigation is needed of the meteorological structure of sand and dust-storms, and measurements of actual attenuation are also needed.

11. Methods of measurement of attenuation on a path

11.1 Direct measurements

On ground-ground paths direct measurement of attenuation may be easily implemented. On Earth-space paths, transmissions from satellites provide the most direct method, but such transmissions are not available for all the locations, frequencies and elevation angles of interest. Consequently, radiometric and radar techniques have been widely used to measure attenuation on Earth-space paths [Fedi *et al.*, 1974].

11.2 Radiometric measurements

With radiometric techniques, attenuation can be measured using the sun as a source, or can be estimated from measurements of sky-noise temperature.

Solar radiometry provides direct and sufficiently accurate measurements of attenuation over a wide dynamic range. However, the application of data obtained with this method is limited both by the motion of the sun and also by the fact that statistics derived therefrom may be biased by diurnal effects. In general, heavy precipitation events do not seem to be uniformly distributed over the day. Therefore the attenuation distributions obtained by observing the sun may have a limited validity.

Measurements of sky-noise temperature are more restricted in terms of the dynamic range within which attenuation at any frequency may be estimated with useful accuracy. However, they provide a simple means of obtaining attenuation statistics at any given elevation angle. But losses due to scattering are not adequately allowed for in this method and the attenuation may be underestimated. Caution should therefore be exercised in applying data obtained at frequencies at which the scattering contribution to the total attenuation is significant [Zavody, 1974]. Measurements made in the United Kingdom at frequencies in the range of 30 to 37 GHz have shown that the error in underestimating the attenuation is unlikely to exceed 15% of the dB figure in vertical polarization, and may reach 35% in horizontal polarization if the effect of scattering is ignored. At 20 GHz, however, the error in these same climatic conditions can probably be ignored for practical purposes [Chada and Lane, 1977].

11.3 Radar measurements

Another way of estimating attenuation on a slant path is the use of well-calibrated weather radar observations. The radar potentially has the ability to observe rain extending over large areas and heights [Crane, 1977]. The technique allows not only the estimation of rain attenuation statistics on a single Earth-space path, but also the estimation of joint attenuation statistics on two or more separate paths (site diversity) [Rogers, 1976].

Several types of radars have been used for this purpose, including single-frequency radars, dual-frequency radars, and dual-polarization radars. One inherent limitation of a single frequency radar is its inability to distinguish regions of rain from those of ice, the two having very different relationships between reflectivity and specific attenuation. The melting layer too may produce a significant contribution which cannot be estimated by the same means as used for rain. In the localized regions of intense rain, drop-size distribution changes may influence the relationship between attenuation and reflectivity.

One means of partially overcoming these difficulties is to use a single-frequency radar simultaneously with other observing instruments such as radiometers, distrometers, rain gauges and satellite beacons. The calibration of a radar with one or more of these devices allows the estimation of the attenuation statistics with high accuracy [Strickland, 1974; Hodge and Austin, 1977; Furuhashi *et al.*, 1980; Goldhirsh, 1980; McEwan *et al.*, 1980; Rogers *et al.*, 1980].

Another way to avoid errors due to the assumed relation between radar reflectivity and specific attenuation is to use two frequencies, one with high attenuation, and the other with negligible attenuation [Joss *et al.*, 1974; Yamada *et al.*, 1978]. This method has been shown to give directly a good measure of the rain attenuation at the frequency of high attenuation up to the melting layer [CCIR, 1978-82c].

The use of polarization diversity radar allows a distinction between rain and other hydrometeors [McCormick and Hendry, 1975]. In addition to making this distinction, another dual-polarization technique allows the characteristics of the drop-size distribution to be determined [Hall *et al.*, 1980]. This method has been shown to be a good predictor of attenuation on an Earth-space path, without that path necessarily originating at the radar site [Cherry *et al.*, 1980]. In particular, it is possible to evaluate separately the contributions to the attenuation due to rain and the melting layer, and to ignore regions of high reflectivity (but negligible attenuation) due to ice particles.

Radar techniques have now advanced to the point that they give a reliable and versatile way of estimating attenuation statistics, path diversity performance and frequency scaling relationships.

12. Propagation delay due to precipitation

In addition to causing attenuation, precipitation can also cause a propagation delay. Calculations of the specific phase delay and group delay through rain have been obtained from Mie scattering theory [Nuspl *et al.*, 1975]. These can be combined with rain rate statistics and estimates of effective path length (see § 4) to predict path delay statistics. A more flexible technique, and one less dependent on the drop-size distribution, is to combine delay/attenuation ratios with attenuation and rain rate statistics. However, because of possible errors due to the "resonance" behaviour of the curves of phase and group delay at high frequencies, it is recommended that these techniques only be used for frequencies below 15 GHz. The significance of rain delay variations on digital satellite communications systems is discussed in Report 564.

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REPORT 882

SCATTERING BY PRECIPITATION

(1982)

1. Introduction

Experimental observations and theoretical studies have shown that scatter caused by precipitation may establish a coupling between antennas provided that the radiation lobes of these antennas intercept a common volume in space and that precipitation occupies some part of the common volume [Crane, 1974; Awaka, 1978]. This scatter phenomenon is clearly not permanent but may play an important role in producing interference between earth stations and terrestrial stations.

Precipitation occurring anywhere within the intersection of the radiation lobes of two antennas will produce coupling. Precipitation is characteristically non-homogeneous. The space within the common volume contributing significantly to the scattering of the unwanted interference signal will correspond to the higher precipitation intensity cores within the small volume cells that occur at rain rates above 10 mm/h and to the thin layer of higher reflectivity (bright band) at lower surface rain rates (Report 563). The amount of coupling as described by the transmission loss between two antennas may be calculated using the bistatic radar equation [Crane, 1974]. The received signal level required for the calculation of transmission loss is obtained by integrating the scattering cross section per unit volume of the precipitation over the entire intersection volume of the radiation lobes of the antennas while taking into account the directivity of the antennas and attenuation due to the intervening precipitation.

The scattering cross section of an elemental volume contributing to the total scattered signal and the specific attenuation of any intervening rain are both directly related to precipitation intensity but produce opposing effects. The relative importance of the two factors in determining the net coupling depends on frequency. At frequencies up to about 8 GHz, an increase in rain rate produces a monotonic increase in coupling, while at much higher frequencies there is a maximum coupling for some intermediate rain rate. Awaka [1978] found a minimum in the transmission loss (maximum coupling) at a rain rate near 10 mm/h for a typical earth station-terrestrial station propagation geometry at frequencies in the 12 to 14 GHz range.

The lack of a monotonic relationship between rain rate and transmission loss complicates the estimation of a distribution function for transmission loss. In contrast to the calculation of an attenuation distribution which may be performed parametrically using either rain rate or the probability of exceeding that rain rate, the calculation of a transmission loss distribution must be made parametrically using rainfall intensity. The resultant transmission loss density function must be integrated to obtain the required distribution.

2. Calculation of coupling by scattering

The precipitation intensity varies markedly over relatively small distances. Observations show that rain can be characterized by volume cells or by thin bright band layers in larger regions of lower intensity (see Report 563). Coupling via precipitation scatter is produced primarily by the volume cells. In the directions of low antenna gain, the volume cells will define the scattering volume. When the common volume is defined by the intersection of the main lobes of the two antennas, coupling occurs when cells are within the common volume. If the cell is larger than the main lobe intersection volume, the antennas parameters define the scattering volume; when the cell is smaller than the main lobe intersection volume, the cell defines the scattering volume.

2.1 General equation

The integral representation of the bistatic scattering equation may be approximated by an equation describing the average scattering properties of the precipitation within the scattering volume [Crane, 1974]:

$$\frac{P_r}{P_T} = \frac{G_1 G_2 \lambda^2 \bar{\eta} V l}{(4\pi)^3 r_1^2 r_2^2} \quad (\text{in appropriate units}) \quad (1)$$

where

- P_r : received power,
- P_T : transmitted power,
- G_1, G_2 : antennas gains,
- $\bar{\eta}$: the average scattering cross section per unit volume,
- V : the scattering volume,
- l : loss produced by attenuation,

$$l = 10^{-\frac{1}{10} \left[\int_{r_1}^{r_2} (\gamma_R + \gamma_a) ds + \int_{r_2}^{r_1} (\gamma_R + \gamma_a) ds \right]}$$

- γ_a : the specific attenuation by atmospheric gases (Report 719),
- γ_R : the specific attenuation for rain (Report 721),
- λ : wavelength,
- r_1, r_2 : the distances between the antennas and the scattering volume.

All the foregoing quantities are expressed in consistent system of units.

2.2 Reflectivity

Scattering is predominantly produced by liquid drops below h_R (see Report 563) and ice and snow above. The radar reflectivity factor, Z , is used to characterize rainfall intensity for scattering computations. The radar reflectivity factor is defined as the sum of the sixth power of the diameters (melted) of the hydrometeors per unit volume and is usually expressed in units of mm^6/m^3 . The effective reflectivity factor, Z_e , is a parameter used to describe the scattering cross-section per unit volume of the precipitation.

$$Z_e = \frac{\lambda^4}{\pi^5} \frac{\bar{\eta}}{M |K|^2} 10^{+18} \quad \text{mm}^6/\text{m}^3 \quad (2)$$

where

- $\bar{\eta}$: scattering cross-section per unit volume (m^2/m^3),
- λ : wavelength (m),

$$|K|^2 = \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2 = 0.93 \text{ at a wavelength of } 0.1 \text{ m}$$

ϵ : relative permittivity of water,

M : polarization decoupling factor ($M = 1$ for radar observations).

At frequencies below 7 GHz, the scattering particles are small in comparison with the wavelength and Rayleigh scattering applies ($Z = Z_e$). Note that the relative permittivity of water is used in the expression for effective reflectivity when scattering is due to ice. At frequencies above 7 GHz, an allowance for the deviation from Rayleigh scatter may be included by using a factor $S = Z_e/Z$.

The effective reflectivity D_z is obtained from power measurements made with radar systems and is often expressed in decibels as:

$$D_z = 10 \log (Z_e/Z_0) \text{ dB}$$

where $Z_0 = 1 \text{ mm}^6/\text{m}^3$.

In rain, the reflectivity factor, Z , is related to rain rate by

$$Z = 400 R^{1.4} \quad \text{mm}^6/\text{m}^3 \quad (3)$$

for the Laws and Parsons drop size distributions.

The polarization decoupling factor is included to describe the anisotropy of precipitation scatter and the possibility of a mismatch between the polarization of the receive antenna and the scattered signal [Crane, 1974; Awaka, 1978; Sakagami, 1980]. In practice the polarization decoupling factor may be different from unity only for mainbeam-mainbeam coupling.

2.3 Scattering volume

Referring to Fig. 1, the scattering volume is defined by the intersection of the common volume of the antennas main lobes and the volume cell. The ice and snow within the cell and above the transition height for attenuation, h_R (see Report 563), contribute to scattering but not to attenuation. The rain both within and outside the cell contributes to the attenuation. For a specified distribution of precipitation within and outside the volume cell, the value of received power may be calculated. For a statistical estimate of the probability of occurrence of a fixed level of received power, the probabilities of occurrence of all possible combinations of volume cells within the common volume and rain along the paths between the cell and the antennas that combine to produce the specified received power must be determined and their composite probability of occurrence must be calculated. The resultant probability density can then be integrated to produce the required received signal level distribution.

The scattering volume, V , is defined by the antenna with the narrowest cross beam dimension, $r\theta$ where θ is the half-power beamwidth, at the range, r , of the volume cell and by the width of the volume cell, D_c ,

$$V \approx \frac{r_1^2 D}{G_1} \quad (4)$$

where antenna 1 has the smallest $r\theta$ value and $D = D_c$. The rain cell width is approximately 2.5 km (see Report 563). If the rain cell is larger than the common volume, $D_c > r_2\theta_2/\sin \alpha$ where α is the scattering angle, then $D = r_2\theta_2 \sin \alpha$.

2.4 Inclusion of attenuation in the calculation

The calculation of the effect of attenuation within the volume cell can be effected using the statistical properties of the cell. Attenuation in the rain region external to the cell must be separately calculated. Since the scattering and attenuation within the cell are calculated using cell data, the additional attenuation cannot be estimated using the several available point-to-path models. An adaption of the path profile model [Crane, 1980] can be used to approximate the additional attenuation for the special case of interference between widely separated earth station and terrestrial station antennas. The path profile may be integrated from one location to another along either antenna beam at varying distances from the volume cell. The resultant expression is:

$$A(d_1, d_2) = \frac{\gamma_R}{\alpha \cos \psi} \left[\frac{1}{u} (e^{uad_0} - e^{uad_1}) - \frac{e^{ba}}{c} (e^{cad_0} - e^{cad_2}) \right] \quad (5)$$

where

$$\gamma_R = kR^\alpha \text{ (see Report 721),}$$

ψ : elevation angle,

$$d_0 = d_1, d_1 \geq d_r,$$

$$d_0 = d_r, d_1 \leq d_r$$

where

$$\begin{aligned}d_i &= 3.8 - \log R \text{ km}, \\b &= 0.83 - 0.39 \log_e R, \\c &= 0.026 - 0.069 \log_e R, \\u &= b/d_i + c,\end{aligned}$$

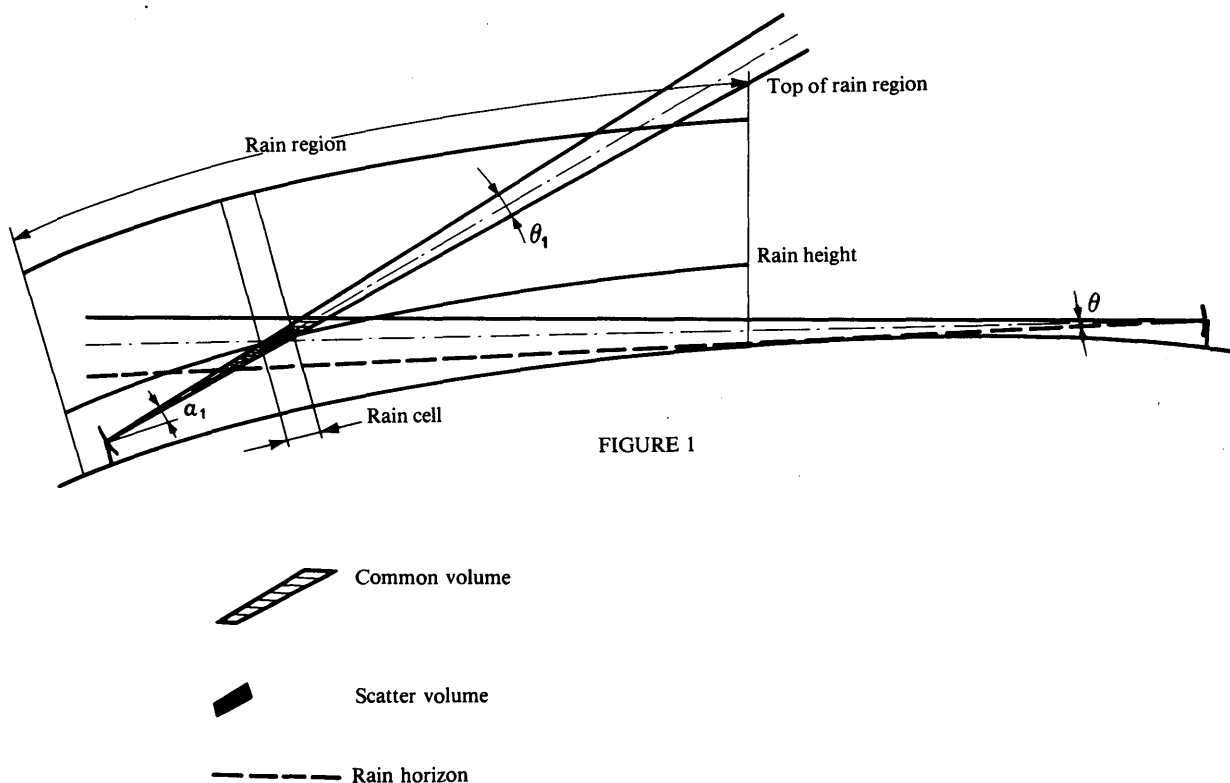
where $d_1 \leq d_2 \leq 22.5$ km are measured along the surface of the Earth from the centre of the volume cell.

3. Distribution function for coupling

The evaluation of the required distribution function is a meteorological problem requiring statistical information about the intensity and location of rain cells and the simultaneous occurrence of rain along the several propagation paths. The required data are not available and models must be employed to perform the required computations. The received signal level may be evaluated for the optimum position of a cell of size D_c within the common volume and the probability of occurrence of that value of received signal adjusted by the ratio of the size of the common volume to the size of the cell if the common volume is larger than the cell. This adjustment should only be made when the received signal from any cell positioned in the common volume is within 3 dB of the value for the cell in the optimum location.

4. Main-lobe to side-lobe coupling

Precipitation scatter coupling between antennas may occur between the main radiation lobes of each antenna (Fig. 1), between a main lobe and a side lobe or between the side lobes. Main-lobe to main-lobe coupling is most important because it can produce received signals of sufficient strength to cause interference for volume cells anywhere within the common volume. Main-lobe to side-lobe or side-lobe to side-lobe coupling is only important when the precipitation is located at one of the stations. If the two antennas are within line-of-sight, the line-of-sight side-lobe to side-lobe coupling will generally produce higher level signals than can be produced by precipitation scatter within the volume produced by main-lobe intersection.



5. Comparison of calculations with measurements

Precipitation occurs in many forms, the most important of which, for bistatic scattering, are rain, snow, melting snow and hail. The characteristics of scattering by rain and snow are reasonably described by the Rayleigh scattering theory; scattering by hail and melting snow are not. Measurements at 4 and 7 GHz [Crane, 1974] show general agreement between computations based on these equations and simultaneous radar measurements of radar reflectivity, Z , made at 1.3 GHz, within a combined measurement error of 0.9 dB r.m.s. These measurements included scattering by snow, melting snow and rain. Measurements of melting snow show a tendency for the transmission loss to be 10 dB lower for near-forward scattering. A similar result is expected for scattering caused by hail.

The experimental data available at present indicate that an analysis [Crane, 1974] based on the use of the Rayleigh scattering theory and the bistatic radar equations, predicts the measured transmission loss for precipitation scatter with an average error of less than approximately 2 dB for frequencies less than about 8 GHz. The agreement is even better if allowance is made for the effect of drop shape departures from Rayleigh scattering. Attenuation effects are not significant in interference problems below 8 GHz.

More detailed information on this topic is to be found in Report 569.

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REPORT 722-1 *

CROSS-POLARIZATION DUE TO THE ATMOSPHERE

(Study Programme 5C/5)

(1978-1982)

1. Introduction

To increase channel capacity without increasing bandwidth, orthogonal polarizations (linear or circular) may be independently used for transmission at the same frequency over the same path. However, "frequency re-use" may be impaired by the possibility that in propagating through the atmosphere, some of the energy transmitted in one polarization state can be transferred to the orthogonal polarization state, thus causing interference between the two channels.

This phenomenon, usually referred to as cross-polarization, may be caused both by rain and hydrometeors other than rain, and may occur during periods of multipath propagation; additionally, cross-polarization may arise due to the characteristics of the antenna systems at each terminal, and this cross-polarization component will then exist as a base level.

When two orthogonal polarizations a and b are transmitted at the same level, the ratio of the co-polarized signal (ac or bc) in a given receiving channel to the cross-polarized signal (bx or ax) in that channel, is known as the *cross-polarization isolation*, and this is of prime importance in systems engineering. These two ratios ac/bx and bc/ax are not necessarily the same. Propagation experiments on the other hand usually measure *cross-polarization discrimination*, which is the ratio of the co-polarized received signal ac to the cross-polarized received signal ax when one polarization only, a , is transmitted. That is to say that the co-polar signal ac , and the cross-polar signal ax , are each measured independently and in the absence of any orthogonally-polarized transmitted signal b . In the context of rain-induced cross-polarization, the above expressions ac/bx , bc/ax , and ac/ax may be considered to be all the same [Oguchi, 1975; Watson *et al.*, 1974]. Both the cross-polarization isolation (XPI) and cross-polarization discrimination (XPD) are normally expressed in decibels.

* This Report is brought to the attention of Study Groups 2, 4, 7, 8, 9, 10 and 11.

2. Cross-polarization due to rain

2.1 General

Experimental evidence has shown that as the size of the raindrops increase their shape departs from spherical and is similar to that of oblate spheroids with an increasingly pronounced flat base in which a concave depression develops for very large drop sizes [Pruppacher and Beard, 1970; Pruppacher and Pitter, 1971]. Furthermore, raindrops may also be inclined to the horizontal [Saunders, 1971]: the phenomenon of raindrop canting may be explained in terms of vertical wind gradients [Brussaard, 1976]. Consequently, a commonly accepted model for a falling raindrop is an oblate spheroid with its major axis canted to the horizontal and with deformation dependent upon the radius of a sphere of equal volume. It is commonly accepted that the raindrop canting angles vary randomly in space and time.

On the basis of measurements below 40 GHz, it appears that cross-polarization due to rain is primarily a coherent phenomenon [Oguchi, 1981; Olsen, 1981a]. In the generally accepted model of coherent propagation, cross-polarization occurs as a result of differential attenuation and differential phase shift between two orthogonal characteristic polarizations. The angle of these characteristic polarizations to the horizontal and "vertical" (i.e. the direction perpendicular to both the horizontal and the propagation path) is often termed the effective canting angle.

If the effective canting angle is zero, no cross-polarization occurs for horizontal and vertical polarizations on a horizontal path. Since the effective canting angle is near zero, the cross-polarization isolation is better on horizontal paths using vertical and horizontal polarizations than on such paths using tilted linear polarizations or circular polarization. Furthermore, since the effective canting angle appears to decrease with increasing altitude, the cross-polarization using vertical and horizontal polarizations on horizontal paths appears to be less significant on propagation paths well above the surface [Oguchi, 1975].

Depolarization occurs for circular polarization for all values of the effective canting angle. Moreover, cross-polarization depends on the angle between the propagation direction of the incident wave and the axis of the oblate raindrops, and is maximum when this angle is 90° (i.e., for horizontal paths).

Extensive calculations, based on a model for equi-oriented falling raindrops, of differential attenuation and differential phase shift are available for rain rates up to 150 mm/h and for frequencies up to 100 GHz [Chu, 1974; Oguchi and Hosoya, 1974; Oguchi, 1977]. The relative contribution of differential attenuation and phase shift is different at different frequencies. Differential phase shift appears to be the dominant factor in rain-induced cross-polarization at frequencies below 10 GHz (at which significant cross-polarization is possible even for low values of attenuation), and differential attenuation becomes increasingly important at higher frequencies.

Once the differential attenuation and phase shift for the equi-oriented raindrop model are known for the various frequencies and rain rates, a knowledge of the distribution of canting angles of the raindrops is needed for the evaluation of cross-polarization discrimination.

2.2 Prediction methods

Most prediction methods now in use are semi-empirical [Olsen, 1981a]. They are modelled on general theories for rain media of randomly-canted raindrops [Olsen, 1981b] with parameters fitted to give approximate agreement with experimental data. A two-parameter model based on a Gaussian distribution of raindrop canting angles is commonly assumed [Kobayashi, 1977; Nowland *et al.*, 1977; Dilworth and Evans, 1979; Chu, 1980].

2.2.1 General expressions

For most practical applications, relations between cross-polarization discrimination (XPD) and the co-polarized path attenuation (CPA) are of utmost importance in predictions based on attenuation statistics. In early applications empirical relations were employed and are still in use to some extent [Morita, 1976]. It is now more common, however, to use semi-empirical relations. A general relationship between XPD and CPA has not yet been fully established, but long-term measurements in the frequency range between about 3 and 37 GHz [Olsen, 1981a] are in approximate agreement with a semi-empirical relation of the following general form [Olsen and Nowland, 1978].

$$XPD = U - V \log (CPA) \quad \text{dB} \quad (1)$$

where

$$U = C(f) + D(\epsilon) + \kappa^2 + I(\tau) \quad (2)$$

$$V = V(f) \quad (3)$$

In this relation the coefficients U and V depend primarily on the frequency f (in GHz), the path elevation angle ϵ , and the polarization tilt angle τ (for linear polarization) relative to the horizontal.

Although the coefficients $C(f)$ and $V(f)$ depend primarily on frequency, they also depend to some extent on the raindrop size distribution, the drop-shape distribution, and the drop temperature. Several models for C and V have been suggested [Olsen and Nowland, 1978; Dissanayake *et al.*, 1980; Cox, 1981], all based on a deterministic relation between the drop shape and volume. The differences in the models are due primarily to the different drop-shape models assumed [Olsen, 1981a] and do not significantly affect the accuracy of equation (1). The coefficient C is approximately logarithmic over a wide range of frequencies and can be approximated by:

$$C(f) = 30 \log(f), \quad 8 \leq f \leq 35 \text{ GHz} \quad (4)$$

for a Pruppacher-Pitter drop-shape model, a Laws and Parsons drop-size distribution, and a rain temperature of 20 °C [Olsen and Nowland, 1978]. The coefficient V is currently assumed to remain constant over a range of frequencies, although it actually varies continuously in frequency, with a value of about 20 at 12 GHz and about 23 at 30 GHz.

There is widespread acceptance [Cox, 1981; Olsen, 1981a] that the term $D(\epsilon)$ varies approximately in elevation angle by:

$$D(\epsilon) = -40 \log(\cos \epsilon) \quad (5)$$

The term κ^2 in equation (2) is believed to depend primarily on the degree of random spread of the raindrop canting angles averaged along the path, although it will also depend on other factors such as drop shape and path elevation angle. As the degree of random spread increases, so does κ^2 and therefore XPD. For a Gaussian model of the raindrop canting angle distribution, $\kappa^2 = 0.0053 \sigma^2$ (σ in degrees), where σ has been termed the effective standard deviation of the raindrop canting angle distribution [Olsen and Nowland, 1978]. However, because of the dependence of κ^2 on several factors, caution should be exercised in attaching physical significance to σ strictly in terms of the canting angle distribution.

The factor $I(\tau)$ in equation (2) is approximately the improvement of linear polarization with respect to circular polarization. Two models have been proposed. The earliest model [Olsen and Nowland, 1978]:

$$I(\tau) = -20 \log(\sin^2 |\varphi - \tau|) \quad \text{dB} \quad (6)$$

gives unrealistically large values of I for $|\varphi - \tau|$ less than a few degrees ($\tau = 45^\circ$ for circular polarization), where φ is the effective raindrop canting angle (i.e., area path average). A more recent model [Chu, 1980; Olsen, 1981b]:

$$I(\tau) = -10 \log \frac{1}{2} \left[1 - \cos(4\tau) e^{-\kappa_m^2} \right] \quad (7)$$

gives more realistic results for all values of τ . In this model, φ is assumed to vary randomly within a rain storm and from storm to storm, and to have a Gaussian distribution with zero mean and standard deviation σ_m , where:

$$\kappa_m^2 = 0.0024 \sigma_m^2 \quad (8)$$

(σ_m in degrees)

Depending on the value of σ_m , it gives nearly identical results to equation (6) when $\varphi = 0$ and $10^\circ < \tau < 80^\circ$. Because of the complexity of the problem, caution should again be exercised in attaching physical significance to σ_m strictly in terms of the canting angle distribution.

The improvement factor I in equation (2) is usually assumed to remain constant for any path orientation and for any attenuation. However, there is evidence that on at least some paths the parameter φ (and possibly κ^2) is dependent on rain intensity [Butler, 1981; CCIR, 1978-1982a]. This results in a dependence of I (and therefore of U) on CPA. The same evidence also suggests that the dependence of I on attenuation does not change the logarithmic form of equation (1), but in effect results in a value of V that can differ significantly from 20, particularly on some terrestrial paths.

Semi-empirical prediction techniques that employ relations between XPD and point rain rate have also been proposed [Olsen and Nowland, 1978; Chu, 1980]. Although not extensively evaluated yet, these techniques may be used to estimate the total cumulative distribution of XPD from the point rain rate distribution and estimates of the effective path length through rain (see Report 721). They are particularly useful at frequencies below about 6 GHz where measured rain attenuation statistics are not usually available. From the relations between XPD and rain rate, it is apparent that XPD decreases as $-20 \log f$ between about 4 and 35 GHz.

Although relations of the form (equation (1)) are being used to predict the total cumulative distributions of XPD from cumulative distributions of CPA , more generally a joint distribution of XPD and CPA may be desired in future design applications. This appears to be particularly important for Earth-space links with small attenuation margins, since XPD varies over a wider range for small values of CPA .

Equation (1) applies only to cross-polarization induced by rain. For links in which the antennas do not have good cross-polarization isolations, the equation is valid only at sufficiently high attenuations. For accurate calculations at low attenuations or in systems in which the antennas are poor or there is misalignment, prediction techniques based on more general theory for propagation between imperfect antennas must be used [Shkarofsky, 1978].

2.2.2 Application

For application to dual-polarized terrestrial systems which normally employ horizontal and vertical polarizations, the last two terms of equation (2) can be combined into a single parameter $U_0 = \kappa^2 + I$. This resultant parameter is quite variable from one path to another even when averaged over a long period of time and seems to be dependent on the height of the path above the surface, path length and the orientation of the path relative to the prevailing wind direction [Oguchi, 1975; Olsen, 1981a].

A value of $U_0 = 9$ appears to provide a lower bound for all measurements of XPD for attenuations greater than about 15 dB [Rooryck and Battesti, 1975]. It should be noted, however, that median or equi-probability fits to some XPD data can give improvements of more than 10 dB relative to this lower bound [e.g. Morita *et al.*, 1973; Rooryck and Battesti, 1975; Watson, 1976]. Values of U_0 for several paths can be obtained from compilations of various experimental measurements [Oguchi, 1975; Olsen, 1981a].

For application to dual-polarized satellite systems, a value of $\kappa = 0$ appears to be sufficiently conservative. However, values of κ corresponding to σ as high as 30° have been suggested [Chu, 1980; Cox, 1981]. A value of κ_m , corresponding to $\sigma_m = 5^\circ$, would appear to give a sufficiently conservative maximum improvement of $I = 15$ dB for $\tau = 0^\circ$ or 90° . Again, higher improvements have been observed [Chu, 1980; Cox, 1981].

3. Cross-polarization due to ice crystals

3.1 General

Cross-polarization due to ice crystals above the melting layer has been observed on slant paths from measurements using satellite beacons [Bostian and Allnutt, 1979; Cox, 1981] and polarization-diversity radars [Hendry and McCormick, 1976; McCormick and Hendry, 1977]. This effect, which is due to differential phase shift, has been shown from the beacon measurements to be considerable even in the absence of significant attenuation and cross-polarization due to rain. Moreover, abrupt changes in the XPD have been observed to coincide with lightning strokes [McEwan *et al.*, 1977; Howell, 1977], suggesting a change in the alignment of the ice crystals. This has been supported by polarization diversity radar measurements of changes in the alignment of ice particles [Hendry and McCormick, 1976].

For large percentages of the time with significant depolarization by ice, the ice crystals appear to have their major axes in the horizontal plane, so that depolarization is minimized for horizontal and vertical polarizations [Cox, 1981]. Several ice-crystal shapes have been observed [Heymsfield and Knollenberg, 1972], but it is not yet clear which cause the largest cross-polarization. Furthermore, it has not yet been established what the alignment mechanisms are, although both aerodynamic-gravitational and electrostatic forces, or a combination thereof, have been suggested [Bostian and Allnutt, 1979]. For the small percentages of time with ice depolarization in which the major axes of the crystals are not contained in the horizontal plane, the strong electrostatic fields in thunderstorms appear to be involved.

The frequency of occurrence and severity of ice crystal depolarization appears to vary with climate and geography, being greater in maritime climates than continental climates [Bostian and Allnutt, 1979; Cox, 1981]. The greater severity in maritime climates has been attributed to the larger ice crystals which form in these climates.

3.2 Models

Although no prediction methods based on meteorological data have been developed, models have been employed for estimating the potential impact of ice-crystal depolarization on systems [Bostian and Allnutt, 1979]. It is commonly accepted that a Rayleigh scattering model for various crystal shapes is applicable up to about 20 or 30 GHz. For this model the frequency dependence of XPD is identical to that for rain, decreasing with increasing frequency as $-20 \log f$. It has therefore been suggested that the effects of ice-crystal depolarization on the overall XPD be accounted for by the addition of a constant [Chu, 1980].

4. Cross-polarization due to other hydrometeors

Dry snow on paths near the ground appears to exhibit some of the same depolarization characteristics as ice crystals on slant paths. It causes significant differential phase shift but little differential attenuation [Hendry *et al.*, 1976]. Moreover, it produces more depolarization than rain for the low attenuation levels characteristic of dry snow [Zufferey, 1976; Dilworth and Evans, 1978]. Wet snow appears to produce differential attenuation rather than differential phase shift, and to be a less significant polarizing medium than rain at all polarizing levels [Watson, 1976; Gutteberg, 1981].

Polarization-diversity radar measurements have shown that the differential phase in heavy snow may be considerably larger on slant paths with elevation angles of 10° to 30° than on terrestrial paths at small elevation angles [Hendry *et al.*, 1980]. This has been attributed to changes in the form of snow with height. Differential propagation effects within the melting layer appear to be small in comparison to the effects of intense rain.

5. Cross-polarization during clear-air conditions

5.1 Mechanisms

5.1.1 General

Virtually all observations of severe deterioration of XPD during clear-weather conditions have been associated with the deep fading of the co-polarized signal that occurs during multipath conditions on terrestrial paths. On many links, the cross-polarized signal has been observed to be quite well correlated with the co-polarized signal for small fade depths, whereas it is not well correlated during the time intervals of deep fades.

Several possible cross-polarization mechanisms have been suggested for the reduction in XPD that can occur, particularly during conditions of multipath fading [Olsen, 1981c]. These mechanisms can be divided into two groups: those in which the cross-polarized patterns of the antennas do not play a role and those in which they have a role.

The mechanisms of the first group are those in which a scattering or reflecting medium produces a cross-polarized scattered wave in addition to a co-polarized wave. Three possibilities have been suggested:

- (a) depolarization of the co-polarized signal by turbulent non-homogeneities along the path
- (b) depolarization of an indirect component of the co-polarized signal due to reflection from a tilted atmospheric layer, and
- (c) depolarization of an indirect component of the co-polarized signal due to scattering or reflection from the ground or water surface along the path.

In the second group of mechanisms, the cross-polarization is caused not by any propagation medium alone, but by the additional effects of the cross-polarized patterns of the antennas:

- (d) coupling of an indirect component of the signal reflected from (or refracted through) an atmospheric layer via the cross-polarized patterns of the antennas;
- (e) the same as (d) but with reflection from the ground or water surface;
- (f) the same as (d) but with multiple reflections between the ground and the atmosphere; and
- (g) refractive bending of the direct wave into the receiving antenna at an off-axis angle.

Several mechanisms in this group have been investigated experimentally or by means of computer simulations.

5.1.2 Influence of the cross-polarized patterns of the antennas

All of these mechanisms will occur to some extent, but the available evidence suggests that one or two are dominant during extreme reductions in XPD. In all cases the most severe reductions in XPD are associated with multipath fading of the co-polarized signal. On the basis of measurements with two or more receiving antennas with different cross-polarized patterns [Martin and Casanova, 1974; Valentin, 1974; Rooryck and Martin, 1977; Sakagami and Morita, 1979; Morita *et al.*, 1979], the dominant cross-polarization mechanisms appear to be the two multipath mechanisms (atmospheric or surface) that

interact with the cross-polarized patterns of both the transmitting and receiving antennas. Which of these is the most significant is not clear, and may be different for overland and overwater paths. Moreover, these mechanisms may have an approximately equal role on some paths and interaction between the surface and an atmospheric layer (a ground-based duct in the extreme case) may be significant. It has been suggested [Olsen, 1981c] that because of the peculiar side-lobe structure of the cross-polarized patterns on some antennas, the surface-reflected wave may affect the cross-polarized signal more than it does the co-polarized signal.

Early work [Ghobrial and Watson, 1973] demonstrated the importance of the absolute side-lobe levels of the cross-polarized antenna patterns. Several other investigators suggested that a relatively flat cross-polarized antenna pattern is also important for minimizing cross-polarization during clear-weather conditions [Martin and Casanova, 1974; Sakagami and Morita, 1979]. It has recently been suggested that the phase-shift pattern between the co- and cross-polarized channels is also significant and that the overall requirement for minimizing cross-polarization during multipath fading is for cross-polarized amplitude and phase patterns to be similar to the co-polarized patterns within the angle-of-arrival range of the multipath rays [Morita *et al.*, 1979; Olsen, 1981c]*.

5.2 Prediction methods

In one semi-empirical model [Inoue, 1975] the total cumulative distribution of XPD was predicted from a theoretical evaluation of surface multipath and refractive-bending mechanisms. Such an approach seems too complicated for situations involving atmospheric multipath. All other methods, therefore, predict the statistical form of the distribution without any reference to the mechanisms. Three methods have been suggested, two of which predict the conditional distribution of XPD for a given attenuation of the co-polarized signal and a third which predicts the total distribution.

One of the first two methods uses a log-normal law for the conditional distribution of the cross-polarized signal level [Battesti and Constantinidis, 1975; Martin, 1977; Rooryck and Martin, 1977]; the other uses a Rice-Nakagami law [Lin, 1977; Mottl, 1977]. The latter Rice-Nakagami distribution reduces to a Rayleigh distribution for large fade depths. Both methods require two empirical parameters and appear to give relatively good agreement with the particular experimental results on which they were based. The similarities and differences between these methods have recently been evaluated [Olsen, 1981c]. The third prediction method employs a Rayleigh distribution for the total cumulative distribution of XPD [Morita *et al.*, 1979].

One similarity between the first two methods is the approximate relationship between CPA and conditional statistics of XPD for large fade depths. In the method based on a log-normal law the empirical relationship [Martin, 1977]:

$$XPD_{median} \approx - CPA + C_1 \quad \text{for } CPA > 15 \text{ dB} \quad (9)$$

was obtained for the conditional median. In that based on a Rice-Nakagami distribution, the approximate theoretical relationship in terms of the root-mean-square (r.m.s.) value of XPD for large values of CPA applies [Olsen, 1981c]:

$$XPD_{r.m.s.} \approx - CPA + C_2 \quad (10)$$

The relationship:

$$XPD \approx - CPA + C_3 \quad (11)$$

between equi-probable values of XPD and CPA has also been found for large fade depths, and the slope of -1 shown to be a consequence of Rayleigh distributed co-polarized and cross-polarized signal amplitudes [Morita *et al.*, 1979]. When the coefficient C_3 was expressed as:

$$C_3 = XPD_0 + Q \quad (12)$$

where XPD_0 is the static value of XPD during unfaded conditions, the coefficient Q was found to be inversely related to the slope of the vertical cross-polarization antenna pattern.

A comparison of the relations (9), (10) and (11), based on one set of data, showed the differences between the coefficients C_1 , C_2 and C_3 to be less than 2 dB [Olsen, 1981c]. Because of this small difference and because these coefficients appear to be fundamental empirical parameters, experimentally obtained values are tabulated in Tale I, along with other relevant information. Administrations are urged to add additional information to this Table, including the corresponding information on the vertical cross-polarization patterns.

* Administrations are urged to investigate further the relative importance of the various mechanisms and the means for alleviating the effects of the most severe ones. Particular attention should be given to measurement of the two-dimensional amplitude and phase patterns of the antennas employed in experiments.

TABLE I – Values of empirical parameters C_1 , C_2 and C_3 and associated experimental information

Reference	Frequency (GHz)	Path length (km)	Transmitted polarization(s)	Period	C_1 , C_2 , C_3	XP_{D0} (dB)	$S^{(1)}$ (dB/deg.)	Remarks
Inoue [1975]	4.15	37.2	Horizontal	Winter 1971 (130 h)	35	> 30	-	C_3 estimated from XP_{D}/CPA equi-probability curve
	6.72	37.2	Circular	Autumn 1971 (130 h)	30	> 30	-	C_3 estimated from XP_{D}/CPA equi-probability curve
Lin [1977]	6.0	42.5	Vertical	Aug. 1974 to Feb. 1975	47.6	25.9	-	C_2 calculated from r.m.s. XP_{D} data
	11.6	42.5	Vertical	Aug. 1974 to Feb. 1975	36.3	19.5	-	C_2 calculated from r.m.s. XP_{D} data
	11.5	25.6	Vertical	Aug. 1974 to Feb. 1975	45.3	42.7	-	
Martin [1977]	7	50	Vertical and horizontal	5 Aug. to 5 Sept. 1973	52.5	40	50	Receiving antenna with relatively sharp cross-polar pattern. C_3 estimated from median XP_{D} data
	7	50	Vertical and horizontal	5 Aug. to 5 Sept. 1973	57	41	6	Receiving antenna with relatively flat cross-polar pattern. C_2 estimated from median XP_{D} data
Morita <i>et al.</i> [1979]	4.15	44.1	Horizontal	Apr. 1977 to Dec. 1978	45	45	110	Receiving antenna with sharp cross-polar amplitude pattern. C_3 estimated from XP_{D}/CPA equi-probability curve
	4.15	44.1	Horizontal	Apr. 1977 to Dec. 1978	54	42	17.5	Receiving antenna with relatively flat cross-polar amplitude patterns. C_3 estimated from XP_{D}/CPA equi-probability curve
	4.15	44.1	Horizontal	Apr. 1977 to Mar. 1978	54	37	7.5	Receiving antenna with very flat cross-polar amplitude and phase patterns. C_3 estimated from XP_{D}/CPA equi-probability curve
Butler [1981]	10.80	16	Vertical	May-Sep. 1979	39	35	-	C_2 calculated from r.m.s. XP_{D} data
	11.08	16	Horizontal	May-Sep. 1979	39	33	-	C_2 calculated from r.m.s. XP_{D} data
	16.53	16	Vertical	May-Sep. 1979	38	33	-	C_2 calculated from r.m.s. XP_{D} data
	16.81	16	Horizontal	May-Sep. 1979	37	40	-	C_2 calculated from r.m.s. XP_{D} data
Nadenenko and Sviatogor [1981]	4	55.7	Vertical	Jul.-Aug. 1979	-	27	-	Value of $C_3 = 27$ obtained, with slope of -0.6 instead of -1 . Path clearance of 13 m for $k = 1$

⁽¹⁾ S : slope of antenna cross-polarization pattern in the vertical plane near the bore sight (e.g. $\pm 0.1^\circ$).

6. Model-oriented cross-polarization measurements

From an experimental point of view, depolarization phenomena can be studied using two different approaches [Capsoni *et al.*, 1980]. The first one, which may be termed system design oriented, consists in directly measuring cross-polarization with an experimental arrangement as similar as possible to an envisaged radio system. In this approach as applied to terrestrial systems, the primary emphasis is on obtaining cumulative statistics of the cross-polar isolation or discrimination for horizontal and/or vertical polarization. The second approach, which may be termed model oriented, aims at characterizing the physical properties of the depolarizing medium in order to establish models which can be subsequently employed in systems design. This approach can lead to a different experimental set-up than the envisaged configuration of an actual system. However, it has the advantage of allowing a better understanding of cross-polarization, which can eventually provide information applicable to any system configuration.

Actual experimental measurements have rarely followed either of these extremes, but have usually been a combination of the two approaches. Thus, although most early measurements utilized horizontal or vertical polarization (or both), there was often considerable emphasis in expressing the results in terms of models [Oguchi, 1975]. More recently, as the characteristics of the medium have become better understood and as better models have been developed, there has been a trend toward measurements that are more model-oriented in their approach [Cox, 1981; Olsen, 1981a].

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RECOMMENDATION 581

THE DEFINITION OF "WORST MONTH"

(1982)

The CCIR,

CONSIDERING

- (a) that performance criteria for radio communication systems usually refer to "any month" as the period of reference;
- (b) that for the design of such systems it is necessary to collect statistics of propagation effects that are relevant to the period of reference of the performance criteria;
- (c) that consequently there is a need for an unambiguous definition for the period of reference, which is meaningful for statistical studies,

UNANIMOUSLY RECOMMENDS

1. that "any month" is understood to be the worst month of a year in terms of overall system performance;
2. that for a preselected threshold for any performance degrading mechanism the worst month of a year is defined as that month in a period of twelve consecutive calendar months, during which the threshold is exceeded for the longest time. The worst month is not necessarily the same month for all threshold levels;
3. that the fraction of time during which a preselected threshold is exceeded in the worst month of a year is referred to as "the annual worst-month time fraction of excess";
4. that the statistic relevant for the performance criteria referring to "any month" is the long-term average of the annual worst-month time fraction of excess.

Note. — Report 723 presents a method for the estimation of the ratio of the average annual worst-month time fraction of excess to the average annual time fraction of excess and summarizes measured values of this ratio.

REPORT 723-1 *

WORST-MONTH STATISTICS

(Question 2/5)

(1978-1982)

1. Introduction

This Report pertains to worst-month statistics of any propagation phenomenon or of any radiometeorological parameter. The calendar month is recommended as a convenient basis for specifying the monthly probability values.

The concept of the worst-month is of importance to the designers of telecommunication systems who have to meet percentage of "any month" performance criteria. The requirement is for a procedure to estimate the percentage of time within a month that a preselected threshold is exceeded. The percentage of time within the worst-month of a year, is of most interest.

This Report proposes a definition for the worst-month, and presents a procedure for estimating the ratio of percentage of time of the worst-month that a preselected threshold is exceeded to the average annual percentage that the same threshold level is exceeded.

* This Report is brought to the attention of Study Groups 1, 2, 4, 7, 8, 9, 10, 11 and the CMV.

2. Concept of worst-month

For a preselected threshold, the worst-month is defined as that month with the highest probability of exceeding that threshold. A worst-month can therefore be established for each threshold level. The statistic of interest is the highest monthly probability of exceeding the preselected threshold in one year. This worst-month statistic requires that the threshold be specified.

A specification of the worst-month for any year requires a knowledge of the monthly probability values for exceeding the preselected threshold for each month within that year. For ease of description, let X_{ij} be the probability of exceeding a threshold level j in the i th month. The worst-month for level j is the month with the highest X_{ij} value, X_{hj} . The calendar month to which X_{hj} belongs may vary from one threshold to another. The worst-month distribution for a particular year is given by X_{hj} as a function of j and is the envelope of the highest monthly probability value of all the monthly cumulative distributions from that year.

The worst-month statistic may be estimated from the observed worst-month values, X_{hj} , obtained from a record of many years. It is better to estimate the statistic using a full set of monthly probability values, X_{ij} , because more information is used providing a more reliable estimate of the extreme value of interest [Gumbel, 1957]. Since in many instances the occurrence of the rare events of interest may be spatially independent if a sufficient spacing exists between the observation locations, observations of X_{ij} from more than one location should be pooled. Caution should be exercised however to insure that the observations are for similar climate and propagation conditions.

An underlying assumption behind the construction of the worst-month statistic is that the rare events of interest can occur at random within any month. The statistical occurrence estimate does not depend on the start or stop time of a "month". The worst-month statistic then applies to a calendar month or to any 30-day period within a "year" of 12 consecutive months.

The "average annual worst-month distribution" is defined by taking the averages of the individual annual worst-month time fractions of excess for each level j .

In practice, most phenomena of interest occur during a limited number of months in a year. Let M be that limited number. The probability that X_{ij} will exceed X_j during one of the M months is $P(X_j)$. The probability that the worst-month value X_{hj} is greater than X_j is then given by:

$$F(X_j) = 1 - (1 - P(X_j))^M \quad (1)$$

3. Analysis of the definition

Examples of cumulative distribution functions of monthly probabilities of exceeding preselected thresholds, X_j , are given in Figs. 1 and 2. Attenuation measurements made at different frequencies in Switzerland [Fiechter, 1974] showed that the distribution of X_j could be approximated by an exponential function. Figure 1 shows the results of measurements carried out at a frequency of 11 GHz over a 120 km path. Qualitatively, the same results were observed at other frequencies where refractive effects were dominant. Figure 2 shows in a similar way the result of long-term measurements carried out using rapid response rain-gauges in the Netherlands [Mawira, 1980].

Using the exponential model to fit the tail of the distribution, the statistic of interest, the average annual-worst-month excess may be obtained. Results for an exponential distribution function are given here for ease of application. The required values needed to estimate the statistic of interest can also be obtained from the empirical distribution function if sufficient data are available.

The statistic of interest is the average value of X_{hj} where the cumulative distribution $F(X_j)$ is given by (1) above.

Using the exponential model:

$$P(X_j) = \begin{cases} C_{0j} e^{-X_j/C_{1j}} & \text{for } M \text{ months} \\ 0 & \text{for } (12 - M) \text{ months} \end{cases} \quad (2)$$

the average worst-month time fraction of excess $\overline{X_{hj}}$ for each level j can be calculated [Brussaard and Watson, 1979].

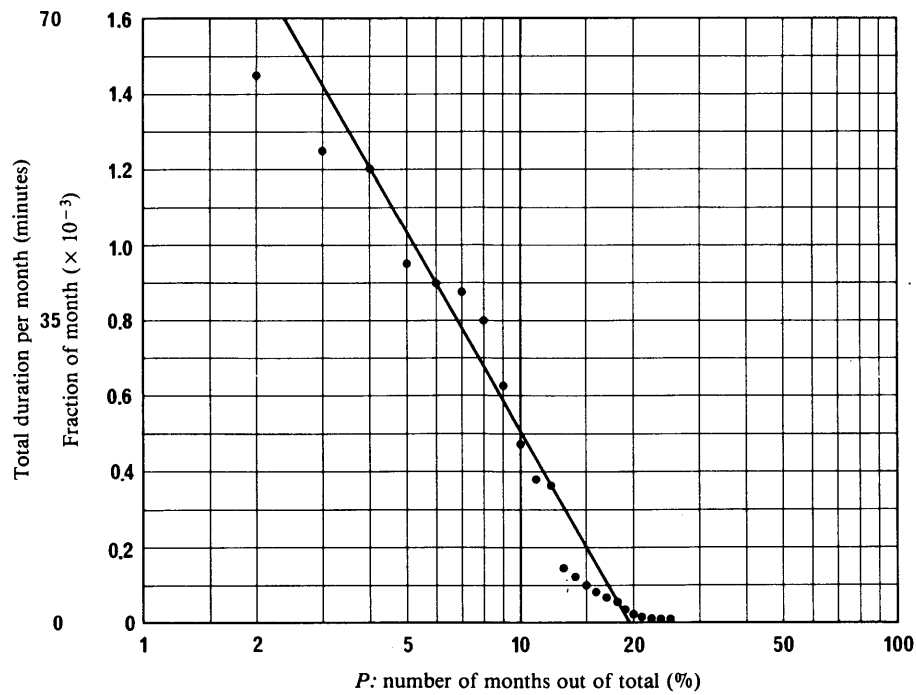


FIGURE 1 – Probability *P* of attenuation threshold being exceeded for the indicated fraction or total time per month [Crane and Debrunner, 1980]

11 GHz
31 months
Attenuation threshold 29 dB
below median value

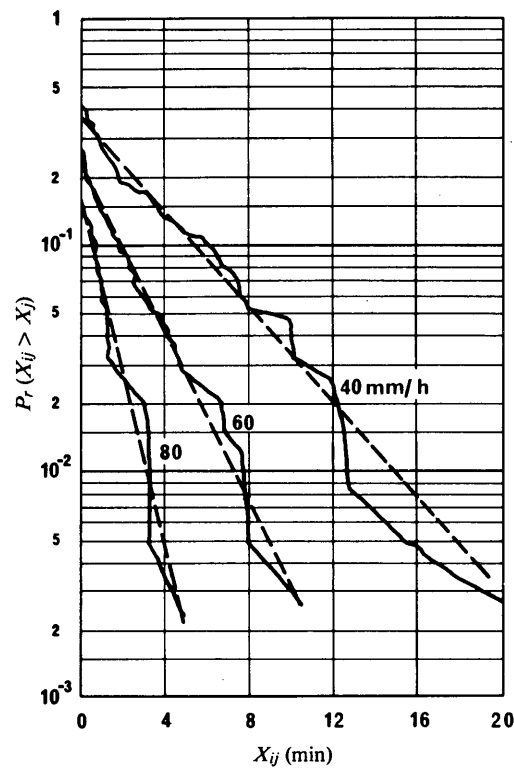


FIGURE 2 – Cumulative distributions of the monthly durations that given rain-rate thresholds are exceeded [Mawira, 1980]

Point rain-rates: 40 mm/h, 60 mm/h, 80 mm/h
331 monthly distributions; 3/1972 to 2/1978

In many cases it is desirable to relate this statistic to the annual probability of exceeding the same threshold in an average year, Y_j . The ratio of the percentage of time the threshold is exceeded in the worst-month, to the percentage of time it is exceeded in an average year, is given by:

$$Q_j = \frac{\overline{X_{hj}}}{Y_j} \quad (3)$$

For the exponential model,

$$Y_j = \frac{M}{12} C_{0j} C_{1j} \quad (4)$$

The ratio is given by:

$$Q_j = 12 \sum_{k=0}^{M-1} (-1)^k \binom{M-1}{k} \frac{C_{0j}^k}{(k+1)^2} \quad (5)$$

From an ensemble of monthly distributions it is easy to estimate the average monthly probability of occurrence of a value that exceeds a given threshold. In the exponential model this probability is given by:

$$\overline{C_{0j}} = \frac{M C_{0j}}{12} \quad (6)$$

Figure 3 shows Q_j , as calculated from (5), as a function of $\overline{C_{0j}}$ for various values of M [Mawira, 1980]. It is clear from the curves that Q_j is not strongly dependent on variations in M for a given value of $\overline{C_{0j}}$.

4. Application

Results of long-term observations of rainfall intensity obtained in the Netherlands [Mawira, 1980], radiometric measurements of slant-path attenuation by the European Space Agency [Brussaard, 1977 and 1979], and three years of measurements in Switzerland [Hofmann, 1979], are shown in Fig. 3 for comparison with the model calculations. From the excellent agreement it appears that the exponential model produces an accurate estimate of Q_j from a knowledge of C_{0j} . These results also show that an accurate knowledge of the seasonal behaviour, as given by the factor M , is not required for the estimation of the conversion factor Q_j .

In order to obtain experimental values of average annual worst-month time fraction of excess, the worst monthly time fraction that the threshold in question is exceeded is to be taken for each year of observation. The required value is the average of all the individual annual worst-month values thus obtained. This average worst-month time percentage is divided by the average yearly time percentage that the same threshold is exceeded to obtain the conversion factor Q_j .

Using the exponential model it is also possible to obtain an estimate of the long-term average value of Q_j from the ensemble of monthly observations. In order to do so, for each threshold level of interest the cumulative distribution of monthly time fractions of excess is to be constructed in a form such as given in Figs. 1 and 2. An exponential fit through these empirical distributions yields the average cumulative probability of excess, $\overline{C_{0j}}$. Then using Fig. 3 the factor Q_j can be estimated. As the full ensemble of monthly observations is used in this procedure statistical stability may be obtained sooner by this method than by averaging individual worst-month distributions as outlined above. For simplicity, the subscript j will be omitted in the following sections.

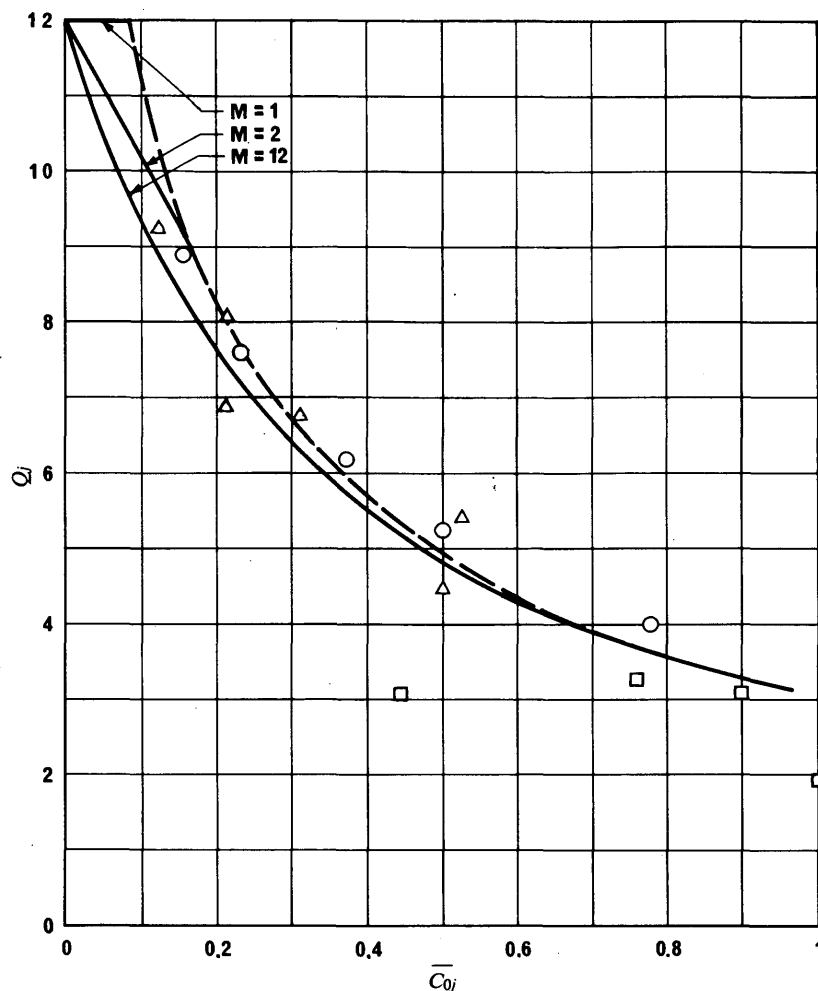


FIGURE 3 – Ratio of annual-worst-month to average annual excess, Q_j , as a function of the average monthly probability of exceeding a given threshold $\bar{C}_{0j}$

- Mawira [1980] (rain rate and rain attenuation)
- △ Brussaard [1977 and 1979] (rain attenuation)
- Hofmann [1979] (rain attenuation)
- — — — Envelope for all values of M

5. Results

5.1 Precipitation effects

Figure 4 presents some observations of the ratio Q of the average annual worst-month probability to the average annual probability as a function of the average annual probability Y . Climatic effects can be seen to be influencing the results.

Detailed examination of rainfall rate statistics over a wide range of intensity thresholds indicates that the worst-month versus annual probability relationship may be closely approximated by a power law [Segal, 1980] of the form

$$Q = AY^{-\beta}$$

Values of $A = 1.64$ and $\beta = 0.130$ yield worst-month ratios in good agreement with average values for different locations in North America and Europe [Fedi, 1979; Mawira, 1980; Segal, 1980]. The observed range of the coefficients for individual locations is $1.20 \leq A \leq 3.30$ and $0.167 \geq \beta \geq 0.074$, respectively. It has been observed that the Q versus Y relationship for rain attenuation is similar to that for rainfall intensity at the same location [Brussaard, 1979; Damosso *et al.*, 1980; Mawira, 1980].

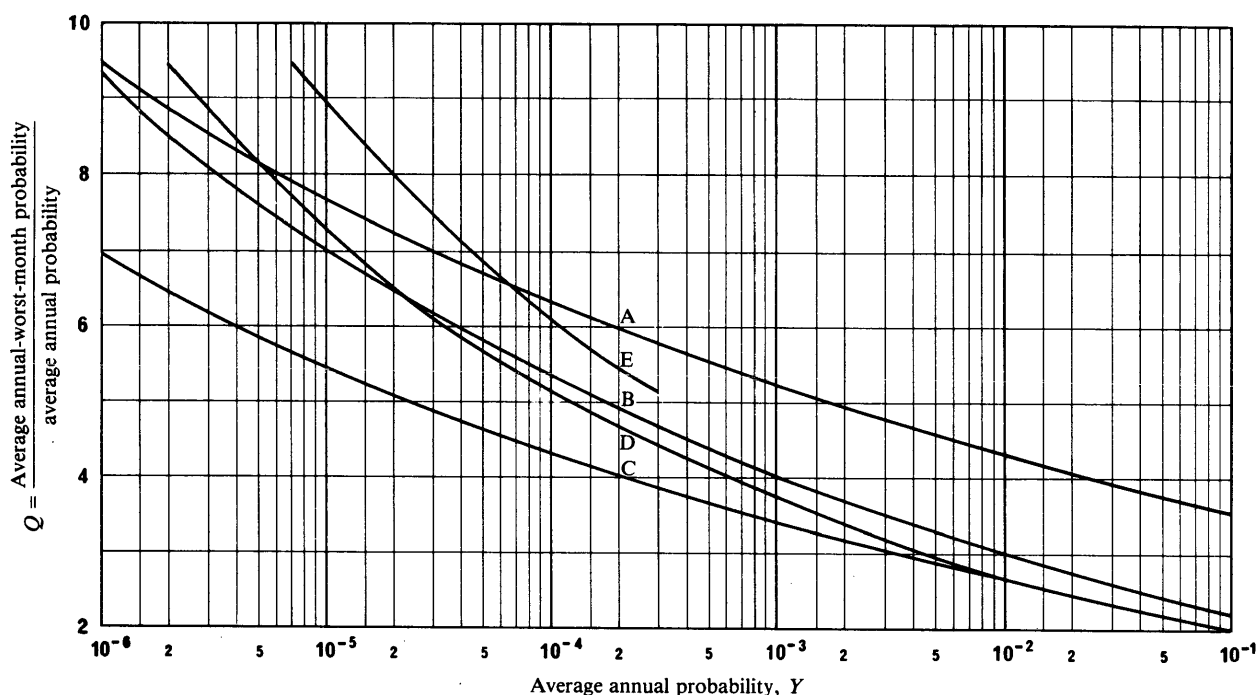


FIGURE 4 – Ratio of annual-worst-month to average annual probability, Q , as a function of average annual probability, Y

Curves A: Prairie + Northern
 B: Central + Mountain
 C: Coastal + Great Lakes
 D: Rain rate and rain attenuation, Europe,
 [Brussaard, 1979; Fedi, 1979; Damosso *et al.*, 1980; Mawira, 1980]
 E: Rain rate, Sweden

} Rain rate, Canada [Segal, 1980]

5.2 Multipath fading

From the example discussed in § 3, it may be concluded that the same type of analysis can be applied to multipath propagation fading; however, there are currently no statistics available in the form outlined in § 4 above regarding worst-month behaviour for purely multipath conditions.

6. Conclusions

It is considered that the definition given in this Report for the annual-worst-month statistic of any radio-electrical or meteorological parameter of interest should be used throughout CCIR documentation. Administrations are urged to analyze long-term statistical data in the manner described above and to submit results to the CCIR as soon as possible. In particular the following information is needed:

- Q as a function of average monthly occurrence probability $\overline{C}_0$ and/or
- Q as a function of average annual exceedance probability Y .

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REPORT 883 *

ATTENUATION OF VISIBLE AND INFRA-RED RADIATION

(Study Programme 8A/5)

(1982)

1. Introduction

The practical utilisation of the spectrum between about 0.5 μm (600 THz) and 20 μm (15 THz) is of increasing interest, especially in view of the advances in laser technology. Despite the effects of absorption and scattering in the troposphere, there are important applications in communications, space research and remote probing. The quantitative assessment of these applications and appropriate selection of frequencies require data on the effects of the atmosphere over the whole band of interest. Unfortunately, these effects are often complex; experimental and theoretical data are sometimes sparse and frequently inconsistent, and measured values of attenuation often depend on the characteristics (e.g. frequency resolution) of the equipment used. Consequently, only an approximate guide can be given at present and much more research is required to facilitate reliable predictions. It is possible, nevertheless, to indicate those portions of the spectrum which are likely to be the most useful and how these may be affected by tropospheric factors.

2. Propagation mechanisms

Visible and infra-red radiation can be attenuated in the atmosphere as the result of absorption and scattering by:

- molecules,
- aerosols,
- hydrometeors (rain, cloud, fog, etc.).

The term "aerosol" is used for small particles (other than fog or cloud droplets), say 10^{-2} to 50 μm diameter, which do not fall rapidly due to gravity. Haze, dust and particles in sea-spray are examples of aerosols. The particle concentration is highly variable in space and time.

The relative contributions of absorption and scatter to the total attenuation will depend on the wavelength and particle size. In addition, there will generally be some rapid fluctuation or "scintillation" in the received signal, especially when the ray path lies close to the Earth's surface. This is due to the irregular variations in refractive index associated with atmospheric turbulence.

For wavelengths other than those on, or close to, molecular absorption lines the major limitation to system reliability will generally be due to mist, fog, cloud or precipitation. However, an abnormal enhancement in water-vapour absorption can occur in some conditions (very high relative humidity). In addition, scintillation may affect the usable bandwidth of a visible or infra-red system.

* This Report is brought to the attention of Study Groups 1 and 2.

3. Molecular effects

The main factor here is selective absorption, especially in the wavelength range above $1\text{ }\mu\text{m}$. The absorption is highly wavelength-dependent and measurements with very high spectral resolution show considerable fine structure in the absorption spectrum. Consequently, it is difficult to quote quantitative data for absorption without specifying the instrumental resolution or bandwidth. Moreover, further spectroscopic measurements are required to provide the necessary detail. It is sufficient here to indicate the locations of the main absorption lines and "windows" of relatively small molecular absorption. More detailed data on fine structure are given in published work (see, for example, the review by Zuev [1974]).

Figure 1a indicates the main features of molecular absorption for transmission in the vertical through the Earth's atmosphere, from sea level and 4 km altitude for temperate, summer conditions. The several absorption lines are mainly due to water vapour and carbon dioxide. There are bands of low absorption, e.g. at:

- (a) 0.4 to $0.8\text{ }\mu\text{m}$ (visible range),
- (b) near 1.7 , 2.2 , 3.5 and $5\text{ }\mu\text{m}$,
- (c) 8 to $13\text{ }\mu\text{m}$.

These bands, especially (c), are of particular interest for communication and radar applications. Above the troposphere, the effect of aerosols and hydrometeors will be negligible and molecular absorption will generally be much less. For example, in the H_2O absorption band centred at about $6\text{ }\mu\text{m}$, the total absorption in a vertical path above 15 km altitude will be about 1 dB . For a ray path at zero elevation angle, from the same altitude, the absorption still does not exceed about 4 dB . An approximate estimate of specific attenuation (dB/km) at sea level is given in Fig. 2.

Both Figs. 1a and 2 refer to a spectral resolution of about $0.1\text{ }\mu\text{m}$. An indication of how the molecular absorption varies with frequency with a much greater resolution ($0.001\text{ }\mu\text{m}$) is given in Fig. 1b.

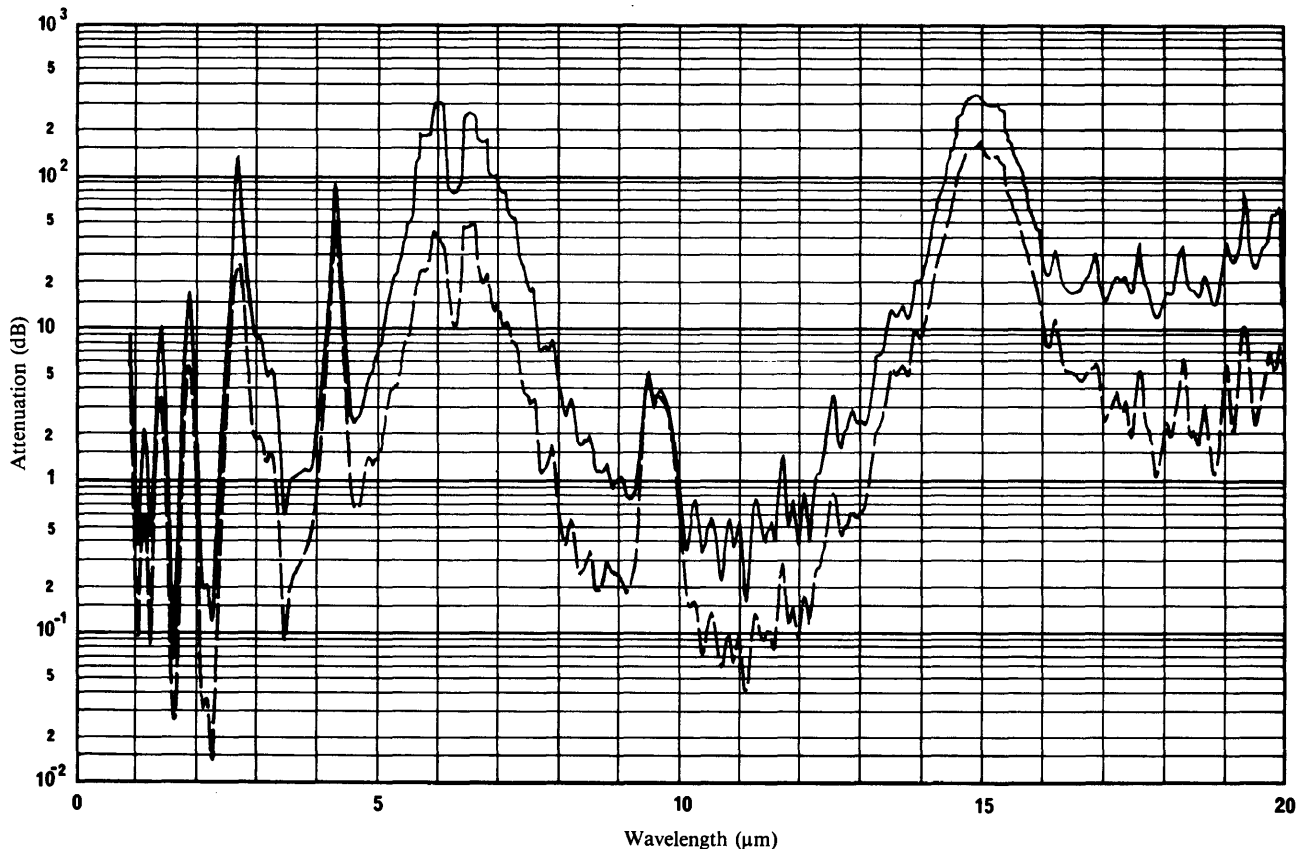


FIGURE 1a – Molecular absorption in clear air through Earth's atmosphere at zenith
(spectral resolution $0.1\text{ }\mu\text{m}$)

————— From sea level
----- From 4 km altitude

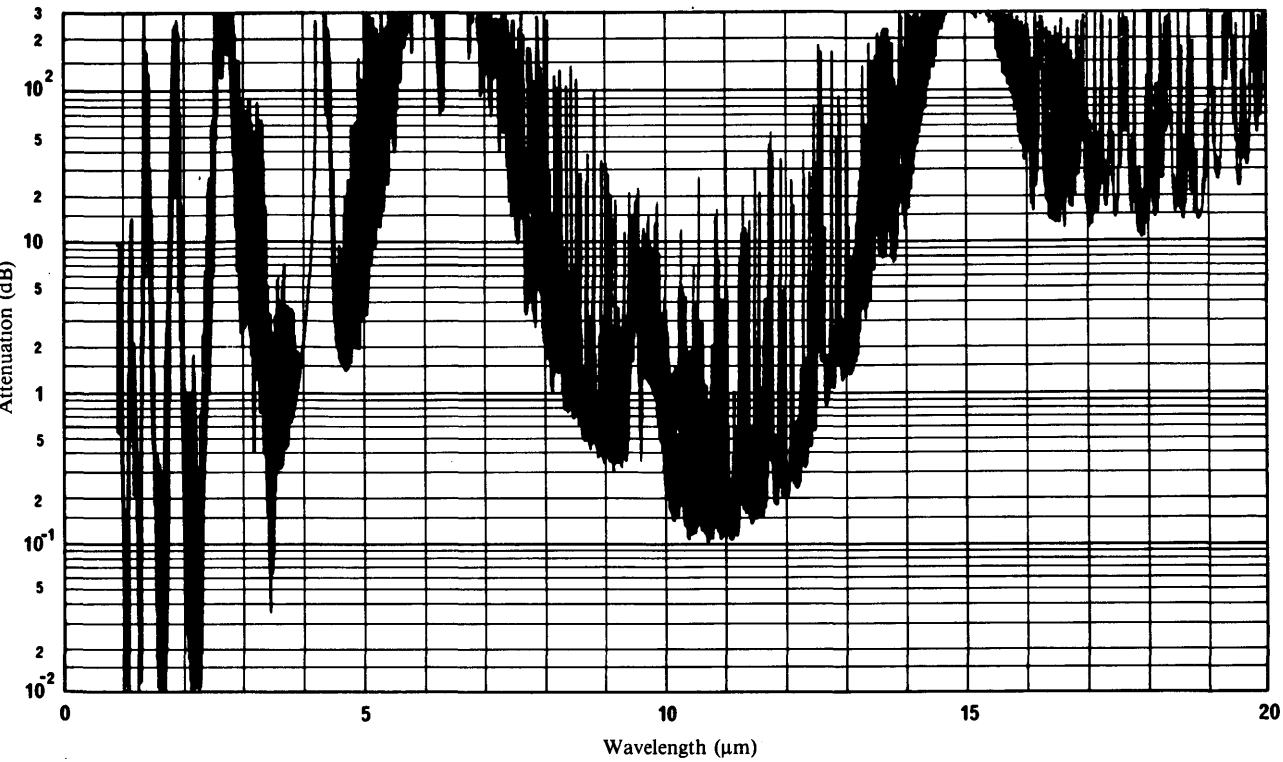


FIGURE 1b – Molecular absorption in clear air through Earth's atmosphere, from sea level, at zenith
(spectral resolution $0.001\ \mu\text{m}$)

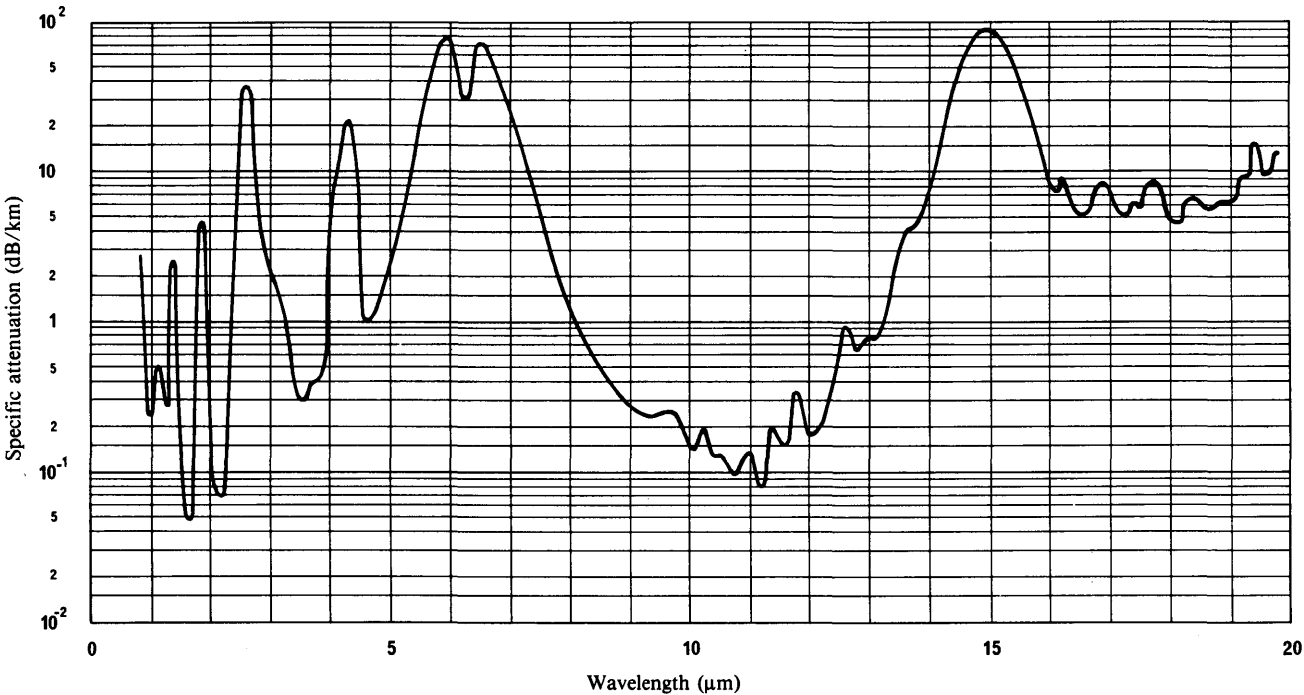


FIGURE 2 – Specific attenuation in clear air at sea level
(spectral resolution $0.1\ \mu\text{m}$)

4. Aerosols (haze, dust, etc.)

Aerosols are always present in the atmosphere to some degree. Unfortunately, their composition, size distribution and concentration are extremely variable. Predictions of the attenuation they cause are therefore difficult. Although their concentration is closely related to optical visibility, there is no unique particle-size distribution for a given visibility. Attenuation can only be estimated from visibility data by very approximate, empirical procedures which must be used with caution. A further complicating factor is the dependence of aerosol size on relative humidity. Consequently, at the present time it is impossible to give more than a general outline of how the attenuation varies with wavelength for a few representative distributions of particle size.

Figure 3 gives an indication of how the total attenuation due to aerosols depends on wavelength. Three different models are assumed for the aerosol size distribution: rural, urban (which includes soot particles) and maritime (largely sea-spray). The concentrations are assumed such that the optical visibility (at about $0.6 \mu\text{m}$) is 25 km for the upper set of curves and 5 km for the lower set. For a given model, the attenuation decreases with increasing wavelength, with the maritime model producing the largest attenuation. The data for this model assume moderate wind speeds, a path located in the first 100 m above the sea, and a relative humidity of about 80%. For a relative humidity of 95% the values for this model could be 3 times greater.

An approximate, but useful, formula for attenuation due to aerosols in the visible range (approximately $0.6 \mu\text{m}$) as a function of visibility is:

$$\alpha \text{ (dB/km)} = 17/V \quad (1)$$

where V is the visibility in km.

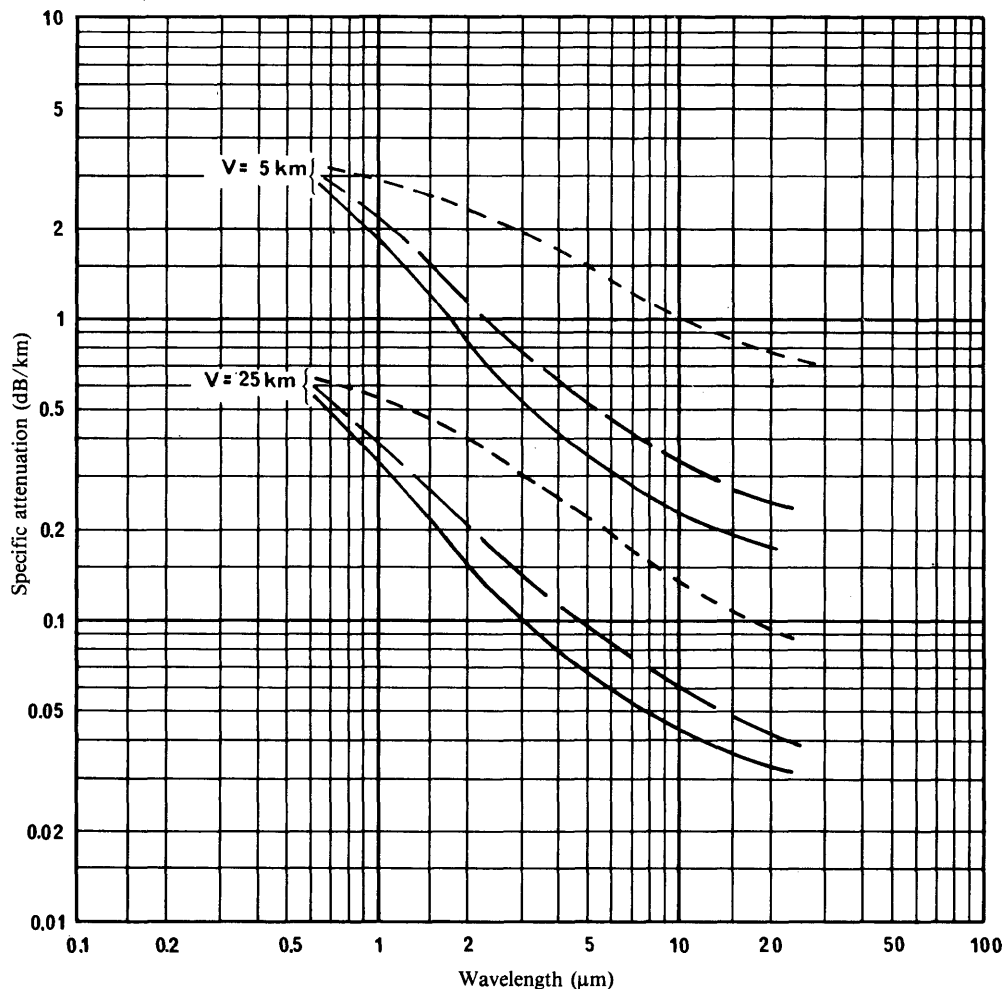


FIGURE 3 - Specific attenuation due to aerosols as function of visibility, V

————— Rural model
 - - - - - Urban model
 - - - - - Maritime model

5. Fog and cloud

Although the smaller particles in fog and cloud could be regarded as a type of aerosol, they are usually treated separately. (As a practical criterion, the distinction between "haze" and "fog" is assumed to occur at a visibility of about 1 km). The radius of fog droplets can range from 1 μm to 100 μm , but a large proportion of drops have radii less than 20 μm and few radii are more than 40 μm . Even so, the variability in size distribution (and the difficulty of measuring it) makes the prediction of attenuation a complex problem. The wavelength dependence of attenuation depends on the drop-size distribution. If the maximum drop radius is less than 10 μm , wavelengths of about 10 μm are attenuated less than those in the visible spectrum. If most of the drops have radii greater than 10 μm , the reverse is true. Hence, the use of optical visibility to characterise the fog can provide only an approximate basis for prediction. For example, for a given visibility, coastal fog will generally have a larger liquid-water content than inland fog. Nevertheless, visibility is a practical parameter which is often used. Figure 4 shows the general trend of attenuation in fog as a function of wavelength and visibility. These results are based largely on calculations, but they are reasonably consistent with the few measurements available. The results of Chu and Hogg [1968], for example, show a general tendency for the attenuation in fog to decrease as the wavelength increases from 0.6 μm . However, a few observations do not conform to this trend, as a consequence of unusual drop-size distributions.

Figure 4 shows that even moderate fog of say 500 m visibility, can cause serious attenuation of optical and infra-red radiation.

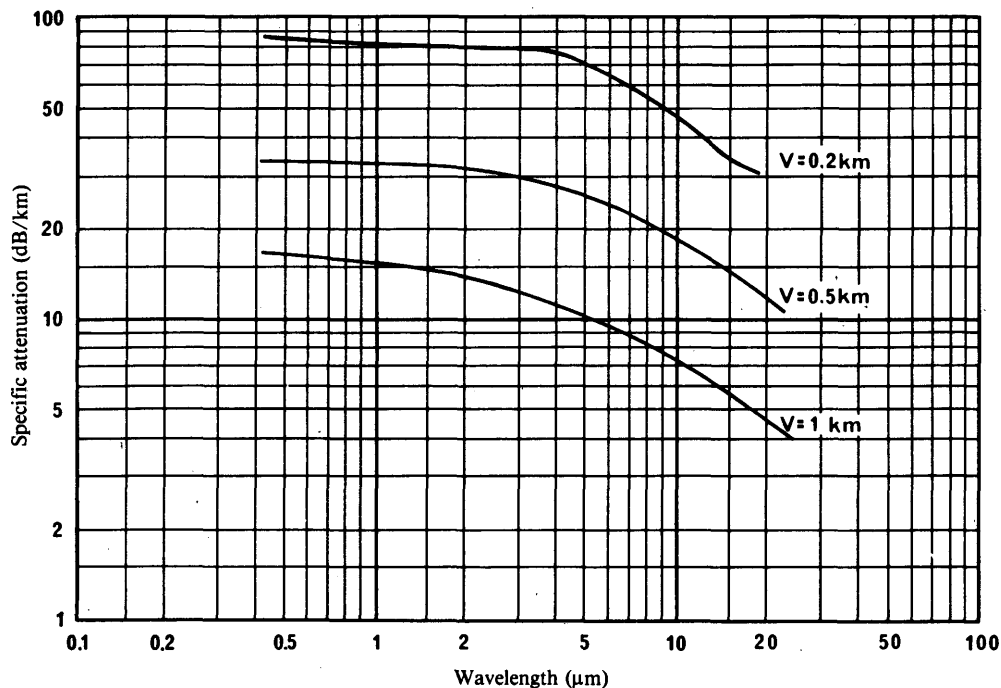


FIGURE 4 – Specific attenuation due to fog as a function of visibility, V

The effect of cloud is even more pronounced. Table I gives calculated values of attenuation for some types of cloud as a function of wavelength, λ . Even fair-weather cumulus causes an attenuation of at least 0.05 dB/m and nimbo-stratus (rain cloud) has values of the order of 0.5 dB/m.

TABLE I - Attenuation (dB/m) of visible and infra-red radiation in cloud

Cloud type	λ (μm)				
	0.5	1	3	5	10
Fair weather cumulus	0.09	0.095	0.1	0.1	0.05
Strato-cumulus	0.18	0.18	0.2	0.21	0.12
Nimbo-stratus (rain cloud)	0.5	0.6	0.6	0.65	0.5

6. Precipitation

In rain, the attenuation for a given rainfall rate is almost independent of wavelength in the visible and near infra-red range since the drops are much larger than the wavelength. Figure 5 shows how the attenuation depends on rainfall rate. The full-line theoretical curve assumes a Laws and Parsons distribution of drop sizes. The range covered by experimental data is also shown. There is a tendency for some measurements in light and moderate rain to exceed the calculated values appreciably. This is probably due to the assumed size distribution underestimating the proportion of small drops.

Very few results on attenuation in snow are available. The data of Chu and Hogg [1968] indicate that, in general, the attenuation tends to increase slightly with wavelength over the range 0.6 to 10 μm . In light snow the attenuation may reach about 8 dB/km at 0.6 μm and 10 dB/km at 10 μm . For heavy snow, these values may well be doubled.

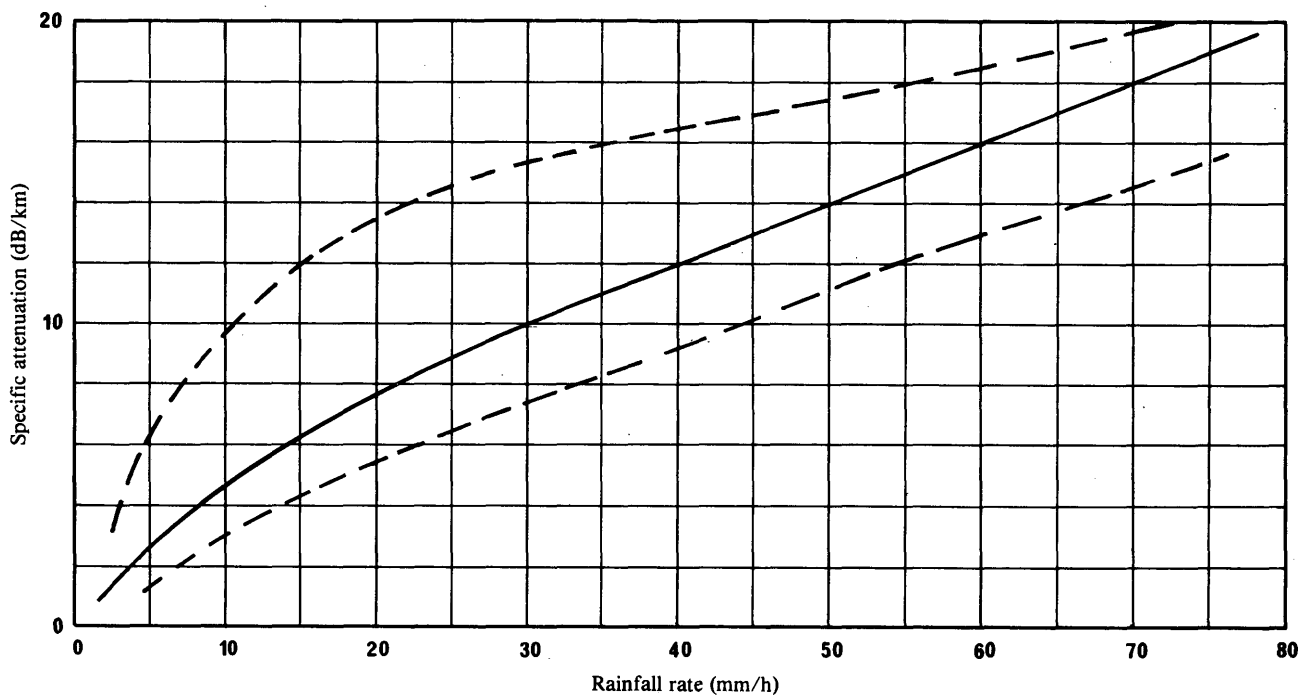


FIGURE 5 - Specific attenuation at optical and infra-red wavelengths due to rain

———— Theoretical curve
 - - - - - Range covered by experimental data

7. Scintillation

Variations in the refractive-index structure of the atmosphere will cause fluctuations in the received signal in an optical or infra-red system. These fluctuations will, in general, decrease with increasing wavelength, with height of the path above ground and with increasing aperture size of the system. It is difficult to provide any general prediction procedure for this effect but, as an indication of the order of magnitude, a 1 km link located in the first 10 to 20 m above ground level may experience fluctuations of say 10 dB when meteorological conditions are such that fluctuations in temperature (i.e. in refractive index) are unusually large. The frequency of the fluctuations will depend, for a given wavelength and path geometry, on the wind speed normal to the path. A dominant frequency component in the range 20 to 100 Hz is typical, but components up to 1 kHz are generally present. There is an extensive collection of published work on optical, including laser, scintillation phenomena. The basic background is given by Tatarskii [1967].

8. Measured statistics for practical systems

Very few of these exist. The results of Chu and Hogg [1968] for a 2.6 km link at 10.6 μm wavelength in New Jersey, USA, show attenuations of about 20, 10 and 5 dB/km exceeded for 2, 4 and 6% of the time respectively (1 year's observations). These results are in contrast to those of Waksberg and Clements [1979], also at 10.6 μm wavelength, for a 1.6 km link in Montreal, for which attenuations of 10 and 5 dB/km were exceeded for only 0.6 and 3% of the time. However, these experiments covered a total period of only 1241 hours and the incidence of fog was very low. In Japan, Kobayashi *et al.* [1977] found attenuations of about 4 and 11 dB/km exceeded for 1.5 and 0.1% of time respectively on a 2.7 km terrestrial link. Scintillation effects were studied in relation to error rates. A colour-television signal of 4 MHz and speech signals were transmitted simultaneously using pulse-position modulation. 120 telephone channels were transmitted using differential pulse-position modulation. For 6.3 Mbit/s digital signals, the bit error ratio exceeded 10^{-6} for 1.5% of the time.

There appear to be no statistics yet for ground-space or space-space systems but the potentialities of the 10 μm "window" for inter-satellite laser systems have been discussed in some detail by McElroy *et al.* [1977].

9. General conclusions

Wavelengths in the window regions (e.g. 0.4 to 0.8 μm ; 3 to 4 μm and near 5 μm ; and 8 to 13 μm) have considerable potential application for short-range systems. The main limitation to reliability will result from conditions of poor visibility (fog, mist, cloud, snow storms). Rain, although it causes a large attenuation, will be less serious for optical and infra-red waves than fog or cloud and will produce less attenuation, for a given rainfall rate, than at wavelengths of 1 to 2 mm. The wavelength-dependence of attenuation in poor visibility conditions is such that the 8 to 13 μm window is likely to provide the most useful band for practical systems.

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SECTION 5D: ASPECTS RELATIVE TO THE TERRESTRIAL BROADCASTING
AND MOBILE SERVICES

Recommendations and Reports

RECOMMENDATION 370-4 *

VHF AND UHF PROPAGATION CURVES FOR THE FREQUENCY
RANGE FROM 30 MHz TO 1000 MHz **

Broadcasting services

(Study Programme 7D/5)

(1951-1953-1956-1959-1963-1966-1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that there is a need to give guidance to engineers in the planning of broadcast services in the VHF and UHF bands;
- (b) that, for stations working in the same or adjacent frequency channels, the determination of the minimum geographical distance of separation required to avoid intolerable interference due to long-distance tropospheric transmission is a matter of great importance;
- (c) that the annexed curves are based on the statistical analysis of a considerable amount of experimental data (see Report 239),

UNANIMOUSLY RECOMMENDS

1. that the curves given in Annex I be adopted for provisional use *** for the following conditions:
 - 1.1 The field strengths have been adjusted to correspond to a power of 1 kW radiated from a half-wave dipole. If field-strength values are to be referred to the free space field radiated by a hypothetical isotropic radiator, these can be obtained from values on the curves by subtracting 2.15 dB.
 - 1.2 The height of the transmitting antenna is defined as its height over the average level of the ground between distances of 3 and 15 km from the transmitter in the direction of the receiver.
 - 1.3 The height of the receiving antenna is defined as the height above local terrain.
 - 1.4 A parameter Δh is used to define the degree of terrain irregularity: it is the difference in heights exceeded by 10% and 90% of the terrain in the range 10 km to 50 km from the transmitter (see Fig. 6 and Report 239).
 - 1.5 Methods for determining field strengths over mixed land and sea paths are described in Report 239.
 - 1.6 The effect of changing the receiving antenna height is given in § 2.3, 3.3 and Fig. 17. It is also referred to in Reports 239 and 567.

* This Recommendation is brought to the attention of Study Groups 10 and 11.

** It must be emphasized that the curves of this Recommendation are intended for use in the planning of broadcasting services for the solution of interference problems over a wide area: they should not be used for point-to-point communication links, for which systems the actual terrain profile may be determined and more accurate methods of field strength prediction may be used.

*** It must be emphasized that the curves are based on data obtained mainly for temperate climates and should be used with caution for other climates. Propagation curves for broadcasting in the African Continent are given on pages 343-379 of the Final Acts of the African VHF/UHF Broadcasting Conference, Geneva, 1963.

- 1.7 Account should be taken of the attenuation through forest and vegetation (see Fig. 2, Report 236).
- 1.8 Improved accuracy of predicted field strengths can be obtained by taking into account terrain local to the receiving location by means of a terrain clearance angle. The method is described in Report 239.

ANNEX I

1. Introduction

1.1 The propagation curves represent field-strength values in VHF and UHF bands as a function of various parameters; some curves refer to land paths, others refer to sea paths. The land path curves were prepared from data obtained mainly from temperate climates as encountered in Europe and North America. The sea path curves were prepared from data obtained mainly from the Mediterranean and the North Sea regions.

1.2 The propagation curves represent the field-strength values exceeded at 50% of the locations for different percentages of time. They correspond to different transmitting antenna heights and a receiving antenna height of 10 m. The land path curves refer to a value of $\Delta h = 50$ m which generally apply to rolling terrain commonly found in Europe and North America.

1.3 For locations other than 50%, probability distribution curves are also presented in this Annex.

1.4 Estimates of mixed-path field strengths should be made in accordance with the methods described in Report 239.

1.5 Since most of the measurements relate to distances less than 500 km, the results given by these curves are less reliable above this distance. The sections of the curves in dashed lines, obtained by extrapolation, should be used with even greater caution.

1.6 All these curves are based on long-term values (several years) and may be regarded as representative of the mean climatic conditions prevailing in all the temperate regions. It should be noted, however, that for brief periods of time (e.g., for some hours or even days), field strengths may be obtained which are much higher than those shown by these curves, particularly over relatively flat terrain.

1.7 It is known that the median field strength varies in different climatic regions, and data for a wide range of such conditions in North America and Western Europe show that it is possible to correlate the observed values of median field strength with the refractive index gradient in the first kilometre of the atmosphere above ground level. If n_s and n_1 are the refractive indices at the surface and at a height of 1 km respectively, and if ΔN is defined as $(n_1 - n_s) \times 10^6$, then in a standard atmosphere, $\Delta N \approx -40$, the 50% curves of Fig. 1 refer to this case. If the mean value of ΔN , in a given region, differs appreciably from -40 , the appropriate median field strengths for all distances beyond the horizon are obtained by applying a correction factor of $-0.5 (\Delta N + 40)$ dB to the curves. If ΔN is not known, but information concerning the mean value of N_s is available, where $N_s = (n_s - 1) \times 10^6$, an alternative correction factor of $0.2 (N_s - 310)$ dB may be used, at least for temperate climates. Whilst those corrections have so far only been established for the geographical areas referred to above, they may serve as a guide to the corrections which may be necessary in other geographical areas. The extent to which it is reliable to apply similar corrections to the curves for field strengths exceeded 1% and 10% of the time is not known. It is expected, however, that a large correction will be required for the 1% and 10% values, in regions where super-refraction is prevalent for an appreciable part of the time.

2. VHF bands

2.1 The curves in Figs. 1, 2a, 3c and 4a represent field-strength values exceeded at 50% of the locations and for 50%, 10%, 5% and 1% of the time for land paths where Δh of 50 m is considered representative. For a different value of Δh , a correction should be applied to the curves as shown in Fig. 7. (See Report 239.) For locations other than 50%, corrections may be obtained from the distribution curves in Fig. 5.

2.2 The curves in Figs. 1, 2a, 2b, 3a, 3b, 4b and 4c represent field-strength values exceeded at 50% of the locations for 50%, 10%, 5% and 1% of the time for sea paths for the Mediterranean and North Sea regions. Generally, the value of Δh for the sea path curves is less than 10 m. It is assumed however that the curves in Figs. 1 and 2a refer to the same values of Δh *.

2.3 The following reduction in the median field-strength values may be expected by changing the receiving antenna height from 10 to 3 m above ground: in Bands I and II, 9 dB in hilly or flat terrain for both urban and rural areas; in Band III, 7 dB for flat terrain in rural areas and 11 dB for urban or hilly terrain. These values apply for distances up to 50 km. For distances in excess of 100 km the values should be halved, with linear interpolation for intermediate distances. Refer also to Report 239.

2.4 The ionosphere, primarily through the effects of sporadic-E ionization, can influence propagation in the lower part of the VHF band, particularly at frequencies below about 90 MHz. In some circumstances this mode of propagation may influence the field strength exceeded for small percentages of the time at distances beyond some 500 km, and near the magnetic equator and in the auroral zone higher percentages of the time may be involved. However these ionospheric effects can usually be ignored in most applications covered by this Recommendation and the propagation curves of this Annex have been prepared on this assumption. Report 259 and Recommendation 534 should be consulted to determine whether the assumption is reasonable.

3. UHF bands

3.1 The curves in Figs. 9, 10 and 11 represent field-strength values exceeded at 50% of the locations and for 50%, 10% and 1% of the time for land paths where Δh of 50 m is considered representative. For different values of Δh , a correction should be applied to the curves as shown in Fig. 8. Correction factors for locations other than 50% may be obtained for distribution curves in Fig. 12.

3.2 The curves in Figs. 13, 14a, 14c, 15a, 15b, 16a and 16b represent field-strength values exceeded at 50% of the locations and for 50%, 10%, 5% and 1% of the time for sea paths for the North Sea and Mediterranean regions. The value of Δh for the sea path curves is less than 10 m.

3.3 A reduction in the median field-strength values may be expected by changing the receiver antenna height from 10 m to 3 m above ground. Figure 17 shows how the median value varies with Δh in rural areas. In suburban areas the median value may be taken as 7 dB, and in urban areas as 14 dB. These values apply for distances up to 50 km. For distances in excess of 100 km the values should be halved, as in Fig. 17, with linear interpolation for intermediate distances.

* In the absence of separate sea and land curves, it is provisionally recommended that for Figs. 1 and 2a the same method used for Δh correction for land paths is applied to sea paths.

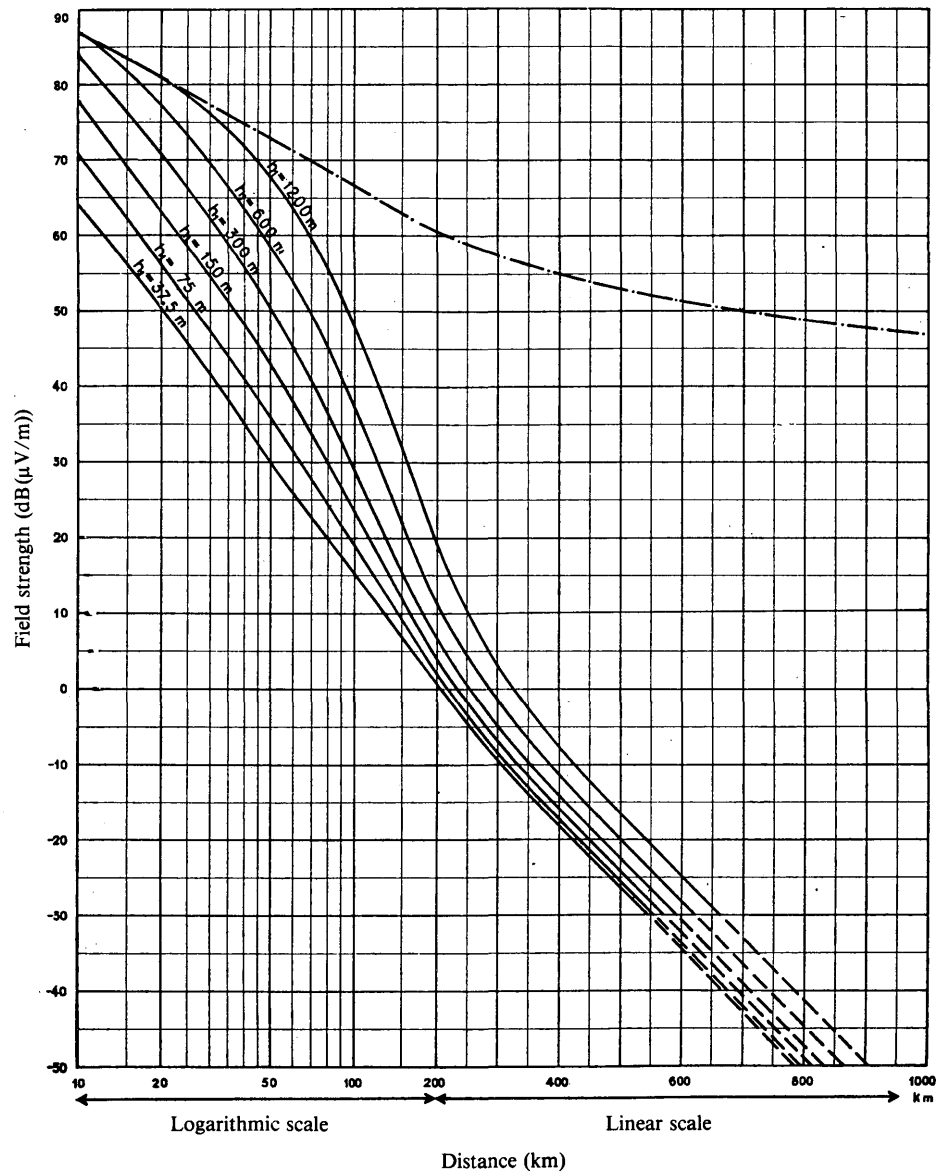


FIGURE 1 – Field strength ($\text{dB}(\mu\text{V/m})$) for 1 kW e.r.p.
 Frequency: 30 to 250 MHz (Bands I, II and III); Land, North Sea and Mediterranean Sea;
 50 % of the time; 50 % of the locations; $h_2 = 10$ m

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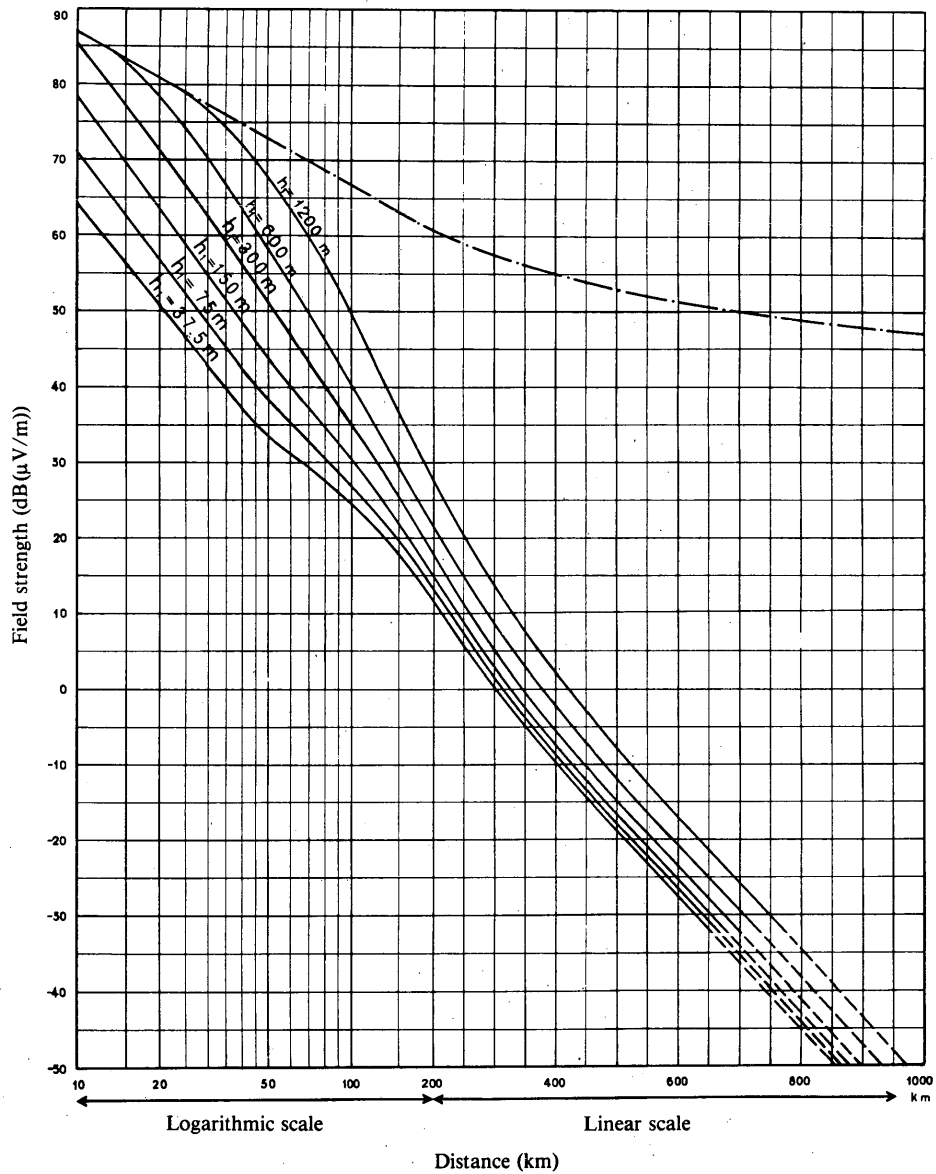


FIGURE 2a – Field strength (dB(μV/m)) for 1 kW e.r.p.
 Frequency: 30 to 250 MHz (Bands I, II and III); Land and North Sea;
 10 % of the time; 50 % of the locations; $h_2 = 10$ m

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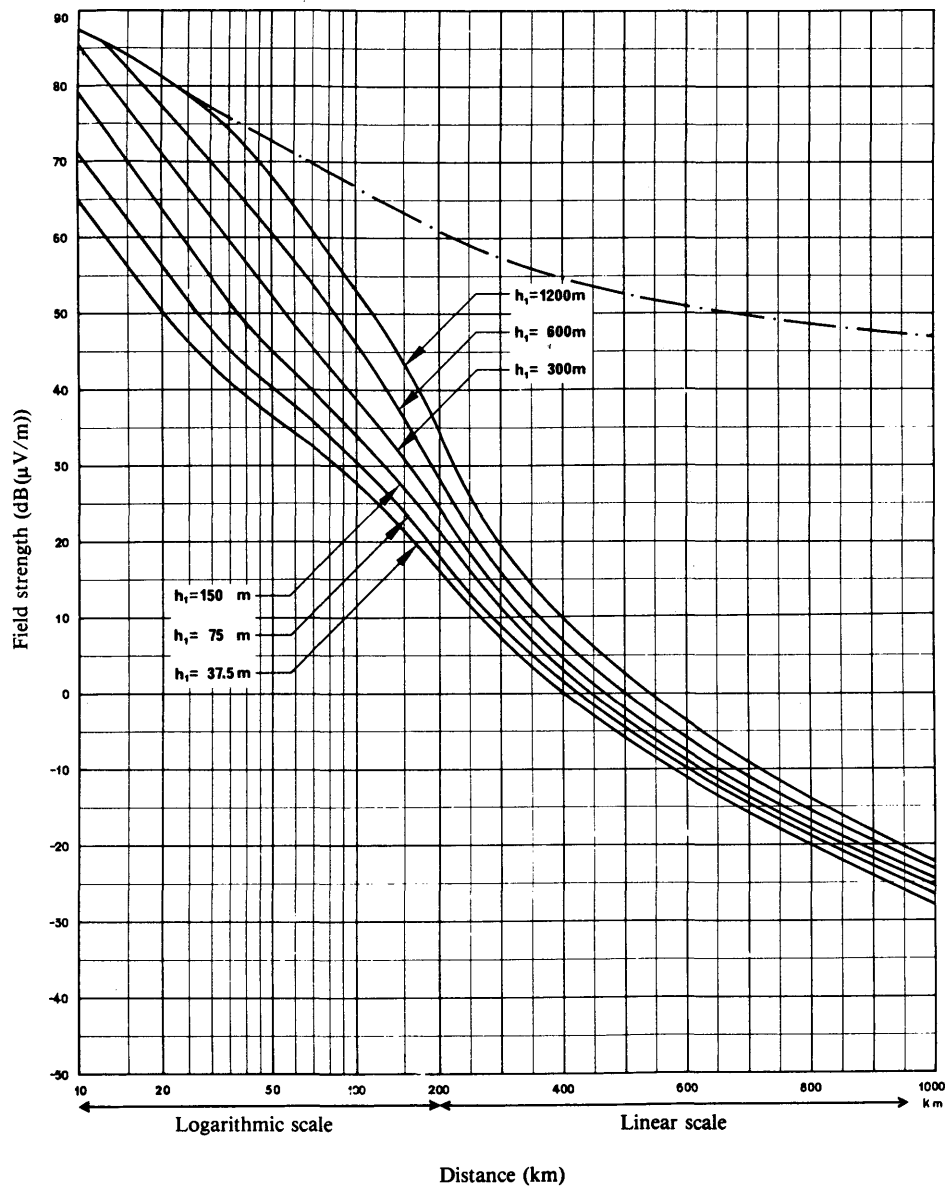


FIGURE 2b – Field strength (dB(μ V/m)) for 1 kW e.r.p.
 Frequency: 30 to 250 MHz (Bands I, II and III); Mediterranean Sea;
 10 % of the time; 50 % of the locations; $h_2 = 10$ m

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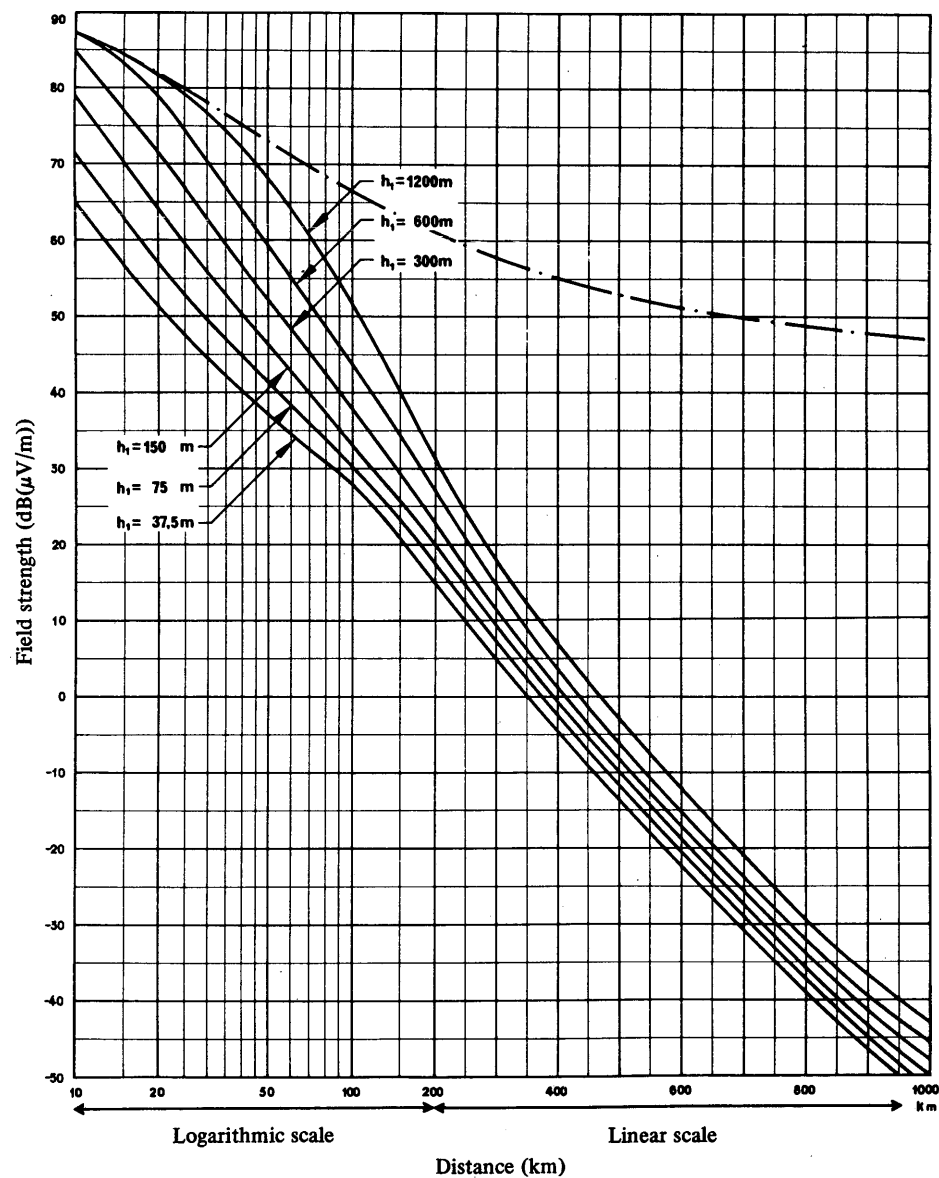


FIGURE 3a – Field strength ($\text{dB}(\mu\text{V}/\text{m})$) for 1 kW e.r.p.
Frequency: 30 to 250 MHz (Bands I, II and III); North Sea;
5% of the time; 50% of the locations; $h_2 = 10$ m

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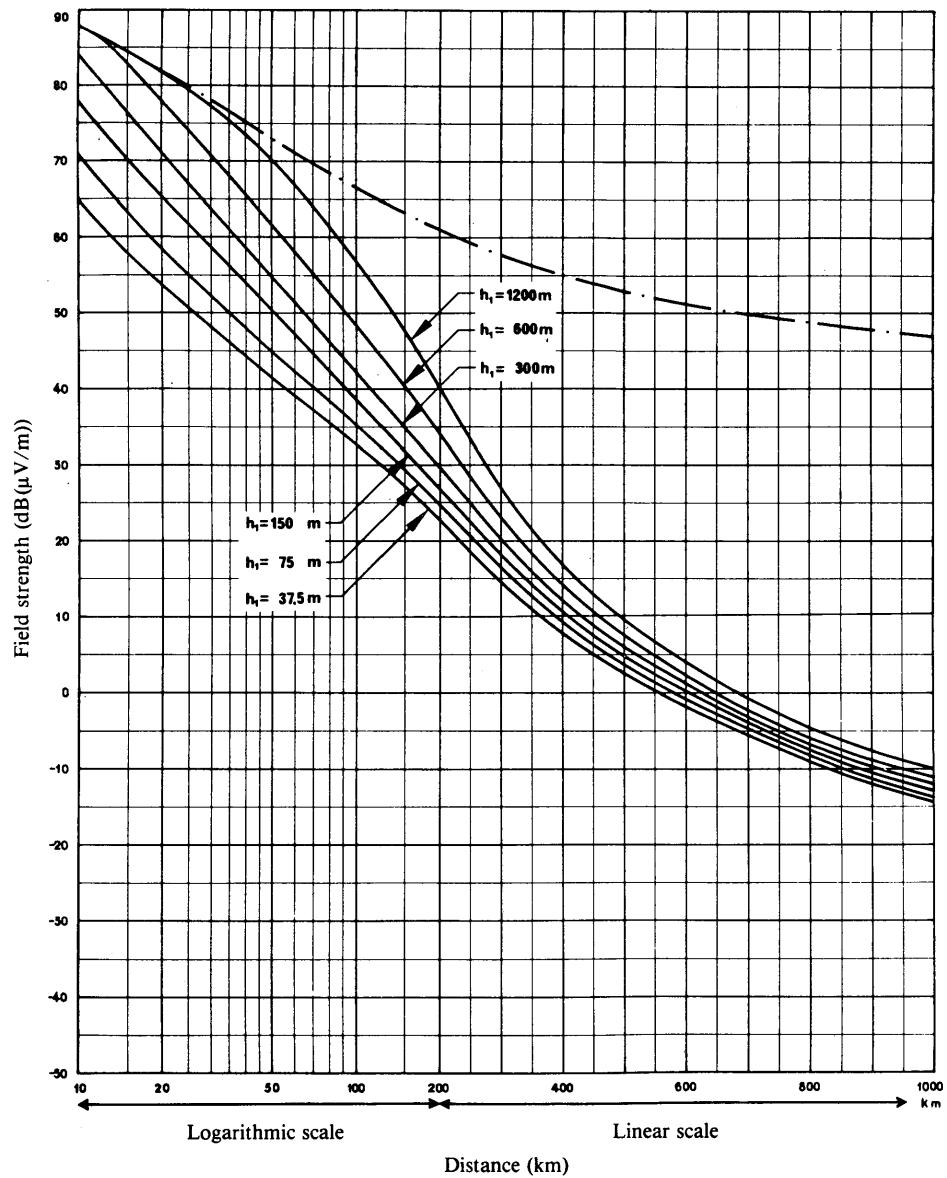


FIGURE 3b – Field strength (dB(μ V/m)) for 1 kW e.r.p.
 Frequency: 30 to 250 MHz (Bands I, II and III); Mediterranean Sea;
 5 % of the time; 50 % of the locations; $h_2 = 10$ m

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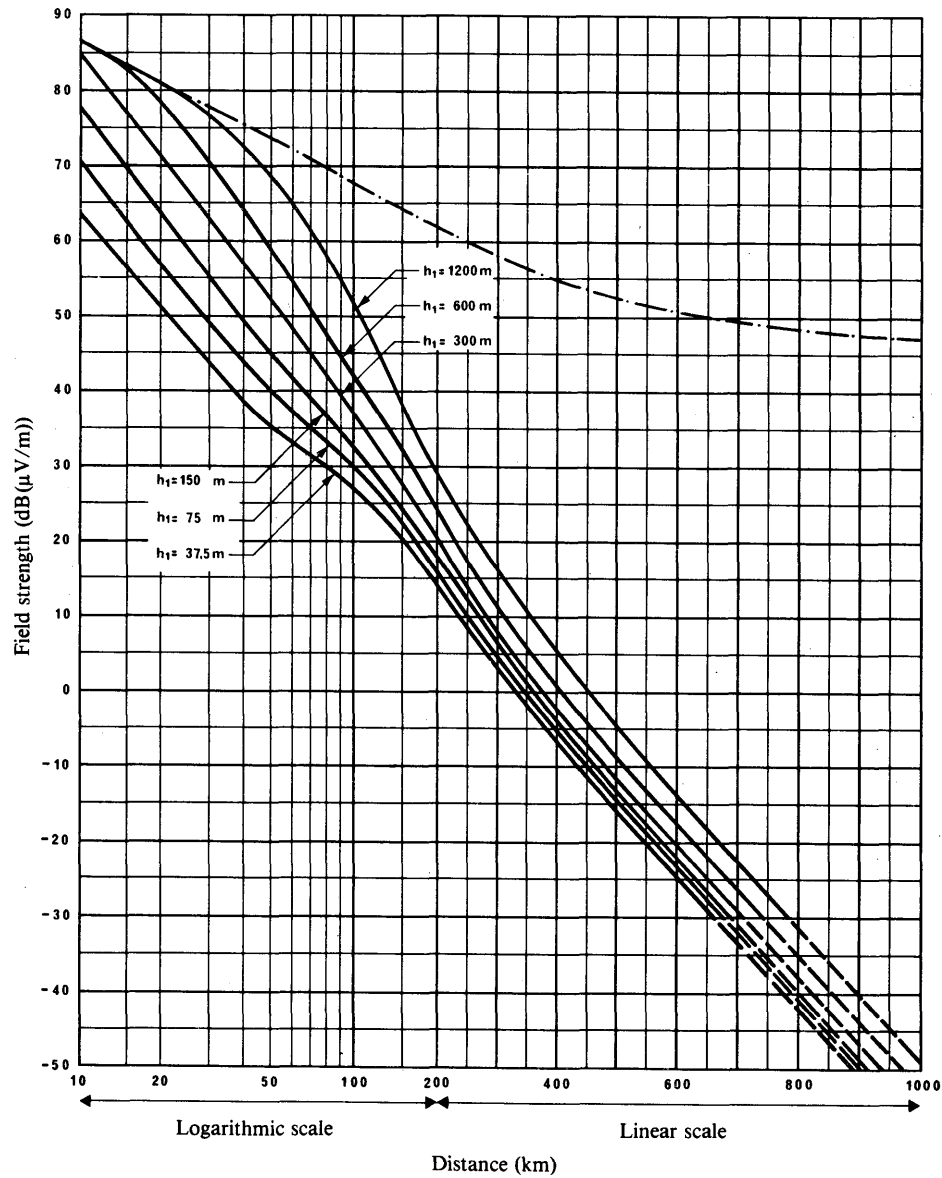


FIGURE 3c — Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 30 to 250 MHz (Bands I, II and III); Land;
5 % of the time; 50 % of the locations; $h_2 = 10$ m

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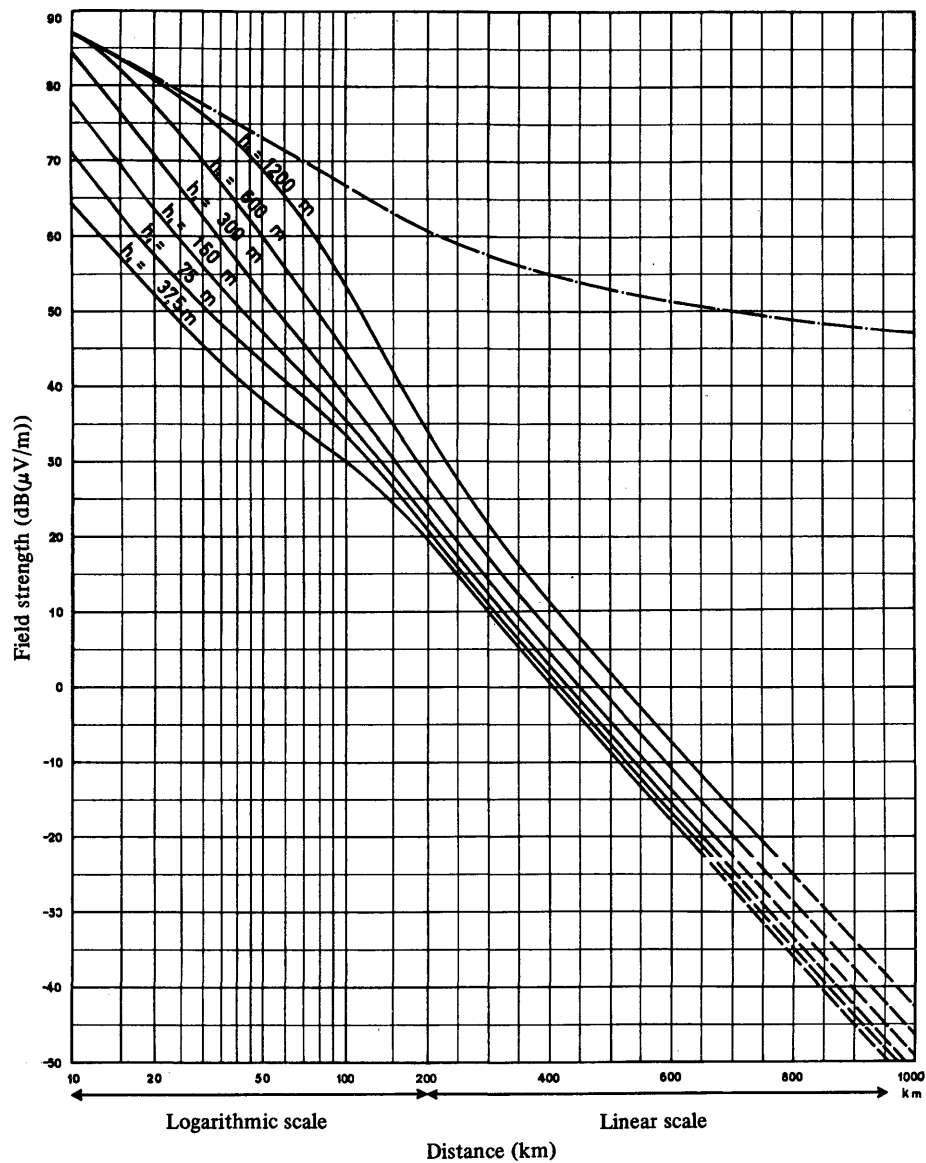


FIGURE 4a – Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 30 to 250 MHz (Bands I, II and III); Land;
1% of the time; 50% of the locations; $h_2 = 10$ m

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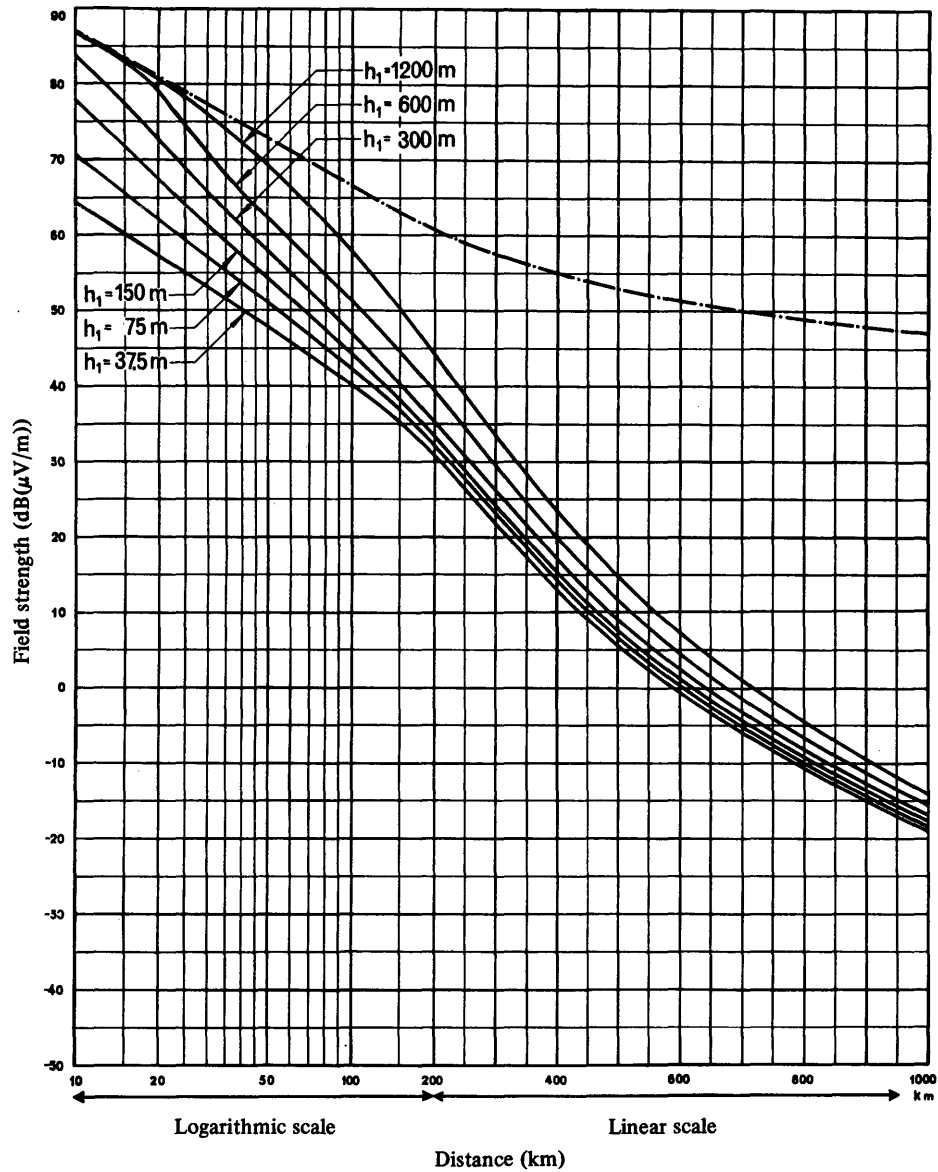


FIGURE 4b – Field strength (dB(μ V/m)) for 1 kW e.r.p.
 Frequency: 30 to 250 MHz (Bands I, II and III); North Sea; 1 % of the time;
 50 % of the locations; $h_2 = 10$ m

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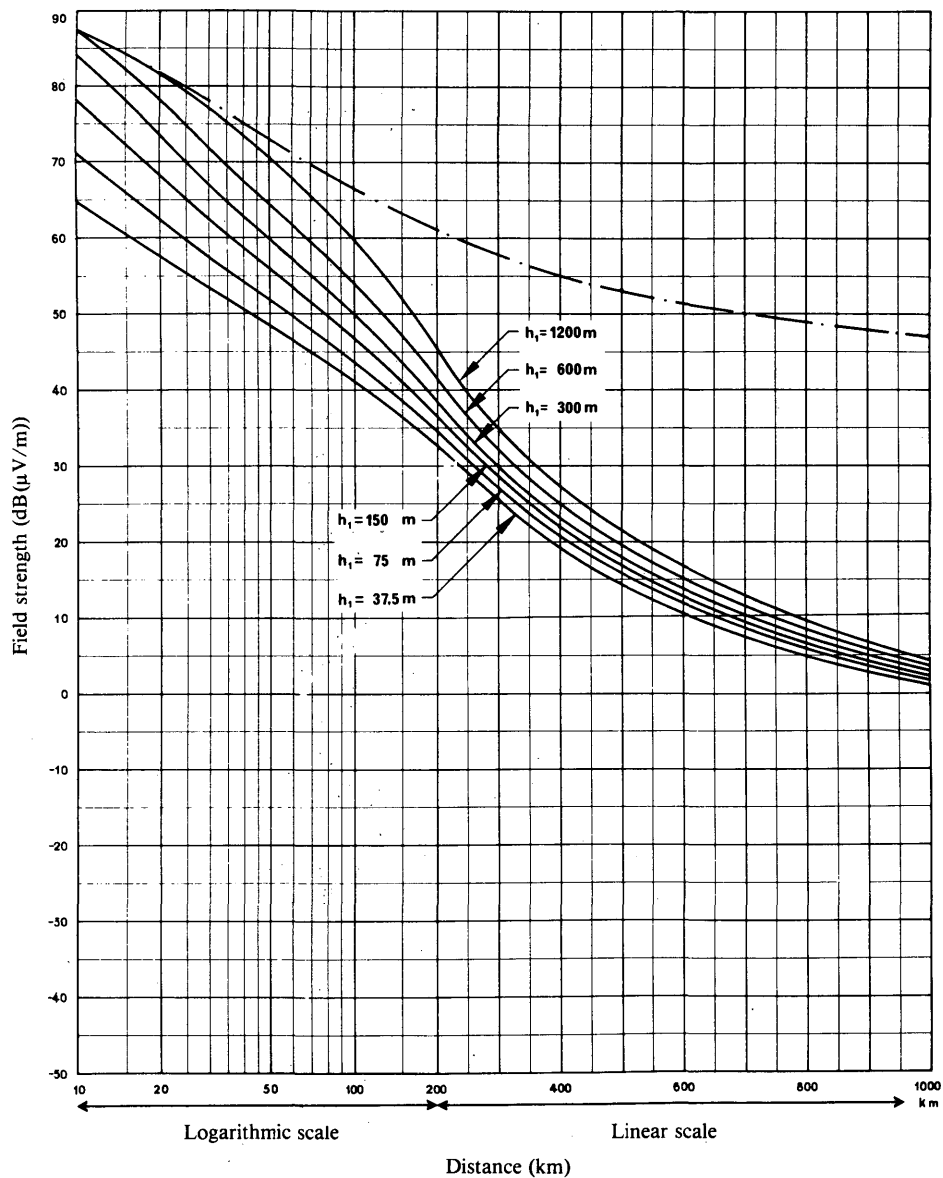


FIGURE 4c – Field strength ($\text{dB}(\mu\text{V/m})$) for 1 kW e.r.p.
 Frequency: 30 to 250 MHz (Bands I, II and III); Mediterranean Sea;
 1 % of the time; 50 % of the locations; $h_2 = 10$ m

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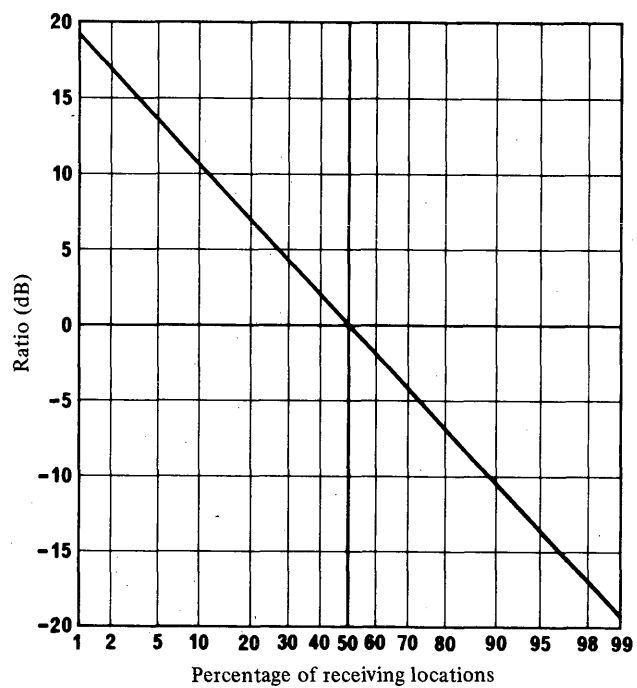


FIGURE 5 – Ratio (dB) of the field strength for a given percentage of the receiving locations to the field strength for 50% of the receiving locations

Frequency : 30 to 250 MHz (Bands I, II and III)

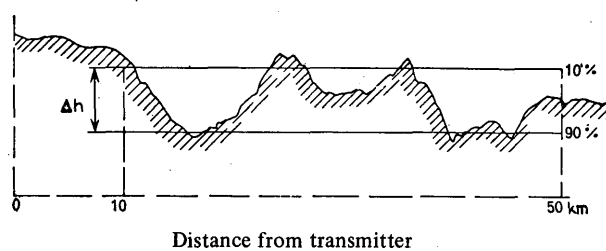


FIGURE 6 – Definition of the parameter Δh

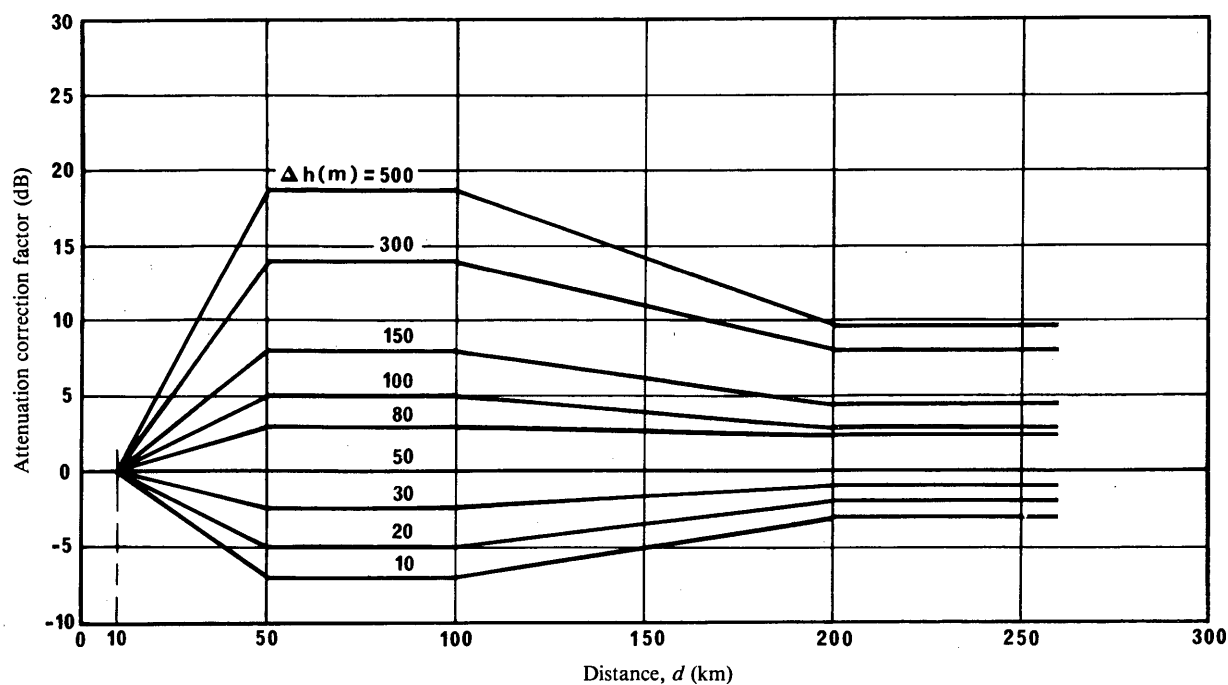


FIGURE 7 – Attenuation correction factor as a function of the distance d (km) and Δh
Frequencies 80 to 250 MHz (Bands II and III)

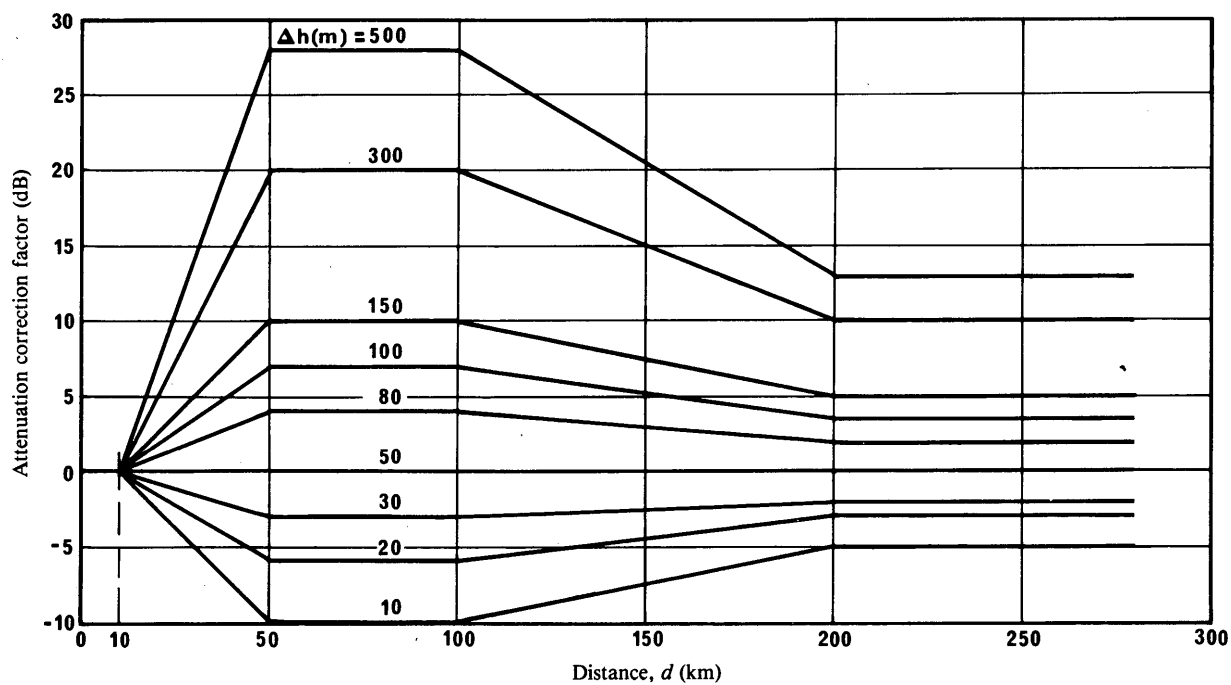


FIGURE 8 – Attenuation correction factor as a function of the distance d (km) and Δh
Frequencies 450 to 1000 MHz (Bands IV and V)

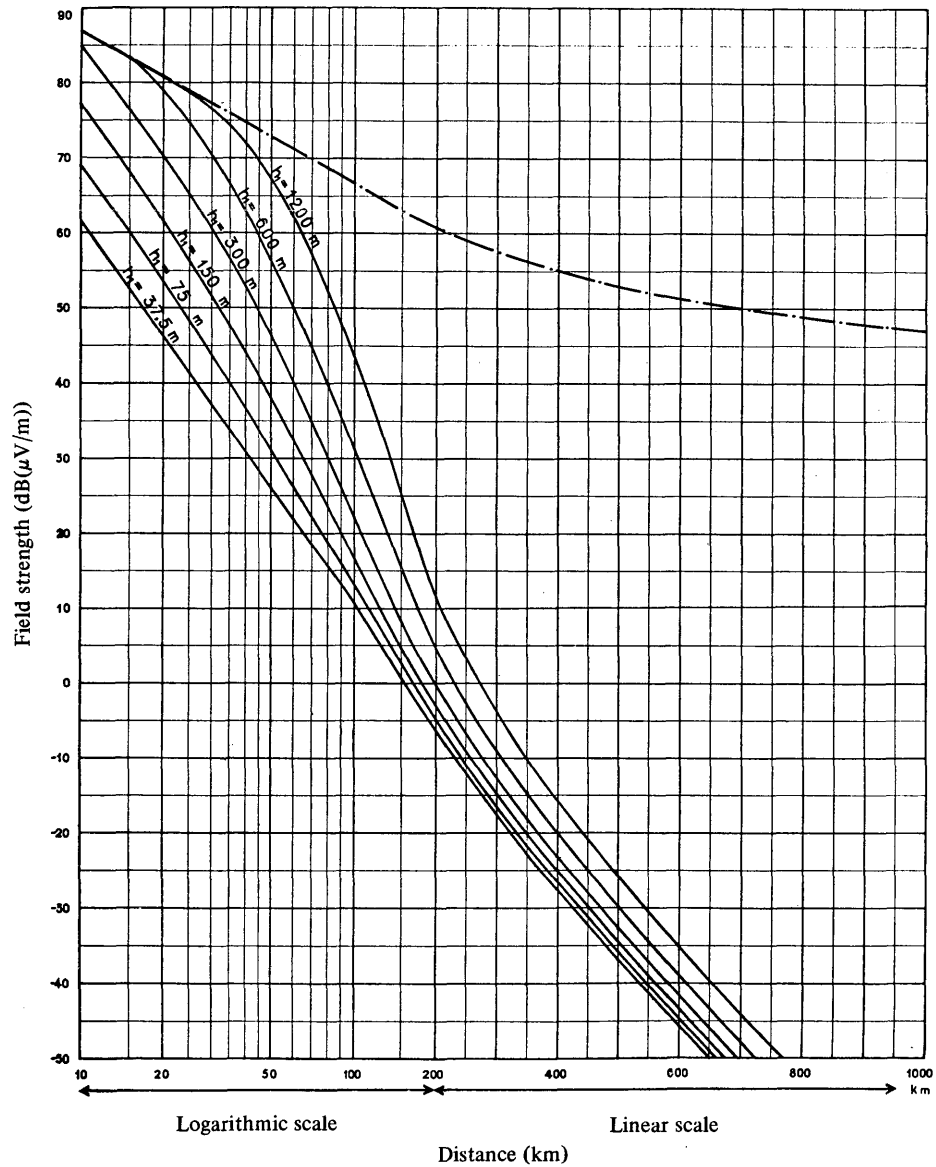
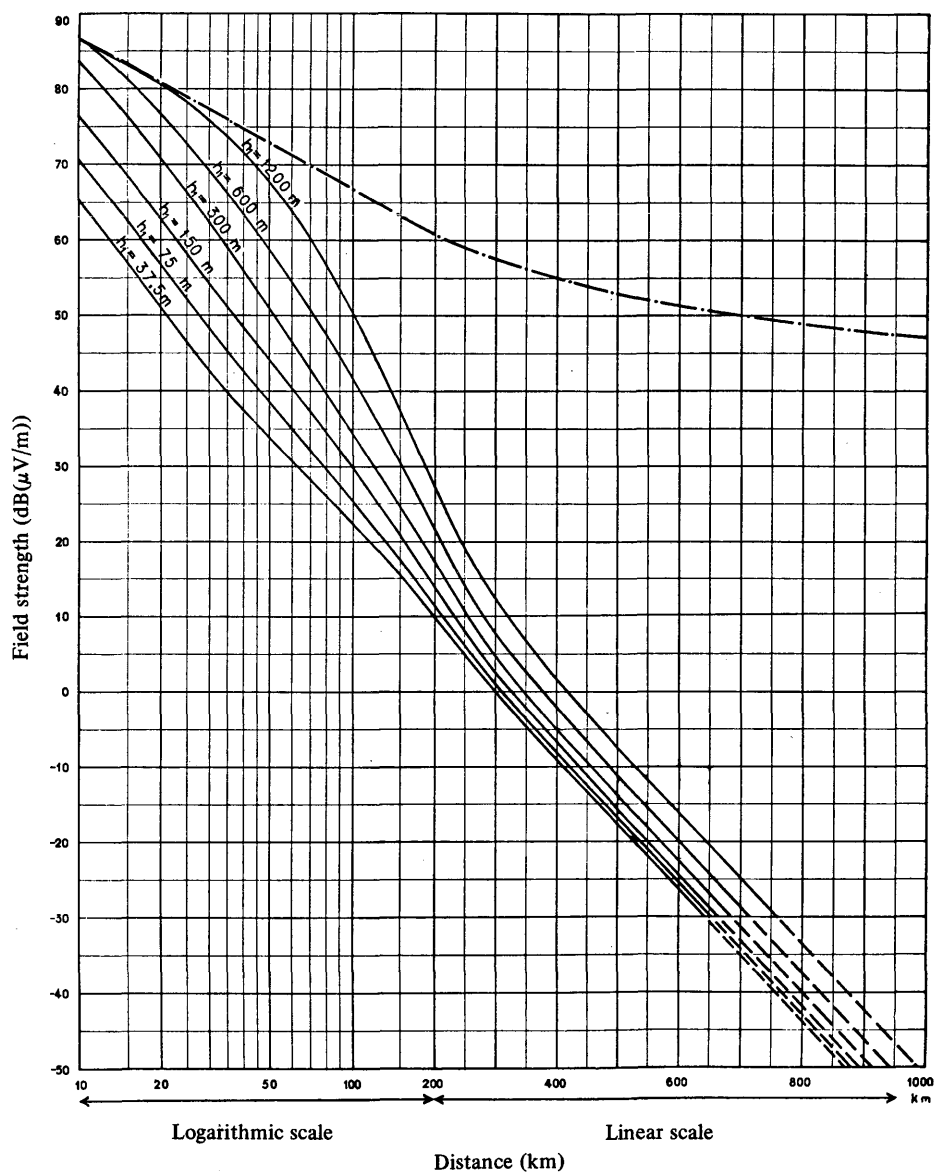


FIGURE 9 – Field strength (dB(μ V/m)) for 1 kW e.r.p.
Frequency: 450 to 1000 MHz (Bands IV and V); Land; 50 % of the time ;
50 % of the locations; $h_2 = 10$ m; $\Delta h = 50$ m

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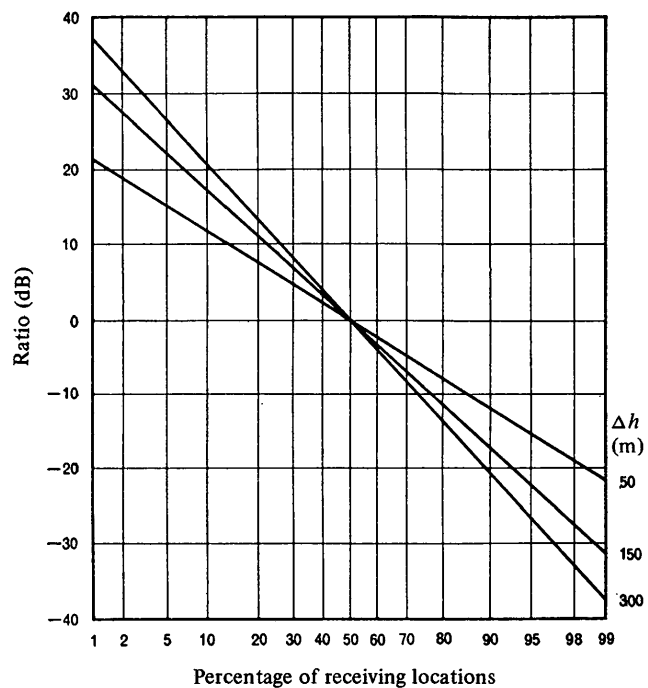


FIGURE 12 – Ratio (dB) of the field strength for a given percentage of the receiving locations to the field strength for 50% of the receiving locations

Frequency : 450 to 1000 MHz (Bands IV and V)

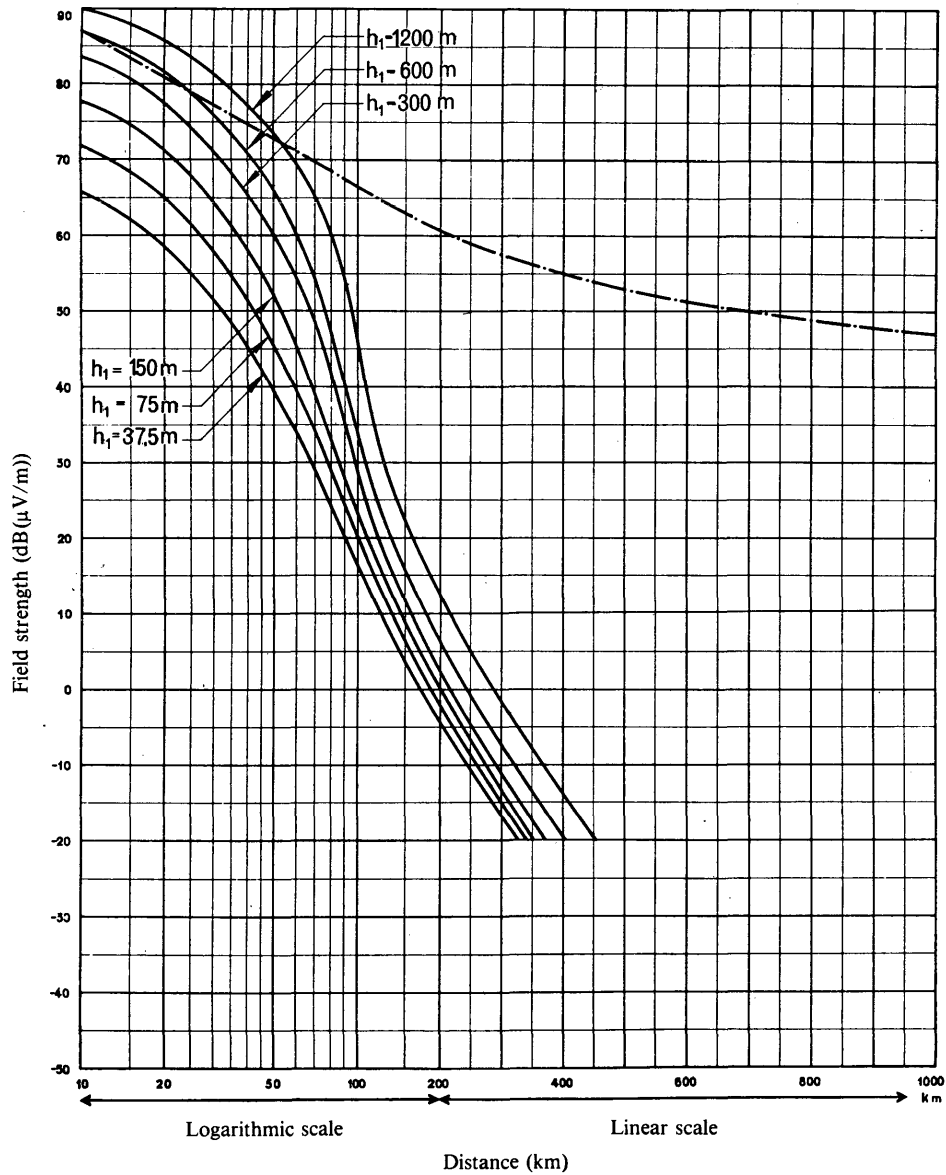


FIGURE 13 – Field strength (dB(μV/m)) for 1 kW e.r.p.
Frequency: 450 to 1000 MHz (Bands IV and V); North Sea and Mediterranean Sea;
50% of the time; 50 % of the locations; $h_2 = 10$ m

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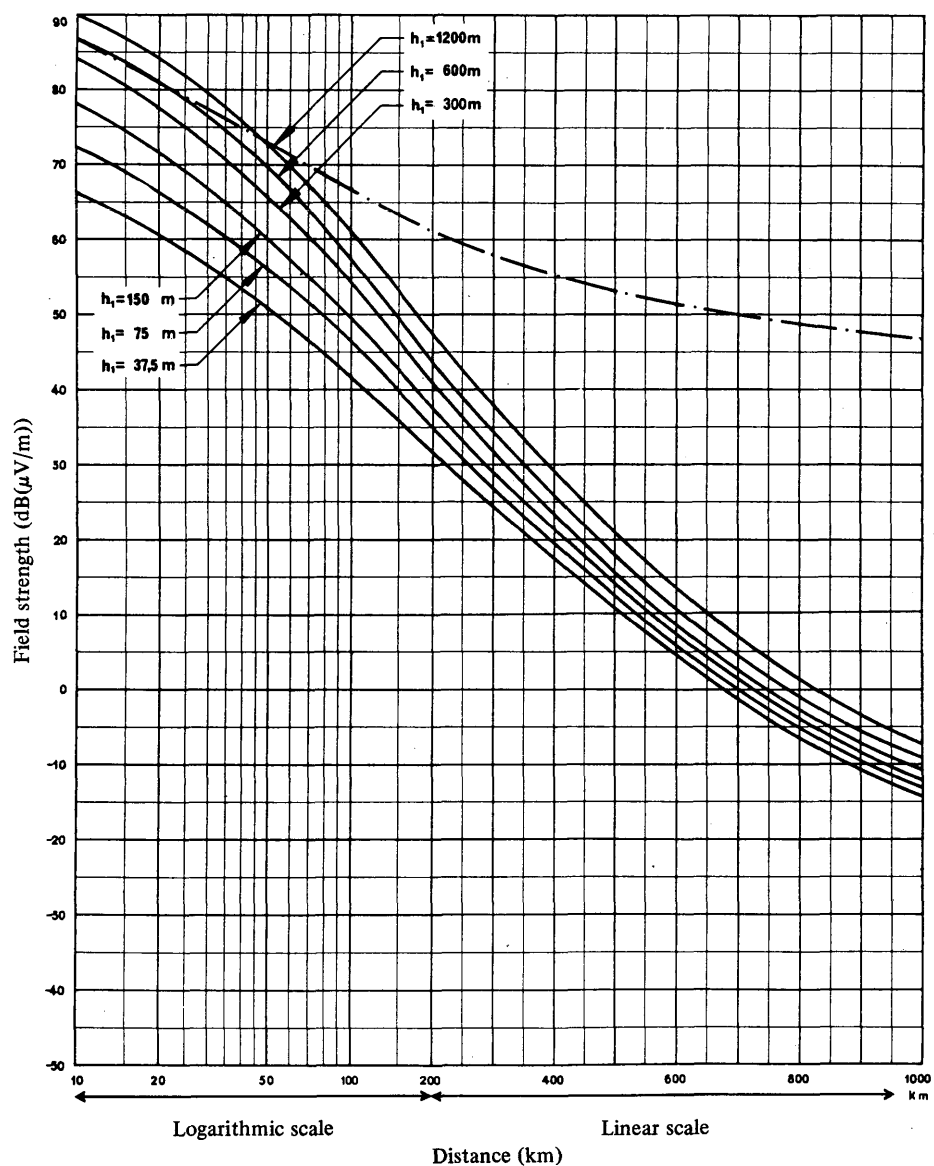


FIGURE 14b – Field strength ($\text{dB}(\mu\text{V}/\text{m})$) for 1 kW e.r.p.
Frequency: 450 to 1000 MHz (Bands IV and V); Mediterranean Sea; 10 % of time;
50 % of the locations; $h_2 = 10$ m

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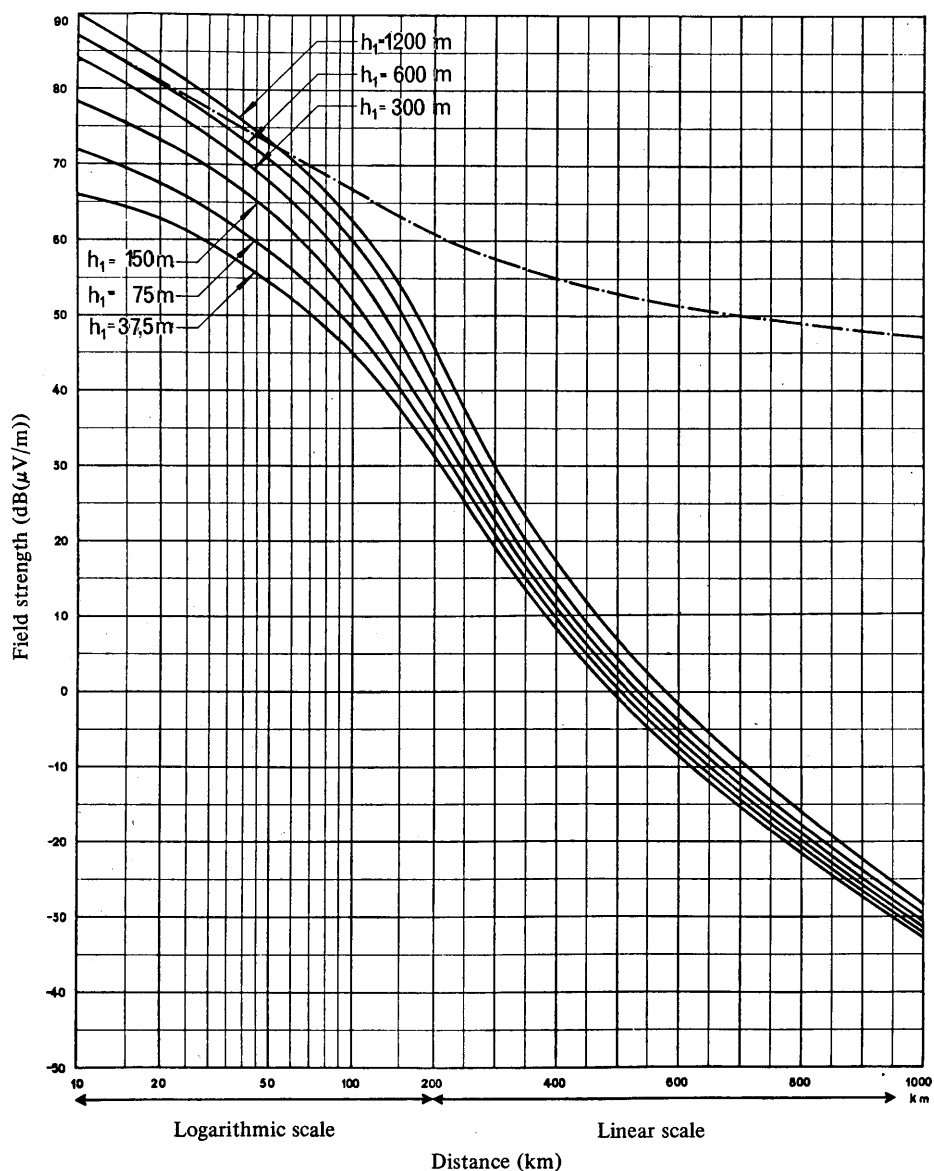
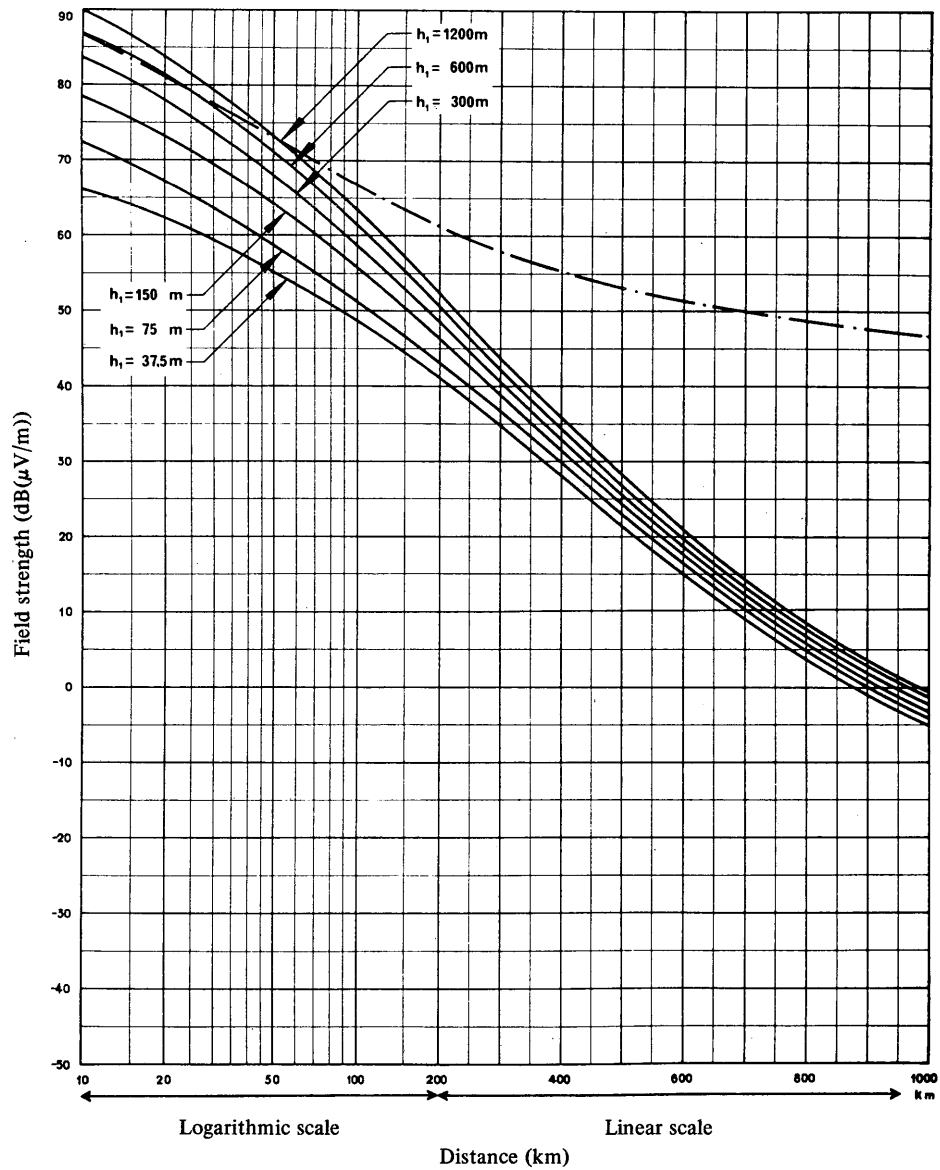


FIGURE 15a – Field strength (dB(μ V/m)) for 1 kW e.r.p.
 Frequency: 450 to 1000 MHz (Bands IV and V); North Sea; 5 % of time;
 50 % of the locations; $h_2 = 10$ m

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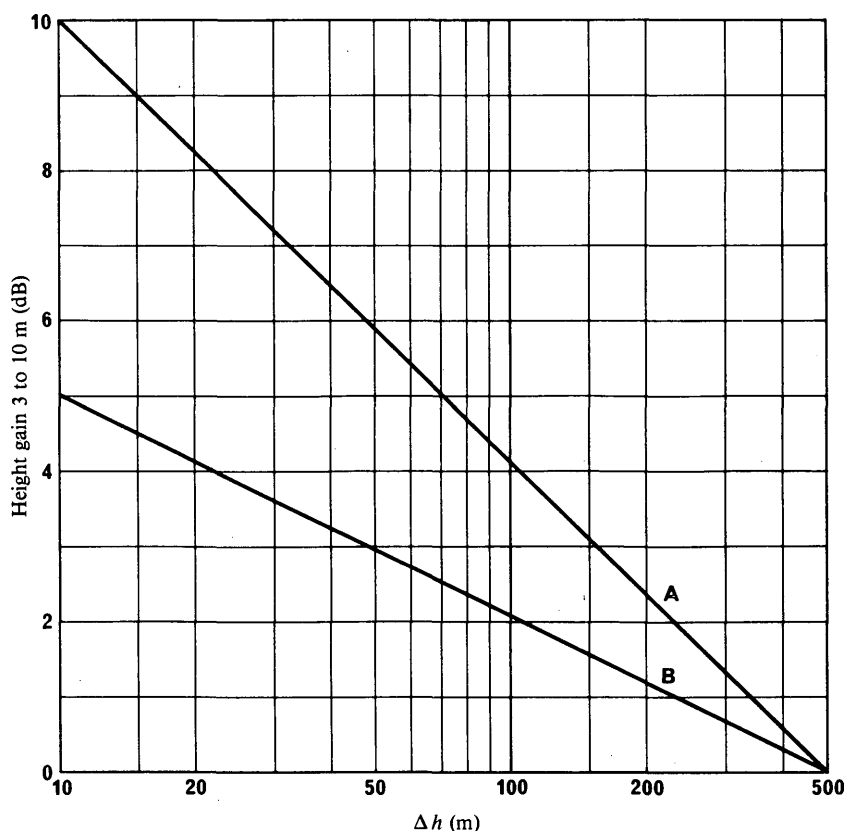


FIGURE 17 – Height-gain factor 3 to 10 m as a function of Δh for frequency 450 to 1000 MHz (Bands IV and V); parameter d represents distance from the transmitter

A: $d \leq 50$ km
B: $d \geq 100$ km

REPORT 239-5 *

PROPAGATION STATISTICS REQUIRED FOR BROADCASTING SERVICES USING THE FREQUENCY RANGE 30 TO 1000 MHz

(Study Programme 7D/5)

(1959-1963-1966-1970-1974-1978-1982)

1. Introduction

This Report gives details of the construction and use of the propagation curves in Recommendation 370, and includes descriptive statistics concerning depolarization phenomena. It also discusses the effects of urban areas and of vegetation on propagation. Section 5 indicates methods for computing field strength over mixed land-sea paths.

Propagation curves for broadcasting in the African Continent are given on pages 343-379 of the Final Acts of the African VHF/UHF Broadcasting Conference, Geneva, 1963. The curves were prepared taking into account the climatic differences expected within the continent of Africa. With transmitters operating in those frequency bands now in service, it is hoped that the African Administrations will make available additional data for comparison with these curves.

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

Report 236, as a companion to this Report, discusses the influence of the terrain on propagation and the theoretical basis for some of the parameters used with curves of field strength versus frequency, distance, antenna heights, and type of terrain. Report 228 discusses the measurement and descriptive analysis of field strengths for broadcast services and shows how propagation curves may be used to describe effective service areas. For point-to-point transmission loss prediction of long-term medians and time variability, other methods of prediction are usually employed. A compilation of some of these methods being studied by the Interim Working Party under Decision 4 has previously been published [NBS, 1967].

2. Construction of the propagation curves

The propagation curves in Recommendation 370 are for within-the-horizon and beyond-the-horizon distances. The two parts were produced by different methods. The curves incorporate a large amount of data made available by many administrations.

2.1 *Beyond-the-horizon distances*

The long-term data for distances beyond the horizon were separated into VHF and UHF classes, and further subdivided for land and sea paths.

2.1.1 *VHF*

In Figs. 1 to 4c of Recommendation 370, the portions of curves corresponding to beyond-the-horizon distances incorporate a very large amount of data over many land and sea paths. These data were obtained with transmitting and receiving antennas at various heights. The data were first normalized for a transmitting antenna height of 300 m by assuming that the field strength at a distance X km from the transmitter, for an antenna height of h_1 m, is the same as the field strength given by the curve for a transmitting antenna height of 300 m at a distance $(X + 70 - 4.1 \sqrt{h_1})$ km. The same formula was then applied to obtain the family of curves in Recommendation 370.

Propagation for distances exceeding 500 km at frequencies below about 90 MHz may be caused by sporadic-E reflection from the ionosphere for small percentages of time. Such effects are treated in Volume VI of the CCIR, in particular in Report 259 and Recommendation 534.

2.1.2 *UHF*

The same procedure was applied to obtain the portions of curves corresponding to beyond-the-horizon distances in Figs. 9, 10, 11, 13, 14a and 14b of Recommendation 370.

However, for oversea paths, and for small percentages of the time, the field strength is relatively independent of the height of the transmitting antenna. For this reason Figs. 16a and 16b, corresponding to 1% of the time, have no antenna height correction for beyond-the-horizon distances. The 5% curves, which are interpolations between the 1% and 10% curves, therefore contain approximately half the height-gain correction.

In the Mediterranean area, the measurements were taken at open coastal sites directly overlooking the sea. In order that they may be applicable for the calculation of co-channel interference in coastal towns, where the field strength may be expected to be lower than at the open sites, they incorporate a correction of approximately 7 dB relative to the measured values. It should be noted that such corrections should be applied to all measured results in the VHF and UHF bands at open coastal sites.

2.2 *Within-the-horizon distances*

Propagation curves for distances within the normal horizon were developed by comparing the data obtained from many mobile surveys and a number of long-term measurements at fixed locations for short path lengths; with theoretical propagation curves for a smooth earth at the appropriate frequencies and antenna heights. The variation in field strength with frequency proved to be relatively minor and the data were separated into VHF and UHF classes, as was done for the beyond-the-horizon distances.

Figure 1 of Recommendation 370 shows the field strength exceeded for 50% of the time at VHF. The curves within the normal horizon distances were derived by comparison with the corresponding theoretical curves for a smooth earth. These curves were then merged smoothly into the corresponding family of curves for distances beyond the horizon, as described in the previous section. Figure 1 of Recommendation 370 thus includes portions of field-strength curves within the horizon and beyond the horizon, as well as intermediate portions which are the result of merging the within-horizon and beyond-horizon curves.

Figures 2a and 4a of Recommendation 370 show field strengths exceeded for 10% and 1% of the time, respectively, at VHF. The derivation of these curves was very similar to those of Fig. 1. The assumption was made that time fading is negligible at short distances, so that the median curves of Fig. 1 may be used as a guide at short distances and merged with the appropriate 10% and 1% curves from the other Figures.

The near-distance field strengths in Figs. 3a, 3b, 4b and 4c of Recommendation 370 which show the 5% and 1% (time) oversea VHF curves, were constructed on a corresponding assumption; namely, that the 5% and 1% field strength for propagation over land and over sea would not be materially different at a distance of 10 km from the transmitter. The sea curves were consequently merged smoothly with the land curves at this distance.

The 5% time curves for propagation over land, Fig. 3c of Recommendation 370, have been derived by linear interpolation between the 1% and 10% time curves, assuming a normal distribution, such that:

$$E(5\%) = 0.653 E(10\%) + 0.347 E(1\%) \quad \text{dB}$$

A set of field-strength versus distance curves was derived for UHF in a similar fashion. These are shown as Figs. 9, 10 and 11 of Recommendation 370 for overland paths and in Figs. 13, 14a, 14b, 15a, 15b, 16a and 16b for oversea paths.

3. Additional measurement data

3.1 North Sea and Baltic Sea areas

Measurements in Bands IV and V, for distances less than 200 km in the North Sea area, indicate that for 50% and 10% of the time, field strengths may be several decibels greater than those derived from Recommendation 370, but there is better agreement for 1% of the time.

As a result of OIRT measurements [Kühn *et al.*, 1969] conducted over a period of 3 years, there is further evidence that the values shown in Recommendation 370 for the North Sea area are applicable to the Baltic Sea area. It was noted, however, that, for small percentages of time, there was a tendency for measured field strengths to be slightly higher than those predicted.

Measurements of field strength made in Sweden over periods ranging from 7 months to 4 years on transmissions over three VHF and three UHF paths in the Baltic Sea area are, as regards the VHF paths, in good agreement with values shown in Recommendation 370 for the North Sea area. The month-to-month variation of field strength is, however, found to be large, and for the worst month the measured field strengths exceeded for 1% and 10% of the month, are greater than the predicted relevant field strengths by 30 to 40 dB.

3.2 Mediterranean Sea area

It should be noted that in the Mediterranean area in particular, field strengths in the summer months [Fedi *et al.*, 1973] are considerably greater than in the winter months. VHF and UHF measurements of field strengths were carried out in Italy [CCIR, 1974-78] on two different paths in the central Mediterranean area. These measurements were made over a two-year period with various receiving antenna heights. The results obtained were compared with those calculated for 1%, 5% and 10% of the time by using the Figures of Recommendation 370, and applying the formula given in § 2.1.1, for the transmitting antenna heights, and a similar formula for the receiving antenna heights. Good agreement was obtained between calculated and measured results at UHF, but measured results were from 3 to 14 dB higher than calculated at VHF.

In addition, measurements conducted in Italy [CCIR, 1978-82a] on 29 grazing or transhorizon paths (four all-land paths, nine primarily sea paths and sixteen mixed land-sea paths) in the period between 1968 and 1977 gave valuable results which could be used for further propagation studies.

3.3 Central Europe

An important conclusion to be drawn from measurements made by the OIRT, on five paths in Central Europe at 1100 MHz over a period of three years, was that the variation of field strength for several paths was considerably greater than indicated by Recommendation 370. These paths are such that they are particularly influenced by the overlapping effects of more than one propagation mechanism. For example, it was observed that over paths of some 200 km in length, the fading range (the difference between the field strength exceeded for 1% and 50% of the time) is of the order of 30 dB, compared with a difference of about 18 dB which would have been expected from the curves of Recommendation 370, drawn for a median frequency of about 700 MHz (middle of Bands IV and V).

Additional measurements carried out in the German Democratic Republic in cooperation with the Administrations of the Socialist Republic of Czechoslovakia and the People's Republic of Poland [CCIR, 1978-82b], over a period of several years, at 1100 MHz, on 9 transhorizon paths with typical conditions for Central Europe, up to distances of 400 km, showed that the fading range lies between the values 19 dB and 32.5 dB. These values are greater by almost 15 dB in comparison with the values which could be expected following Recommendation 370 and were observed for distances up to 250 km. This difference decreases with the distance, but is still 3 dB at a distance of 400 km. In addition, a difference of 9 dB was observed between the measured and predicted fading range at 500 MHz on paths with lengths of approximately 200 km.

3.4 *North America*

Measurements by Canada of VHF and UHF signal strengths exceeded for 50% and 10% of the time, over non line-of-sight paths between 125 and 250 km in length in the Great Lakes region of continental North America, show that significant diurnal and seasonal variations of signal strength occur [Palmer, 1980]. Signal strengths exceeded for both 50% and 10% of the time have minimum values during the afternoon and in winter and maximum values during the night and in summer. The diurnal variability of median signal strength is 5 to 9 dB in summer and 2 to 3 dB in winter. The seasonal variability ranges between 6 and 15 dB, the higher values being observed on paths, a significant fraction of which is over water. Signal strengths exceeded for 10% of the time exhibit diurnal variations of 2 to 6 dB in winter and between 10 and 26 dB in summer. The seasonal variation is 2 to 6 dB at noon and 15 to 25 dB at night. As for the median values of signal strength, the higher values of diurnal and seasonal variability are observed on paths, a significant fraction of which is over water.

Measurements carried out in the Gulf of Mexico have shown that the field strengths, particularly in the summer, may exceed the figures given by the curves in Recommendation 370 for the North Sea by as much as 20 dB for distances exceeding some 200 km.

3.5 *Asia*

Measurement data obtained from certain regions in India show systematically lower values than those expected from the VHF propagation curves in Recommendation 370, by 5 to 10 dB. Based on that data, collected by All India Radio, provisional VHF land propagation curves were derived for tropical India for 50% of the time and 50% of the locations (see Fig. 1). [CCIR, 1978-82c].

Measurements made in India [CCIR, 1978-82d] indicated that the difference between the field strengths exceeded for 10% and 90% of the time, on VHF Band III television signals over a transhorizon path of length of 216 km is 4.2 dB for the whole year and 3.5 and 5.5 dB in summer and winter respectively, showing marginal seasonal changes.

In addition, anomalous propagation of VHF Band I television signals, believed to be due to super-refraction has been observed in India during the pre-monsoon months [CCIR, 1978-82e] indicating that these signals could propagate, for a considerable period of time, over distances of the order of 1000 km.

3.6 *Other areas*

Some observations indicate that in particular conditions and for small, but not insignificant, percentages of time perceptible signals may be received from high-power transmitters at distances exceeding 4000 km in tropical regions. For example, a field strength of 0.15 $\mu\text{V/m}$ for an effective radiated power of 1 kW and transmission frequency of 417 MHz was measured at a distance of 4740 km (across the Atlantic Ocean) for approximately 2% of the year [Misme, 1966].

4. **Influence of irregularities in the terrain**

Random selection of broadcast receiving locations on or near roads and in valleys, results in higher values of the median transmission loss than are seen with most carefully selected receiving sites. Terrain roughness first increases the expected or median field strength by breaking up the destructive phasing between direct line-of-sight propagation and radio waves reflected or diffracted by the ground. Then increasing terrain irregularity and terrain clutter will reduce signals due to shadowing, absorption (including attenuation caused by vegetation) and the scattering and divergence or defocusing of diffracted waves. Convergence or focusing and specular reflection also play a part in these multipath phenomena, as does average refraction, turbulence and stratification of the refractive-index structure of the atmosphere.

Two phenomena play a major part in determining the complex standing waves which determine antenna height gain at a fixed distance from a transmitter. With reflection or diffraction from a surface which is sufficiently smooth and sufficiently large, a linear height gain is to be expected for lower heights, and as a receiving antenna is raised above irregularities and clutter, a height gain is to be expected for the quite different reasons mentioned in the preceding paragraph.

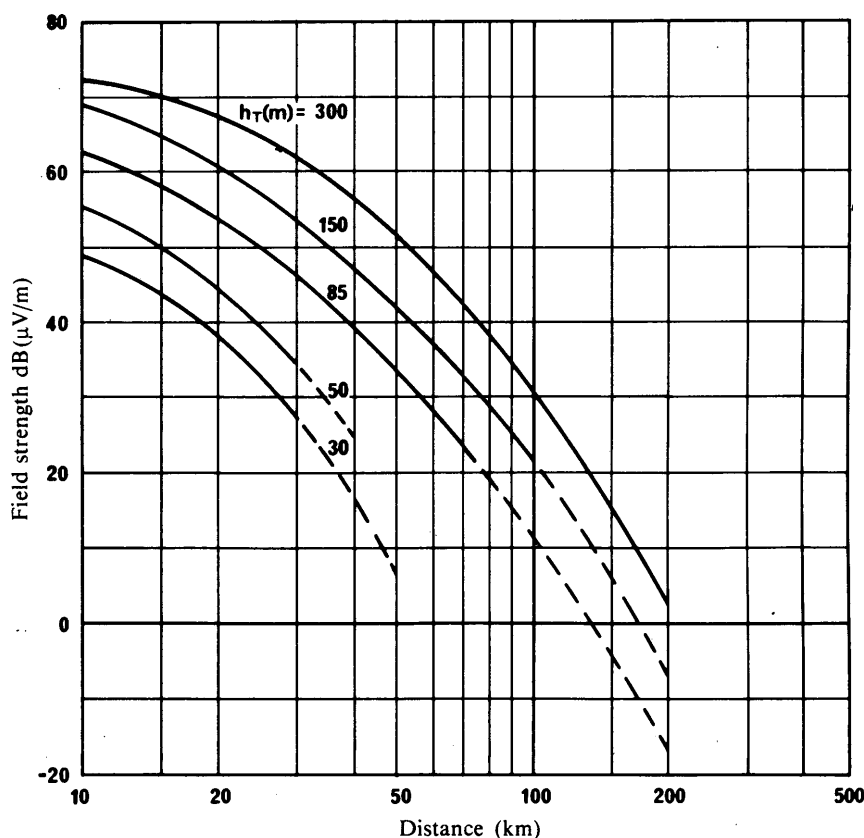


FIGURE 1 — Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency: 60–250 MHz (Bands I, II and III) Indian tropical region; 50% of the time; 50% of the locations; $h_2 = 10$ m

(see also Fig. 1 of Recommendation 370)

Depolarization phenomena are discussed in Report 122 and some recent measurements are discussed below. Here again site selection is of prime importance, either to reject unwanted signals, for instance, or to take advantage of depolarization with diversity; polarization discrimination is better in open country and with high signal levels than when field strengths are low, as, for example, where a UHF receiving antenna is surrounded by obstacles.

The nature of the receiving site also has other important influences on wave polarization phenomena. For example, VHF observations in the Federal Republic of Germany have shown that, in shadow regions, whereas reflections have little effect on horizontally polarized signals, their effects on vertically polarized signals are often great enough to distort FM reception seriously.

It is useful now to discuss some aspects of the problems arising from irregular terrain, vegetation, etc., with special reference to the use of VHF and UHF propagation curves.

4.1 The parameter Δh

The parameter Δh is used to define the degree of terrain irregularity. It is the difference in the heights exceeded by 10% and 90% of the terrain, including any sea path, over propagation paths in the range of 10 km to 50 km from the transmitter (see Fig. 6 of Recommendation 370). Computer methods for derivation of Δh are given in [Thélot, 1981]. All of the curves for propagation over land refer to the kind of rolling irregular terrain found in many parts of Europe and North America, for which a value of Δh of 50 m is considered representative. The influence of irregularities in the terrain increases with frequency. It is therefore of more importance in the UHF (Bands IV and V) than in the VHF (Bands I, II and III). For this reason the parameter $\Delta h/\lambda$ is used in some cases (see § 4.3 for example).

If one could visualize an ideal experiment in which long-term recordings are made at a large number of locations, then the distribution of time median for each and every site will result in a location distribution such as Fig. 5 of Recommendation 370 for VHF over typical rolling terrain for a Δh of 50 m.

It is further assumed that the change in the range of variation, i.e., the slope, of this location distribution is approximately unaffected by the roughness of the terrain at VHF, so that the distribution of Fig. 5 of Recommendation 370 may be assumed to apply for most practical values of Δh .

At UHF, typical location distributions for various values of Δh are shown in Fig. 12 of Recommendation 370; the changes in the range of variation cannot be assumed to be negligible.

Not only does the range of variation of the location distribution increase with the terrain roughness, but also the average received field strengths are reduced as the terrain becomes rougher, i.e., Δh becomes greater. Again, this effect increases with frequency. Recent measurements in the Czechoslovak Socialist Republic and the United Kingdom confirm that the corrections given in Figs. 7 and 8 of Recommendation 370 apply for distances up to 100 km in Bands III, IV and V [EBU, 1965]. Measurements carried out by the OIRT [Kühn, 1968] have indicated the requirement for using the same correction factor in Band II as in Band III.

In the above, the attenuation correction factor which is given in Figs. 7 and 8 of Recommendation 370 should be subtracted from the field strength for the required value of Δh .

Recent work has shown the single parameter Δh to be inadequate to define precisely the attenuation correction factor. It has been found, for example, that any location along transmission paths broadly defined by $\Delta h \approx 50$ m, the median field strength predicted may be in error by more than 20 dB, although it is generally within 10 dB, the error in the VHF bands tending to be less than at UHF. For values of Δh other than 50 m, these errors may be even greater. The Δh correction may be of less relevance for paths greatly in excess of 50 km particularly if the type of terrain is changing. For interference calculations over great distances, the Δh correction should therefore be applied with caution in order not to underestimate interfering signal strengths.

Efforts have been made to improve accuracy by the introduction of further terrain parameters on an empirical basis. These methods are listed below and may be used in cases where the prediction accuracy required is greater than that associated with the use of parameter Δh alone:

4.1.1 A method developed in the Federal Republic of Germany in which the mean slope of the terrain plays an important role in the derivation of the factor, as does the r.m.s., value of Δh .

4.1.2 A method developed in the People's Republic of Poland and based upon a modification of the TASO method [LaGrone, 1960], in which the factor is dependent upon both Δh and the mean wavelength of terrain undulations.

4.1.3 A method developed in the United Kingdom [EBU, 1965] in which factors dependent upon Δh and the mean slope of the terrain are used. A similar method has also been developed in Japan for the prediction of field strengths [Okumura *et al.*, 1968].

4.1.4 The various prediction methods described above are all based either on modifications of the field strength derived for propagation over a smooth spherical earth or on the assumption of well-defined diffracting obstacles along the transmission path. However, in a further method, recently developed in Japan [Okumura *et al.*, 1968], the free-space field strength is taken as the initial standard of reference for propagation over any kind of terrain.

4.2 Receiver terrain correction

If more precision is required for predicting the field strength for reception conditions in specific areas, e.g., in a small receiving area, a correction may be made based on a "terrain clearance angle". This angle, θ , should be representative of those angles in the reception area, which are measured between the horizontal at the receiving antenna and the line which clears all obstacles within 16 km in the direction of the transmitter. The example in Fig. 2 also indicates the sign convention which is negative if the line to the obstacles is above the horizontal.

From the terrain clearance angles, appropriate correction factors are given in Fig. 3; they should be applied to the results from Recommendation 370 for 50% of the locations (Figs. 5 and 12 of Recommendation 370 relating to other percentages may not be applicable to results thus corrected).

Corrections for terrain clearance angles outside the range -5° to 0.5° , are not given in Fig. 3, because of the smaller number of paths concerned in the study. However, they may be obtained tentatively by linear interpolation between the curves of Fig. 3 and limiting values of 30 dB for VHF and 40 dB for UHF at 1.5° and -40 dB for both VHF and UHF at -15° , subject to the condition that the free-space field strength is not exceeded.

EBU calculations for over 200 paths in the Federal Republic of Germany, Finland, France and the United Kingdom indicate that when applying the correction as defined above statistically a reduction of about 4 dB in the difference between the predicted value and a reference value, the latter being determined using the computer method referred to in § 6.1, may be achieved.

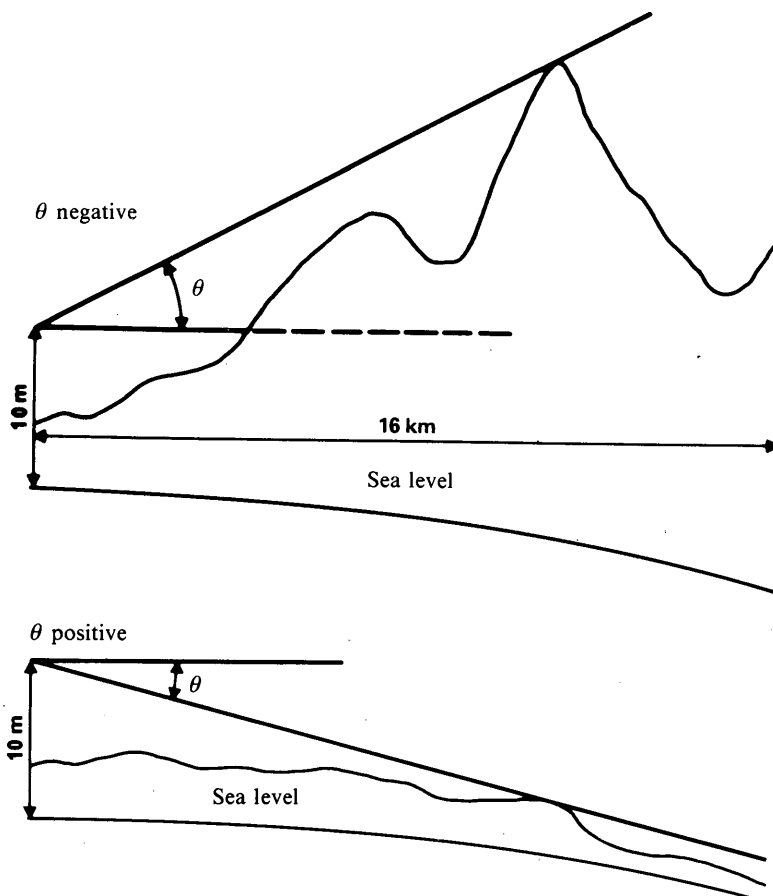


FIGURE 2 — Terrain clearance angle

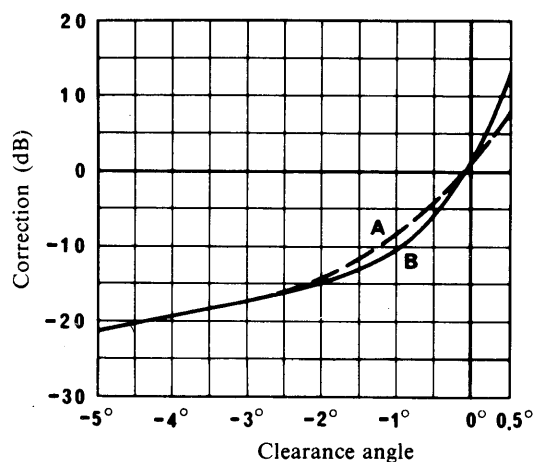


FIGURE 3 — Receiving terrain clearance angle correction

Curves A: VHF
B: UHF

4.3 Path-to-path variability

A recent survey of land mobile and broadcast system data (20 MHz to 10 GHz) in the USA [Longley, 1976] has shown the expected large variability of data from one path to another of the same length. This variability increases with radio frequency and terrain irregularity and is strongly influenced by the presence of buildings and trees near the path terminals. However, by normalizing the terrain irregularity parameter Δh with respect to wavelength (λ), the standard deviation σ_L of the path-to-path variability, for paths of approximately equal length, may be estimated for $(\Delta h/\lambda) < 3000$ by

$$\sigma_L = 6 + 0.69 (\Delta h/\lambda)^{1/2} - 0.0063 (\Delta h/\lambda) \quad \text{dB} \quad (1) *$$

or for $(\Delta h/\lambda) \geq 3000$ by

$$\sigma_L = 25 \text{ dB} \quad (2)$$

Except for data obtained above 300 MHz in a rugged mountainous area, 90% of all observed standard deviations fell within 2 dB of the values calculated by (1) and (2).

A comparison of equations (1) and (2) was made with a body of independent measurements at 172 and 410 MHz over 130 paths (in a flat, forested area of Florida, a hilly, forested area of California and in the rugged, arid mountains of Arizona) with antenna heights of 1 m or less. The differences between equations (1) or (2) and the observed standard deviations were within 1.5 dB for values of $\Delta h/\lambda$ from 15 to 175.

4.4 Effect of change in the height of the receiving antenna

4.4.1 Variation in field strength with height

Work by various administrations has indicated the field strength reduction which may be expected in changing the receiving antenna height from 10 m to 3 m above ground level. The values which may be used are given in Recommendation 370 although more recent work in the United Kingdom [CCIR, 1978-82f] suggests that the effect of changing receiving antenna height on received signal levels in Band II does not depend on distance; however, further measurements are needed.

Measurements made in the United Kingdom further indicate that, whereas horizontally-polarized and vertically-polarized signal components of transmissions both exhibit linear field-strength variation over the range 10 m to 3 m above ground level, there is little change in the received vertical component at heights below 3 m.

At any specific location in an area, the actual field strength variation may differ by many decibels from the median value.

4.4.2 Ratio between field strengths in town and in surrounding areas

Presently available evidence suggests that, provided receiving antenna heights are sufficiently above the local roof level, the received field strength will be substantially that given by the curves in Recommendation 370.

Experience has shown that in Bands I and II no great difference exists between field strengths measured at a height of 10 m in rural and urban areas. In Band III, work done in the People's Republic of Poland has shown that field strengths at a height of 10 m in suburban areas are much the same as in equivalent rural areas, and the maximum attenuation in the centre of an urban area is as follows: in an urban area of 400 000 people, 16 dB at 10 m and 6 dB at 16 m (the average roof level) and in an urban area of 80 000 population [TASO, 1959], 12 dB at 10 m. In heavily built-up areas, the received field strength may be reduced by 6 to 16 dB, dependent upon the character of the buildings in the area. Further detailed measurements made in Band IV in the People's Republic of Poland [Ogulewicz, 1971] have attempted to relate the attenuation in built-up areas with a building density factor. This work was carried out at the limit of the service area, with low angles of arrival of the received signal, and showed that the

* The coefficients in equation (1) differ from those [Longley, 1976] where Δh is defined as a function of distance rather than for a fixed range of 10 to 50 km.

attenuation could range from 3 dB to 28 dB, for low and high values of building density factors, respectively. However, it is recognized that, in areas of high density of buildings, the excess height gain (with reference to a 10 m standard) must be taken into account; the main value being equal to approximately 12 dB for large cities where the height of the receiving antenna is doubled. For the UHF bands, recent work in the United Kingdom has shown a median loss of 9 dB for urban areas in south-east England. Experiments made in Italy, at VHF and UHF, in heavily built-up areas have shown that the additional loss factor depends principally on the density and height of the buildings, on the angle of arrival of the wave at the receiving antenna and on the orientation of the street with respect to the direction of the transmitter from the receiving site.

It is desirable to obtain larger statistical samples for each type of urban situation.

4.4.3 *Rooftop versus indoor antennas*

The performance of existing rooftop and indoor antennas in New York City has been related to both signal strength measurements and subjective determination of television picture quality. Point-to-point transmission loss distributions were log-normal with standard deviations of 16 and 14 dB, respectively, for rooftop and indoor measurements. Median values for these distributions differed by amounts ranging from 16 to 35 dB depending on the frequency, the type of building, and the type of path. This difference was about 7 dB greater at 570 MHz than at 55 MHz, 10 dB greater for reinforced concrete buildings than for wooden buildings, and 5 dB greater for locations on Manhattan Island than for locations outside Manhattan Island.

In the United Kingdom, measurements made at UHF (600 MHz) inside two-storey suburban houses, on the ground floor and in the lofts, show a mean attenuation of 19 dB and 10 dB respectively, compared with measurements at 10 m in the street outside the house [Sofaer and Bell, 1966].

4.5 *Depolarization phenomena*

The depolarization factor is considered here to be the ratio of the amplitude of the orthogonally polarized component, produced by some propagation mechanism, to the amplitude of the original plane polarized wave.

Where the transmitter itself is at a clear site, the polarization discrimination achieved at rooftop level in built-up areas by the use of orthogonal polarization, may have a median value of 18 dB; with corresponding values exceeded at 90% and 10% of receiving sites, 9 dB and 29 dB respectively (see Report 122). Measurements carried out in the United Kingdom show close agreement with the above median value for receiving antenna heights between 2.5 m and 10 m. The discrimination is better in open country and worse at cluttered receiving sites, or where reception is poor; also the United Kingdom measurements show that the discrimination is poor for low receiving antenna heights.

Measurements made in the Federal Republic of Germany, at 520 and 700 MHz have indicated 1 to 2 dB more depolarization for vertically, as compared with horizontally, polarized waves. Also, studies in the United Kingdom at 570 MHz have shown that the discrimination obtained with a vertically polarized antenna directed 180° away from an incident horizontally polarized wave, exceeds the front-to-back ratio (16 dB) of the antenna by 6 dB.

Studies have been made in the Czechoslovak Socialist Republic [Králik *et al.*, 1961 and 1962] and by other administrations on the effect of the type of terrain in the vicinity of the receiving site. Measurements have been made at a frequency of 570 MHz within the service area, and show that depolarization increases in a similar manner to diffraction loss, with an increase in the roughness of the terrain at the receiving site. Results are summarized in Table I.

The last item in Table I shows that a wooded environment causes much greater depolarization than that found in other areas having a similar path loss.

Measurements made in the the Federal Republic of Germany, at 520 and 700 MHz near Heidelberg, indicated the effects of frequency and building density to be negligible. The effect of variation in the parameter Δh is shown in Table II.

TABLE I

Type of terrain	Median path loss relative to free space (dB)	Polarization discrimination exceeded at 90 % of sites (dB)
Suburban, optical to transmitter	7	18
Suburban, in slight diffraction zone	26	13
Suburban, in moderate diffraction zone	31	10
Suburban, in deep diffraction zone	40	4
Thickly wooded area (in leaf) with no obstruction due to terrain	27	2

TABLE II

Type of terrain	Δh (m)	Polarization discrimination exceeded at 90 % of sites (dB)	Polarization discrimination exceeded at 50 % of sites (dB)
Flat	10	20	30
Hilly	50	14	27
Mountainous	200	0	16

4.6 Attenuation due to vegetation

Attenuation through woodland and vegetation varies with frequency. In practice it has been observed, however, that attenuation due to vegetation does not exceed values of the order of 30 dB for frequencies below about 500 MHz [Ogulewicz, 1972].

Measurements [Sofaer and Bell, 1966] made behind deciduous woods in summer and winter indicate that, although the attenuation due to foliage is not negligible at UHF, it is significantly less than that due to bare trees.

Comparative measurements for horizontally and vertically polarized waves have been recorded, and, although the difference is not always marked, there appears to be a tendency for the attenuation to be slightly greater with vertical polarization.

Propagation through forested terrain is treated in greater detail in Report 236.

4.7 Attenuation due to buildings

Attenuation due to buildings also varies with frequency. Work in Japan [Kinase, 1969] gives values of attenuation behind buildings as a function of the frequency, the height of buildings, their extent in the transmitter direction and the angle of arrival. A parameter is introduced, which represents the effects of environmental clutter in the vicinity of the receiving site. This is in addition to the correction for terrain irregularities. Results show good agreement with measurements at 100, 200 and 700 MHz.

Measurements in the United Kingdom [Sofaer and Bell, 1966] give values of attenuation behind various types of buildings at UHF (600 MHz) of as much as 30 dB.

Measurements made in the Federal Republic of Germany have shown that, at 190 MHz, the field strength over line-of-sight paths is 3 dB lower with vertical as compared with horizontal polarization, and for shadowed regions, the difference increases to 4.5 dB. Other measurements in shadowed regions at 97 MHz have shown this difference to be 5 dB with a deviation of ± 5.2 dB. At 500 MHz, the propagation differences between polarizations are much less marked and the corresponding values are 0 dB and 1.5 dB. The subjective quality of television pictures was found to correlate with these measurements.

5. Mixed land/sea paths

When the transmission path is over a mixture of land and sea, an estimate must be made of the effect of the mixed path on the received signal. For general planning purposes a suitable interpolation between curves for all land and all sea propagation in Recommendation 370 may be made (Method A).

When the average value of the horizon angles from receiving antennas in the reception area can be estimated, a method developed in Sweden [Rue, 1976] may be employed (Method B).

In specific cases the character of the land/sea profile between the transmitter and the point of reception may be incorporated in a prediction calculation, using a computer, [Causebrook and King, 1974] giving an individual estimate for the mixed path (see § 6.1).

Other computer methods can also be used [Longley and Rice, 1968; Causebrook and Lee, 1972; Causebrook *et al.*, 1969] for making estimates of received field strengths over mixed paths.

5.1 Method A

The following method can be used for interpolation between the land and sea curves of Recommendation 370; all field strengths are in dB(μ V/m):

$E_{L,t}$: field strength for land path equal in length to the mixed path for $t\%$ of the time for $\Delta h = 50$ m,

$E_{S,t}$: field strength for sea path equal in length to the mixed path for $t\%$ of the time,

$E_{M,t}$: field strength for mixed path, for $t\%$ of the time,

d_S : length of sea path,

d_T : length of total path.

The median field strength for mixed-path ($E_{M,t}$) for all values of t in the VHF band, and for t equal to 10% and 50% in the UHF band can be determined by using the following formula:

$$E_{M,t} = E_{L,t} + \frac{d_S}{d_T} [E_{S,t} - E_{L,t}] \quad (3)$$

In the case of t equal to 1% and 5% in the UHF band the median field strength can be determined from the formula:

$$E_{M,t} = E_{L,t} + A [E_{S,t} - E_{L,t}] \quad (4)$$

where A is an interpolation factor given in Fig. 4.

A Δh correction factor may be applied for $E_{L,t}$ using the appropriate value from Figs. 7 and 8 in Recommendation 370.

This method cannot be applied for distances well beyond horizon range.

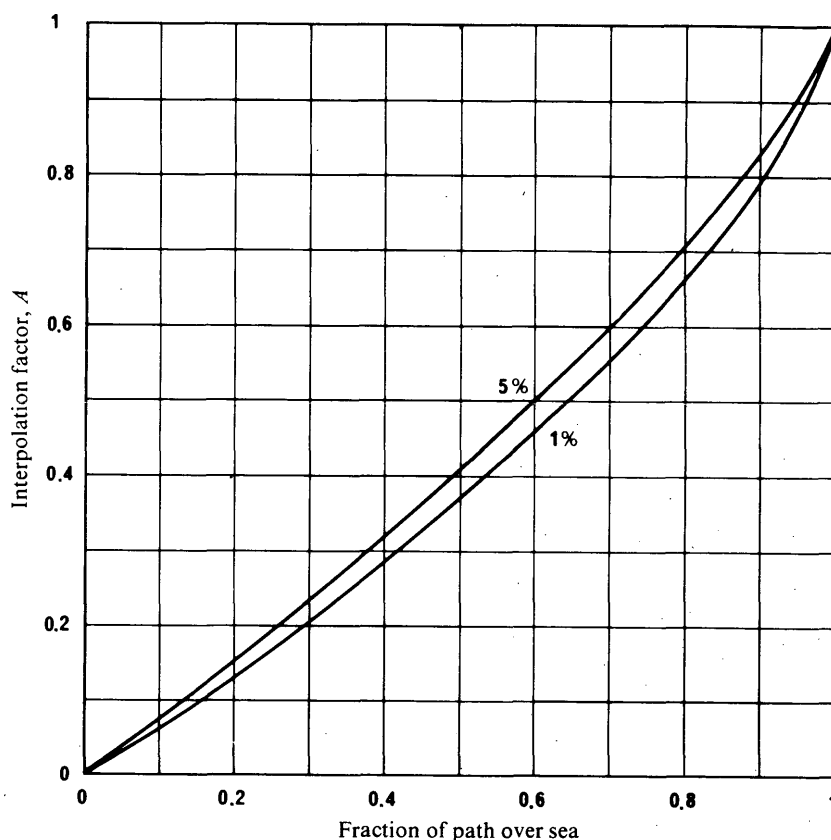


FIGURE 4 — Interpolation for mixed land/sea paths

5.2 Method B

Like Method A, Method B [Rue, 1976] may also be used in conjunction with the propagation curves of Recommendation 370, for all land and all sea paths in order to estimate field strengths over a mixed path when an estimate can be made of the average value of the horizon angle from receiving antennas in the reception area.

6. Computer methods for field-strength calculation

For field-strength calculation over individual paths where a great degree of accuracy is required, computer-oriented methods may be used.

6.1 A full scale computer method has been developed in the United Kingdom [Causebrook and King, 1974] for individual path profiles of any type. Features of this method, which is based on diffraction theory and the statistical analysis of measurements, include a variable effective Earth-curvature factor which is made dependent on the appropriate time percentage, and an allowance for ducting phenomena at UHF for small time percentages.

6.2 The above method will generally provide the most accurate predictions but simple computer methods from the USA [Longley and Rice, 1968] and the UK [Causebrook and Lee, 1972; Causebrook *et al.*, 1969] are also available and may be satisfactory in many applications.

Modifications of the UK method have been made in the People's Republic of Poland [CCIR, 1978-82g] and Italy [CCIR 1978-82a] to take more fully into account the influence of mountainous terrain and the tropospheric parameters appropriate to the specific regions. Good agreement was obtained between calculated and measured results.

A simple, small-computer oriented method has been developed in the Socialist Federal Republic of Yugoslavia [CCIR, 1978-82h] for coordination and planning purposes in the VHF and UHF bands, also giving prediction results in good agreement with the measured data.

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[1978-82]: a. 5/340 (Italy); b. 5/303 (German Democratic Republic); c. 5/216 (India); d. 5/215 (India); e. 5/214 (India); f. 5/266 (United Kingdom); g. 5/79 (Poland (People's Republic of)); h. 5/119 (Yugoslavia (Socialist Federal Republic of)).

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RECOMMENDATION 528-1 *

**PROPAGATION CURVES FOR AERONAUTICAL SERVICES
USING THE VHF, UHF AND SHF BANDS**

(Study Programme 7F/5)

(1978-1982)

The CCIR,

CONSIDERING

- (a) that there is a need to give guidance to engineers in the planning of radio services in the VHF, UHF, and SHF bands;
- (b) that the propagation model used to generate the curves given in Annex II is based on a considerable amount of experimental data (see Annex I);
- (c) that the aeronautical service often provides a safety of life function and therefore requires a higher standard of availability than many other services;
- (d) that a time availability of 0.95 should be used to obtain more reliable service,

UNANIMOUSLY RECOMMENDS

that the curves given in Annex II be adopted to determine the basic transmission losses for 5%, 50% and 95% of the time for antenna heights (for both the ground station and aircraft) likely to be encountered in the aeronautical services.

Note. — It must be emphasized that these curves are based on data obtained mainly for a continental temperate climate. The curves should be used with caution for other climates.

ANNEX I

DEVELOPMENT AND APPLICATION OF THE CURVES

Transmission loss prediction methods given in [NBS, 1967] have been extended and incorporated into the IF-77 propagation model [Johnson and Gierhart, 1979] that determine basic transmission losses for 5%, 50% and 95% of the time for antenna heights applicable to the aeronautical services [Johnson and Gierhart, 1978]. These methods are based on a considerable amount of experimental data, and extensive comparisons of predictions with data have been made [Johnson and Gierhart, 1979]. In performing these calculations, a smooth (terrain parameter $\Delta h = 0$) Earth with an effective Earth radius factor k of $4/3$ (surface refractivity $N_s = 301$) was used along with compensation for the excessive ray bending associated with the $k = 4/3$ model at high altitudes. Constants for average ground horizontal polarization, isotropic antennas, and long-term power fading statistics for a continental temperate climate were also used. Although these parameters may be considered either reasonable or worst-case for many applications, the curves should be used with caution if conditions differ drastically from those assumed.

With the exception of a region "near" the radio horizon, values of median basic transmission loss for "within-the-horizon" paths were obtained by adding the attenuation due to atmospheric absorption (in decibels) to the transmission loss corresponding to free-space conditions. Within the region "near" the radio horizon, values of the transmission loss were calculated using geometric optics, to account for interference between the direct ray and a ray reflected from the surface of the Earth. Segments of curves resulting from these two methods were joined to form a curve that shows median basic transmission loss as increasing monotonically with distance.

The two-ray interference model was not used exclusively for within-the-horizon calculations, because the lobing structure obtained from it for short paths is highly dependent on surface characteristics (roughness as well as electrical constants), atmospheric conditions (the effective Earth radius is variable in time), and antenna characteristics (polarization, orientation and gain pattern). Such curves would often be more misleading than useful, i.e., the detailed structure of the lobing is highly dependent on parameters that are difficult to determine with sufficient precision. However, the lobing structure is given statistical consideration in the calculation of variability.

* This Recommendation is brought to the attention of Study Group 8.

For time availabilities other than 0.50, the basic transmission loss, L_b , curves do not always increase monotonically with distance. This occurs because variability changes with distance can sometimes overcome the median level changes. Variability includes contributions from both hourly-median or long-term power fading (Report 238) and within-the-hour or short-term phase interference fading (Report 415). Both surface reflection and tropospheric multipath are included in the short-term fading.

The curves provided in Annex II are selected curves from a much larger set of computer-generated smoothed curves [Johnson and Gierhart, 1980].

The basic transmission loss, $L_b(0.05)$ curves may be used to estimate L_b values for an unwanted interfering signal that is exceeded during 95% (100% - 5%) of the time. Median (50%) propagation conditions may be estimated with the $L_b(0.50)$ curves. The $L_b(0.95)$ curves may be used to estimate the service range for a wanted signal at which service would be available for 95% of the time in the absence of interference.

The expected protection ratio or wanted-to-unwanted signal ratio exceeded at the receiver for at least 95% of the time, $R(0.95)$, can be estimated using the Annex II curves as follows:

$$R(0.95) = R(0.50) + Y_R(0.95) \quad (1)$$

$$R(0.50) = [P_t + G_t + G_r - L_b(0.50)]_{\text{wanted}} - [P_t + G_t + G_r - L_b(0.50)]_{\text{unwanted}} \quad (2)$$

and

$$Y_R = - \sqrt{[L_b(0.95) - L_b(0.50)]_{\text{wanted}}^2 + [L_b(0.05) - L_b(0.50)]_{\text{unwanted}}^2} \quad (3)$$

In equation (2), P_t is the transmitted power, and G_t and G_r are the isotropic gains of the transmitting and receiving antennas expressed in dB.

Additional variabilities could easily be included in equation (3) for such things as antenna gain when variabilities for them can be determined. Continuous (100%) or simultaneous channel utilization is implicit in the $R(0.95)$ formulation provided above so that the impact of intermittent transmitter operation must be considered separately.

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ANNEX II

DESCRIPTION OF THE CURVES

The aeronautical curves are contained in Figs. 1 to 6. The following points are to be noted:

1. Figures 1 to 6 show median values of the basic transmission loss, L_b , for the frequencies 125, 300, 1200, 5100, 9400 and 15 500 MHz.
2. Each figure consists of three curve sets where the upper, middle and lower sets provide $L_b(0.05)$, $L_b(0.50)$, and $L_b(0.95)$, respectively. These correspond to time availabilities of 5, 50 and 95%. For example, $L_b(0.95) = 200$ dB means that the basic transmission loss would be 200 dB or less during 95% of the time.
3. The antenna heights shown vary from 15 m to 20 000 m covering both ground station and aircraft heights.
4. The development and application of these curves are discussed in Annex I.
5. At zero distance $L_b(0.50)$ is simply the free-space value corresponding to a path length equal to the difference in antenna heights. The free-space curves shown were calculated for a 19 985 m height difference.

Code for antenna heights

Code	H_1 (m)	H_2 (m)
A	15	1000
B	1000	1000
C	15	10000
D	1000	10000
E	15	20000
F	1000	20000
G	10000	10000
H	10000	20000
I	20000	20000

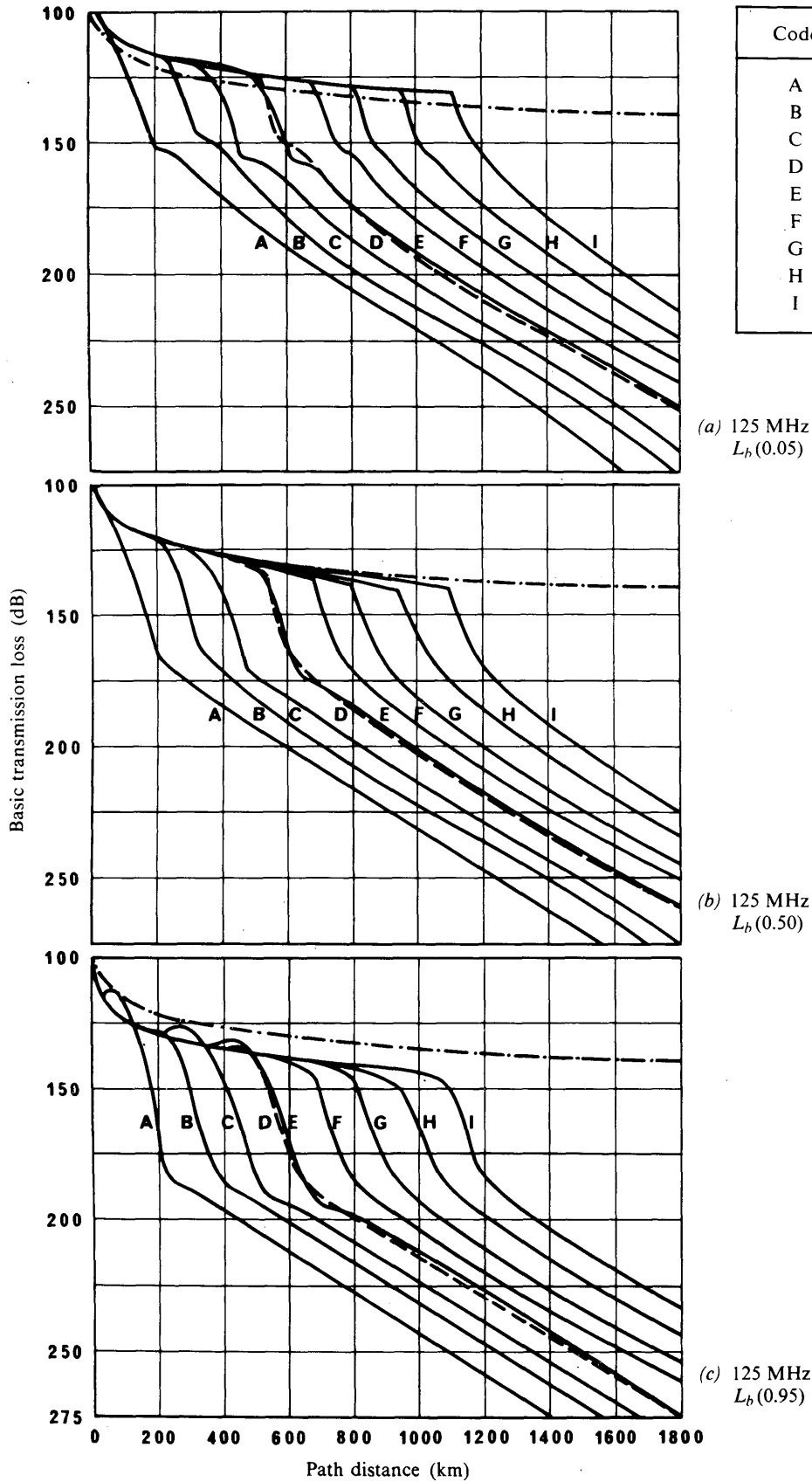


FIGURE 1 — Basic transmission loss at 125 MHz for 5%, 50% and 95% of the time

The dotted-line curve is that for free space

Code for antenna heights

Code	H_1 (m)	H_2 (m)
A	15	1000
B	1000	1000
C	15	10000
D	1000	10000
E	15	20000
F	1000	20000
G	10000	10000
H	10000	20000
I	20000	20000

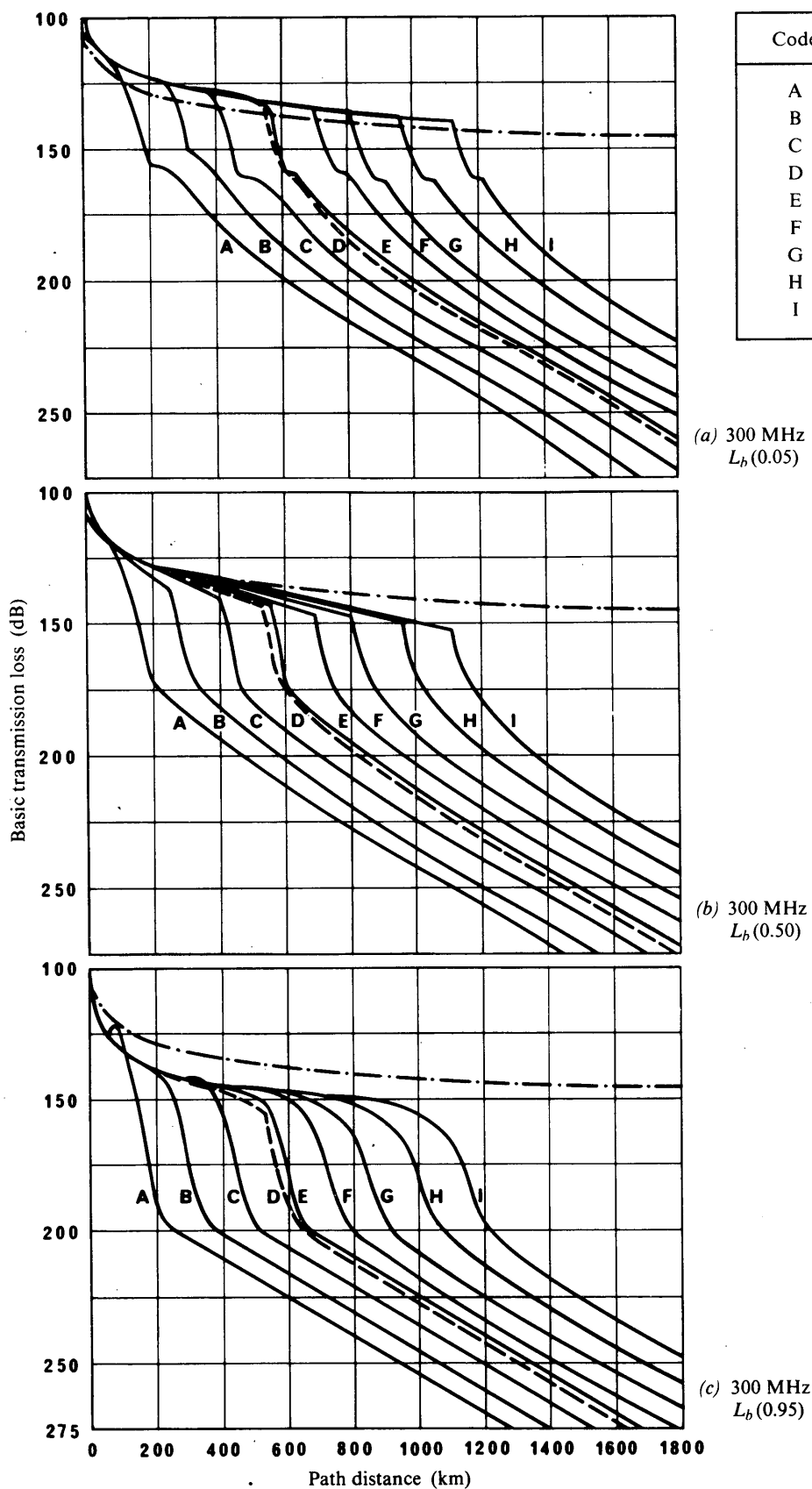


FIGURE 2 — Basic transmission loss at 300 MHz for 5%, 50% and 95% of the time

The dotted-line curve is that for free space

Code for antenna heights

Code	H_1 (m)	H_2 (m)
A	15	1000
B	1000	1000
C	15	10000
D	1000	10000
E	15	20000
F	1000	20000
G	10000	10000
H	10000	20000
I	20000	20000

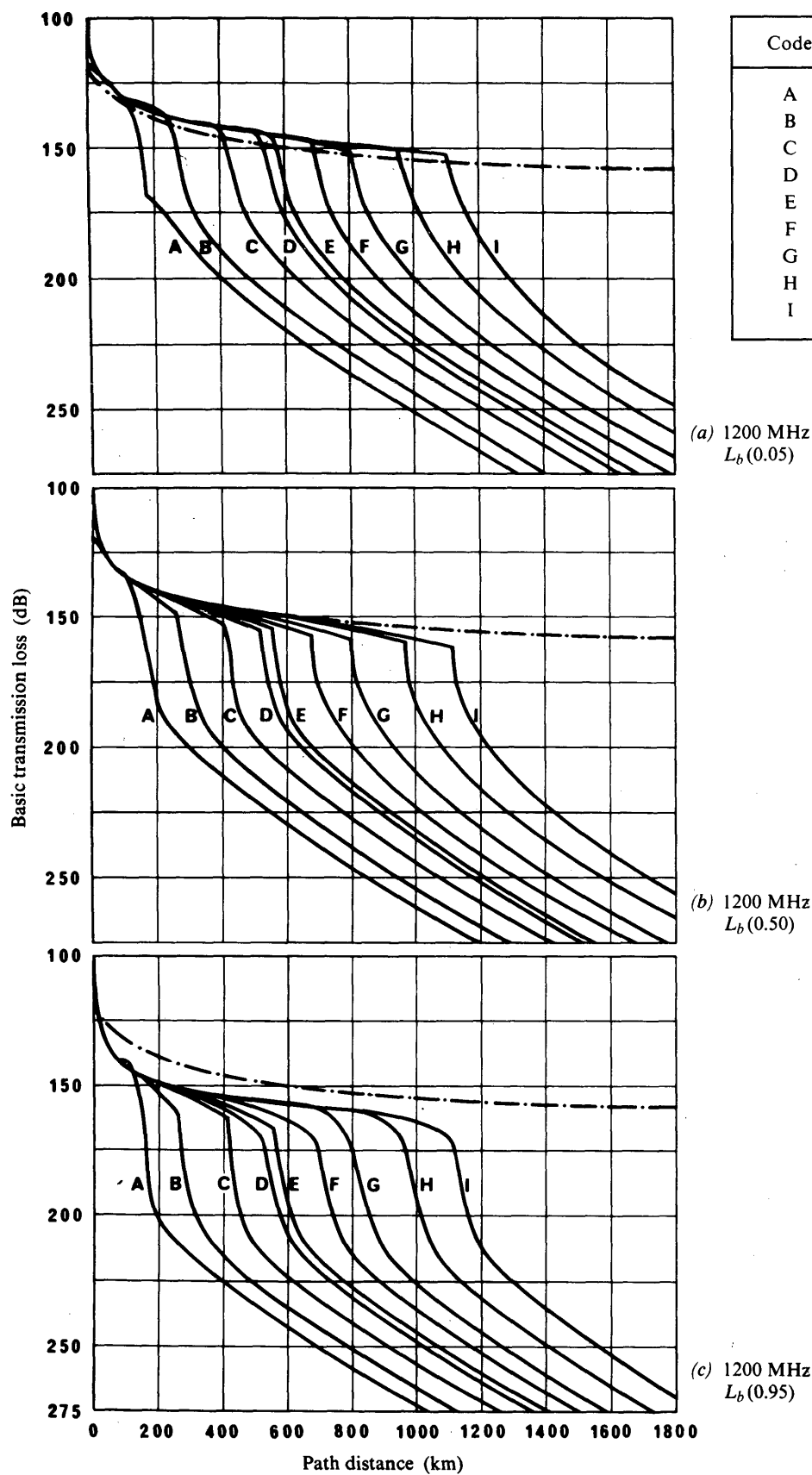


FIGURE 3 — Basic transmission loss at 1200 MHz for 5%, 50% and 95% of the time

The dotted-line curve is that for free space

Code for antenna heights

Code	H_1 (m)	H_2 (m)
A	15	1000
B	1000	1000
C	15	10000
D	1000	10000
E	15	20000
F	1000	20000
G	10000	10000
H	10000	20000
I	20000	20000

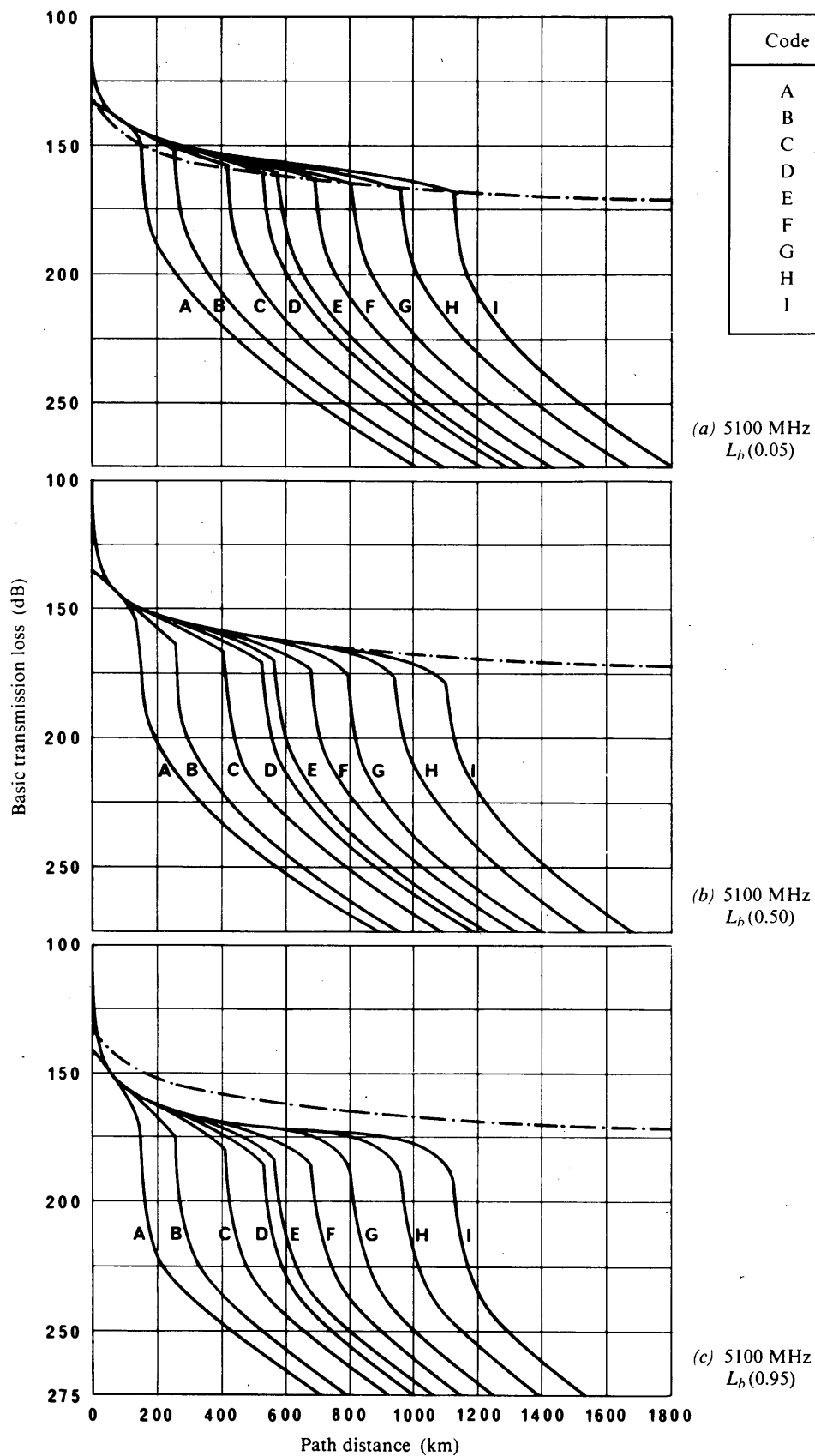
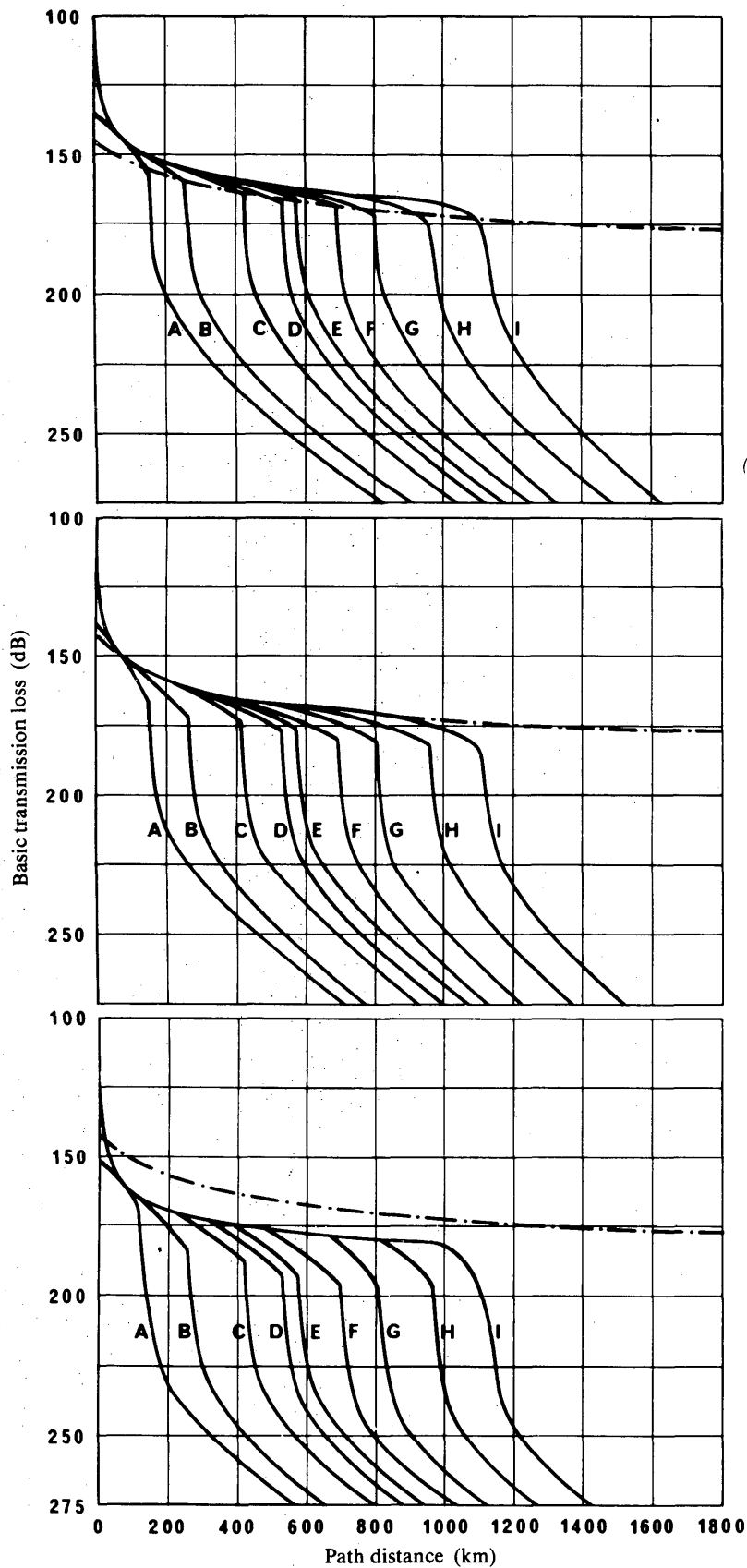


FIGURE 4 — Basic transmission loss at 5100 MHz for 5%, 50% and 95% of the time

The dotted-line curve is that for free space

Code for antenna heights

Code	H_1 (m)	H_2 (m)
A	15	1000
B	1000	1000
C	15	10000
D	1000	10000
E	15	20000
F	1000	20000
G	10000	10000
H	10000	20000
I	20000	20000



(a) 9400 MHz
 $L_b(0.05)$

(b) 9400 MHz
 $L_b(0.50)$

(c) 9400 MHz
 $L_b(0.95)$

FIGURE 5 — Basic transmission loss at 9400 MHz for 5%, 50% and 95% of the time

The dotted-line curve is that for free space

Code for antenna heights

Code	H_1 (m)	H_2 (m)
A	15	1000
B	1000	1000
C	15	10000
D	1000	10000
E	15	20000
F	1000	20000
G	10000	10000
H	10000	20000
I	20000	20000

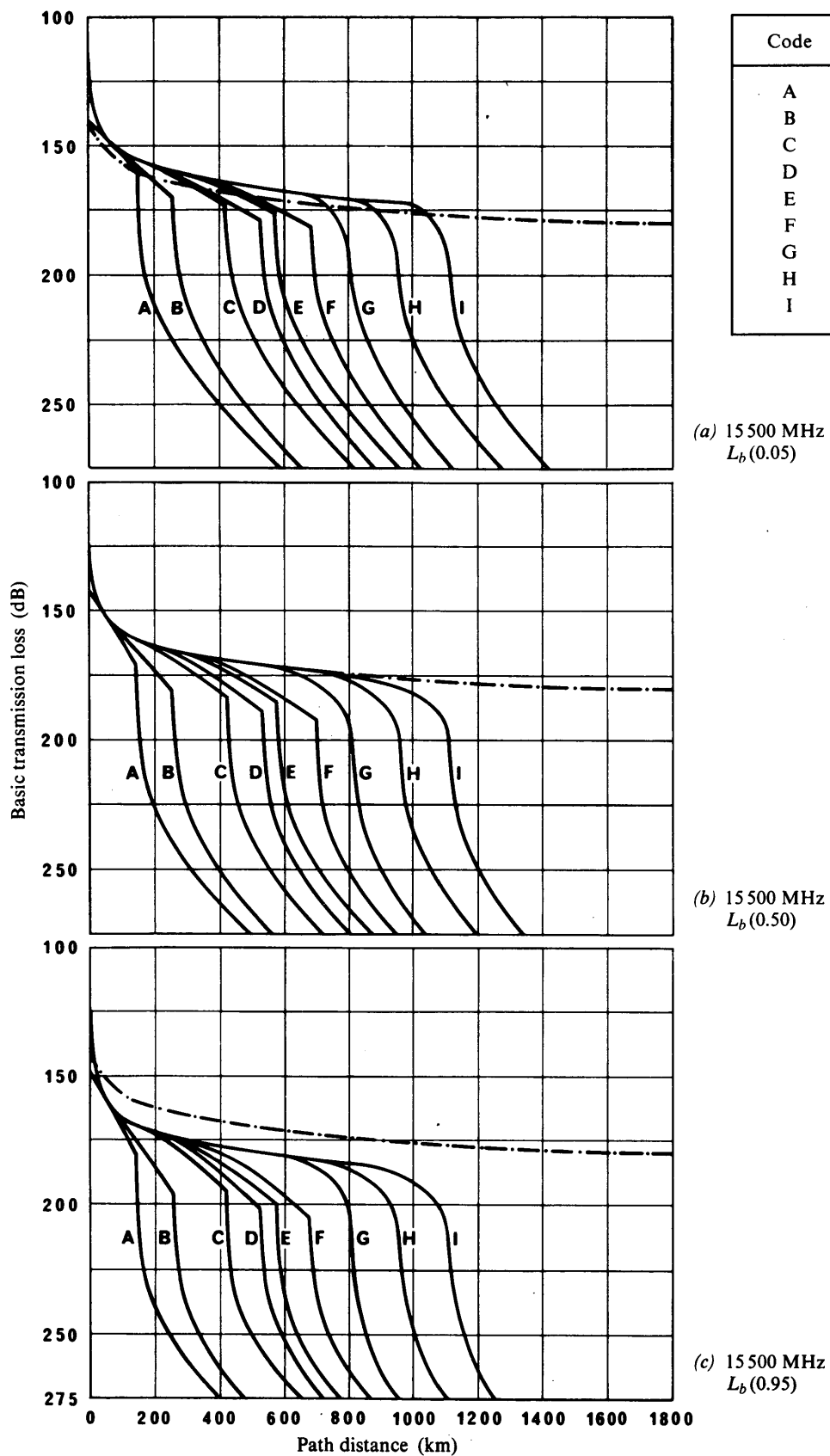


FIGURE 6 — Basic transmission loss at 15 500 MHz for 5%, 50% and 95% of the time

The dotted-line curve is that for free space

RECOMMENDATION 529 *

VHF AND UHF PROPAGATION CURVES FOR LAND MOBILE SERVICES

(Study Programme 7E/5)

(1978)

The CCIR,

CONSIDERING

that there is a need to give guidance to engineers in the planning of land mobile radio services in the VHF and UHF bands,

UNANIMOUSLY RECOMMENDS

that the methods given in Report 567 be adopted ** for provisional use to determine the field strength at antenna heights likely to be encountered in the land mobile service.

REPORT 567-2 ***

**METHODS AND STATISTICS FOR ESTIMATING FIELD-STRENGTH VALUES
IN THE LAND MOBILE SERVICES USING THE FREQUENCY RANGE 30 MHz TO 1 GHz**

(Study Programme 7E/5)

(1978-1982)

1. Introduction

For the lower part of the VHF range and for frequencies slightly below 30 MHz this Report provides a means for calculating the expected field strengths for mobile services.

The propagation curves given in this Report for frequencies in the range of 100 to 250 MHz were constructed from those of Recommendation 370 using experimental height-gain functions for the lower antenna heights, i.e., those given in § 2 of this present Report. Measured results obtained under conditions relevant to the land mobile services should be employed where these are available. Two other sets of propagation curves for frequencies near 450 and 900 MHz were taken from a Japanese publication [Okumura *et al.*, 1968].

Computer methods for calculating field strengths are given in Report 239.

2. Propagation curves

Figures 1 and 2 show curves for 450 MHz and 900 MHz at mobile antenna heights of 1.5 m, fixed station heights between 30 and 1000 m, 50% of the locations and 50% of the time. These particular curves were derived from measurements made in urban areas of Japan [Okumura *et al.*, 1968], and should be compared with data from other areas where available.

Measurements made in Japan have shown that the height gain factor from 1.5 to 3 m is 3 dB in urban areas for the UHF band [Okumura *et al.*, 1968]. This value can be used to estimate the median field strength for mobile antenna heights of 3 m using the data for Bands IV and V **** for urban areas as given in Figs. 1 and 2.

* This Recommendation is brought to the attention of Study Group 8.

** It must be emphasized that the curves relating to UHF bands are based on data for specific urban areas, and should be used with caution for other areas.

*** This Report is brought to the attention of Study Group 8.

**** For information concerning these bands, see Note ⁽¹⁾ to Table II.

Table I [Hata, 1980] provides an empirical formula for calculating basic transmission loss for distances up to 20 km relating to Figs. 1 and 2.

TABLE I - Empirical formula for basic transmission loss

$L_b = 69.55 + 26.16 \log f - 13.82 \log h_1 - a(h_2) + (44.9 - 6.55 \log h_1) \log R \quad \text{dB}$	
correction factor for h_2 :	
$a(h_2) = (1.1 \log f - 0.7)h_2 - (1.56 \log f - 0.8)$	
Where:	
f : frequency	450-1000 MHz
h_1 : base station effective antenna height	30-200 m
h_2 : vehicular station antenna height	1-10 m
R : distance	1-20 km

Figure 9 provides a correction factor for use with Fig. 1 where the density of buildings in the vicinity of the mobile station is greater or less than the reference density for which the curves were derived (15% of the area covered by buildings).

Figures 3, 4 and 5 show propagation curves which are valid for frequencies approximately between 100 and 250 MHz, mobile antenna heights of 3 m, fixed antenna heights between 10 m and 600 m, for rural conditions, for 50% of the locations, and for 50%, 10% and 1% of the time.

The curves in Figs. 3, 4 and 5 were derived from corresponding curves in Recommendation 370 with appropriate corrections for a mobile station antenna height of 3 m. A correction of 8 dB was applied for distances up to 50 km and 4 dB for distances greater than 100 km with linear interpolation for intermediate distances. The 8 dB correction was derived from Table II by interpolation between Bands II and III.

The mobile station height correction factors used here and those shown in Table II for rural areas were based on work described in various publications, [Uhlén, 1962; Králík *et al.*, 1962; Kinase, 1969; Okumura *et al.*, 1968; Ogulewicz, 1971] and work done in the United Kingdom. However, more recent work in the United Kingdom suggests that height correction factors in Band II may not be distance dependent.

The curves for fixed station antenna heights of 20 m and 10 m were derived from the 37.5 m curve by applying correction factors of -10 dB and -19.5 dB for distances up to 50 km and -4.5 dB and -9.5 dB for distances in excess of 100 km. These correction factors are based on a theoretical study by the Federal Republic of Germany [CCIR, 1970-74].

Field-strength measurements carried out in rural areas in the People's Republic of Poland at frequencies between 34 and 306 MHz have shown good agreement with the propagation curves of Recommendation 370 when allowance is made for terrain effects.

Measurements carried out in the Canadian arctic [Palmer, 1980] at frequencies of 148 and 450 MHz at distances up to 100 km suggest that in such regions field strengths may be greater than those predicted by Fig. 3.

Measurements carried out in the People's Republic of Poland [Kisło, 1977] over a trans-horizon path on a frequency of 342 MHz have shown that the 1% values of field strength exceed the values estimated on the CCIR curves by 2 to 8 dB and that the 1% and 10% values show marked variations between day and night.

The relationship between the field strength, E' (dB(μ V/m), for 1 kW radiated from a halfwave dipole) as found from the curves in this Report and the basic transmission loss, L_b , (i.e., the loss between isotropic antennas) is given by:

$$L_b = 139.4 + 20 \log f_{\text{MHz}} - E' \quad \text{dB} \quad (1)$$

The transmission loss between halfwave dipoles, L_d is given by:

$$L_d = 135.1 + 20 \log f_{\text{MHz}} - E' \quad \text{dB} \quad (2)$$

Recommendation 525 explains the calculation of free-space attenuation.

Measurements made in a multipath situation may not reflect the relationships shown in equations (1) and (2) above.

Field-strength data taken in several metropolitan areas in the United States at 900 MHz (see § 5.2 below) generally show good agreement with the distance trends of the curves for urban areas shown in Figs. 1 and 2. However, some of the surveys showed significant differences of average field-strength levels from these curves.

TABLE II - Correction factor for reduction of antenna height to 3 m

Zone	Bands I, II ⁽¹⁾	Bands III ⁽¹⁾	Bands IV, V ⁽¹⁾
Rural (dB)	9	7	as given by Fig. 17 of Rec. 370 for $d < 50$ km
Urban (dB)	9	11	14

⁽¹⁾ The frequency bands are as follows:

Band I : 41 to 68 MHz
 Band II : 87.5 to 100 MHz
 Band III: 162 to 230 MHz
 Band IV: 470 to 582 MHz
 Band V : 582 to 960 MHz

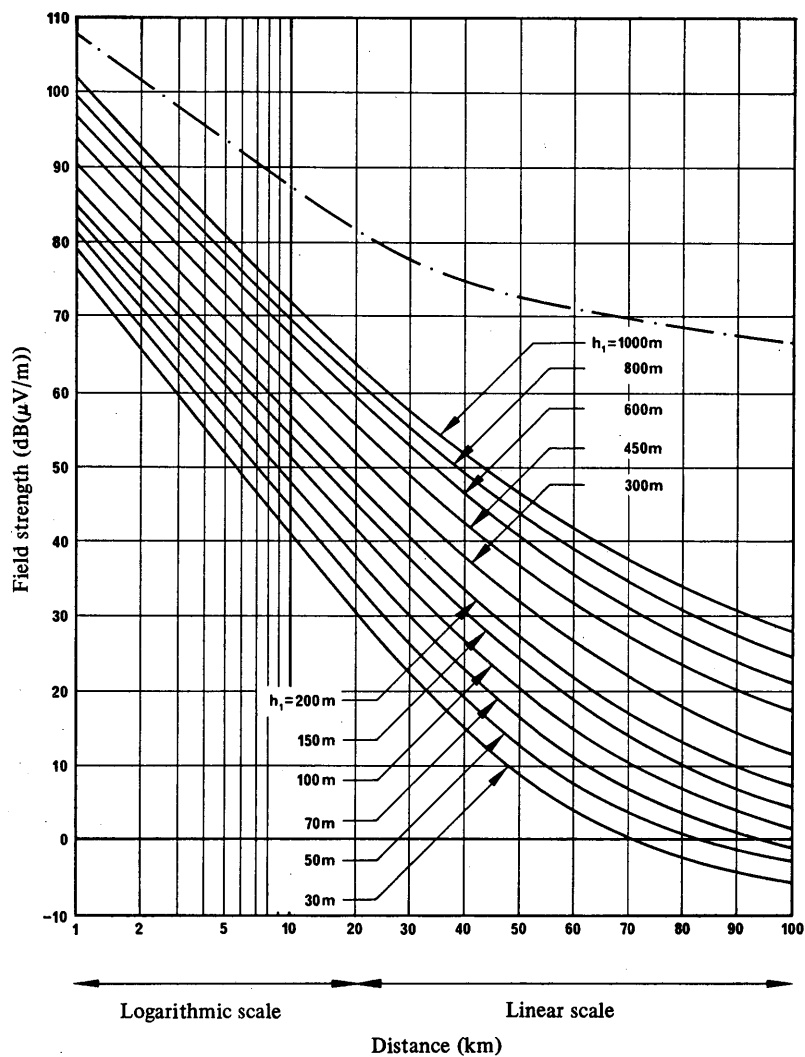


FIGURE 1 - Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency ≈ 450 MHz, urban area, 50 % of the time ; 50 % of the locations;
 $h_2 = 1.5$ m

..... Free space

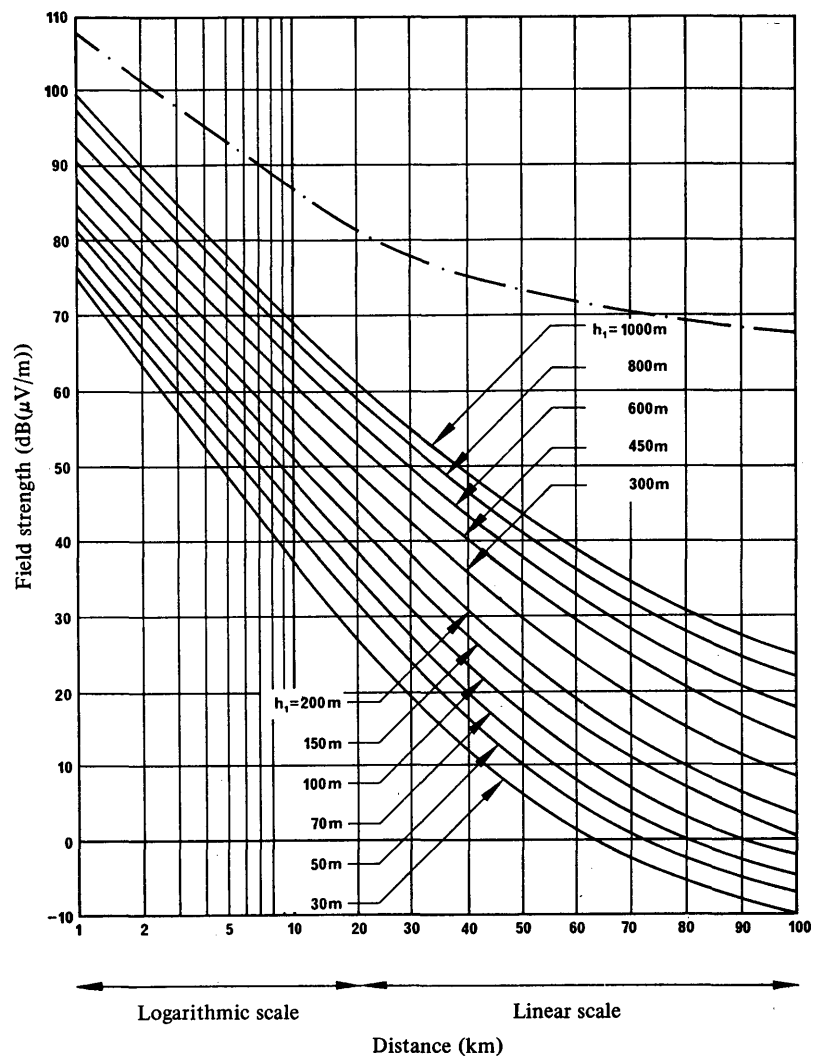


FIGURE 2 – Field strength (dB(μV/m)) for 1 kW e.r.p.

Frequency $\approx$ 900 MHz, urban area 50 % of the time ; 50 % of the locations ;
 $h_2 = 1.5$ m

..... Free space

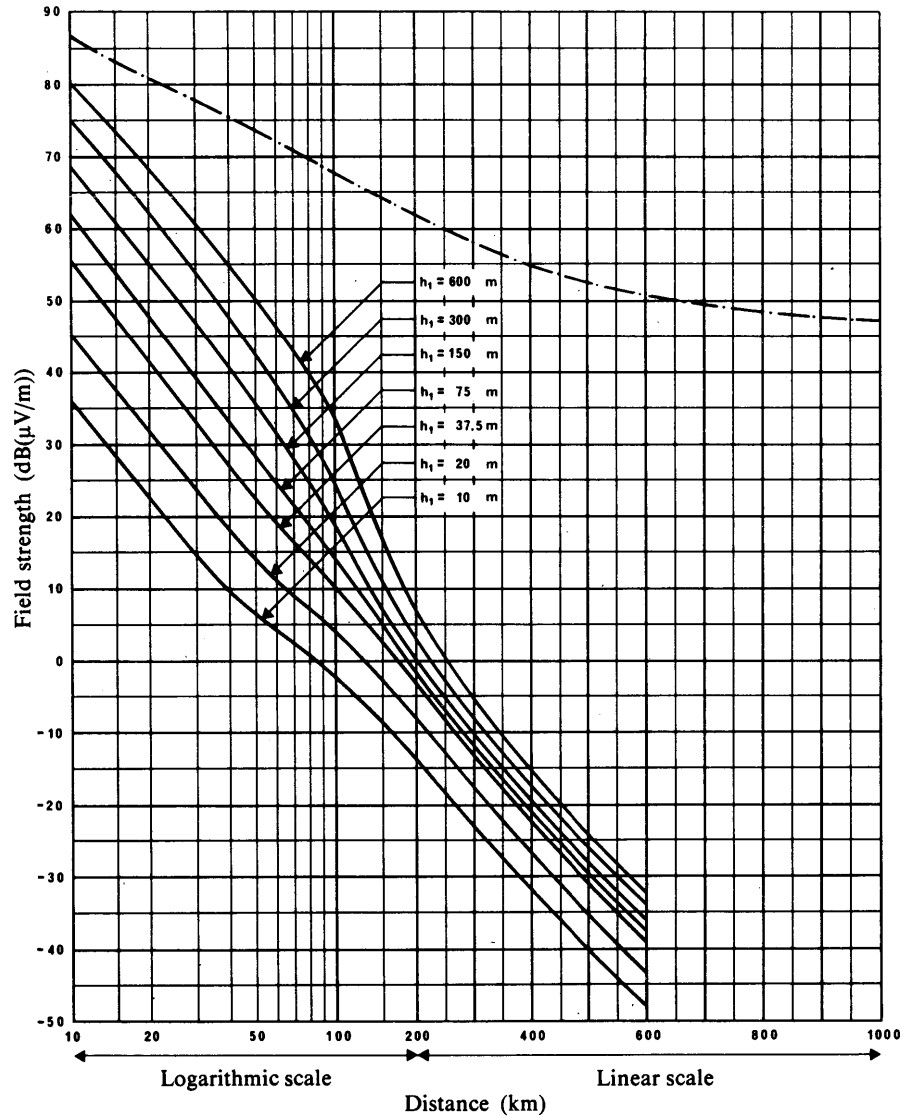


FIGURE 3 — Field strength ($\text{dB}(\mu\text{V/m})$) for 1 kW e.r.p.

Frequency $\approx 150 \text{ MHz}$, land, rural, 50% of the time; 50% of the locations; $h_2 = 3 \text{ m}$

— — — Free space

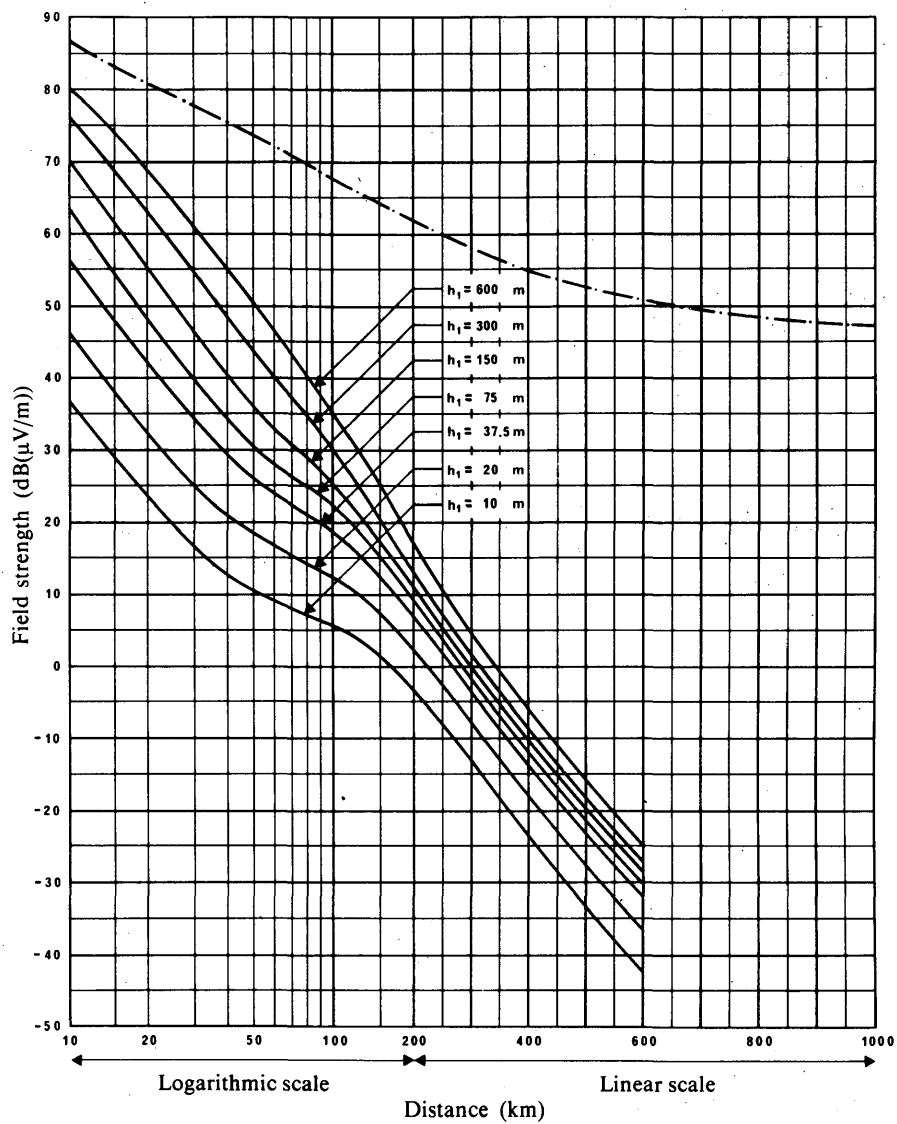


FIGURE 4 — Field strength ($\text{dB}(\mu\text{V/m})$) for 1 kW e.r.p.

Frequency ≈ 150 MHz, land, rural, 10% of the time ; 50% of the locations ; $h_2 = 3$ m

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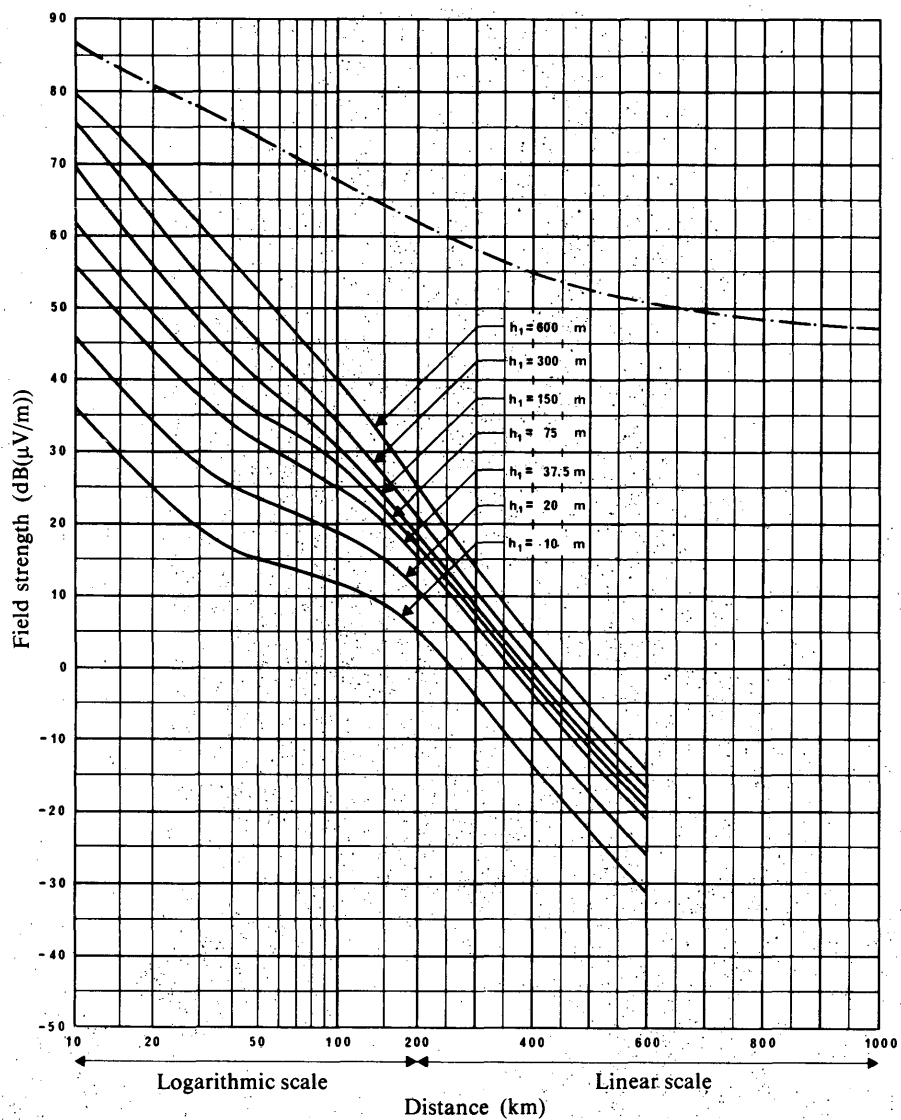


FIGURE 5 — *Field strength (dB(μV/m)) for 1 kW e.r.p.*

Frequency ≈ 150 MHz, land, rural, 1% of the time ; 50% of the locations ; $h_2 = 3$ m

— — — Free space

3. Calculation of field-strength values

For line-of-sight paths for frequencies at VHF and slightly lower the field strengths may be calculated using the method described below which is based on work done in the People's Republic of Poland [Wojnar, 1977], following work done in the United States [Bullington, 1957].

The use of an effective antenna height based on the electrical characteristics of the ground is especially applicable at the lower frequencies, for lower antenna heights, with vertical polarization, and over wet ground.

A first order estimate of the median field-strength E ($\mu\text{V/m}$) is given by:

$$E = 88 \sqrt{p_t} \frac{h_t h_r}{\lambda d^2} \quad (3)$$

where

p_t : effective radiated power of the transmitter, using a half-wave dipole antenna, (W),

d : distance between antennas (km),

h_t : effective height of the transmitting antenna (m),

h_r : effective height of the receiving antenna (m),

λ : wavelength (m).

These effective heights are given by:

$$h_t = \sqrt{h_1^2 + h_0^2} \quad (4)$$

$$h_r = \sqrt{h_2^2 + h_0^2} \quad (5)$$

where

h_1 : actual height of the transmitting antenna (m),

h_2 : actual height of the receiving antenna (m), and

h_0 : (m) is obtained:

$$\text{for vertical polarization } h_0 = \frac{\lambda}{2\pi} ((\epsilon_r + 1)^2 + (60\lambda\sigma)^2)^{\frac{1}{4}} \quad \text{m} \quad (6)$$

$$\text{for horizontal polarization } h_0 = \frac{\lambda}{2\pi} ((\epsilon_r - 1)^2 + (60\lambda\sigma)^2)^{-\frac{1}{4}} \quad \text{m} \quad (7)$$

where

λ : wavelength (m),

ϵ_r : relative permittivity,

σ : conductivity of the ground (S/m).

The effective heights h_t , h_r can be obtained from Fig. 6 for heights h_1 , h_2 and parameter h_0 (m). The values (in metres) of h_0 are derived from Fig. 7 or Fig. 8 depending on whether the polarization is vertical or horizontal and as a function of frequency and the electrical characteristics of the ground. Heights for other electrical characteristics of ground values can be obtained by interpolation from the curves provided, or calculated from equations (6) and (7) using information on the electrical characteristics of the ground from Recommendation 527.

Equation (3) is valid within the region where the field decreases monotonically with distance up to the radio horizon.

Corrections for terrain morphology, vegetation and man-made structures may be added to equation (3), and can be obtained from Recommendation 370 (Fig. 7 and Fig. 8a) and Report 239 respectively.

At distances beyond the radio horizon at frequencies below 90 MHz and for small percentages of time, the effects of the ionosphere may be important; Volume VI of the CCIR is concerned with the effects of the ionosphere.

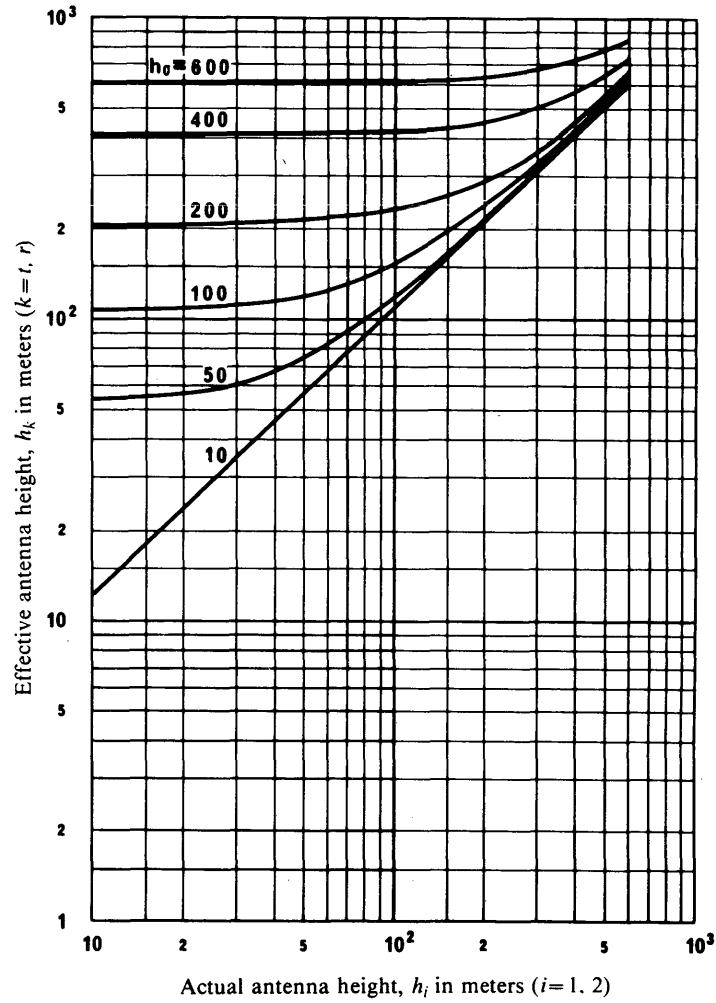


FIGURE 6 — Determination of effective antenna heights in meters on the basis of the actual heights and the parameter h_0 of Figs. 7 and 8

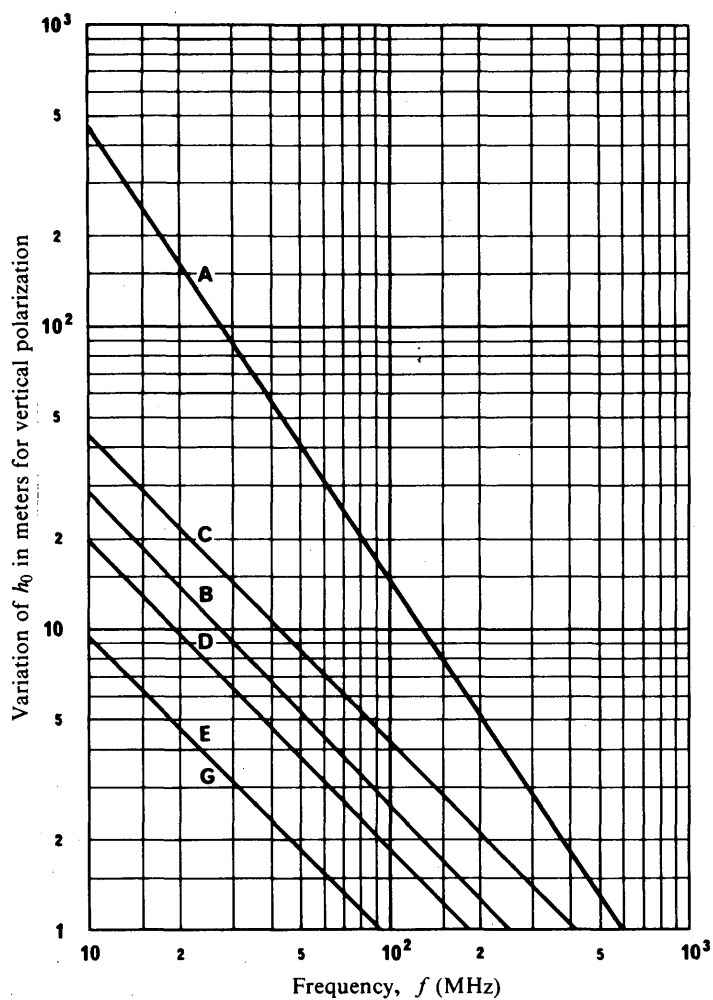


FIGURE 7 — Variation of h_0 in meters with frequency (MHz)
Vertical polarization

Type of terrain (Recommendation 527)

Curves A : sea water (average salinity) 20° C

B : wet ground

C : fresh water, 20° C

D : medium dry ground

E : very dry ground

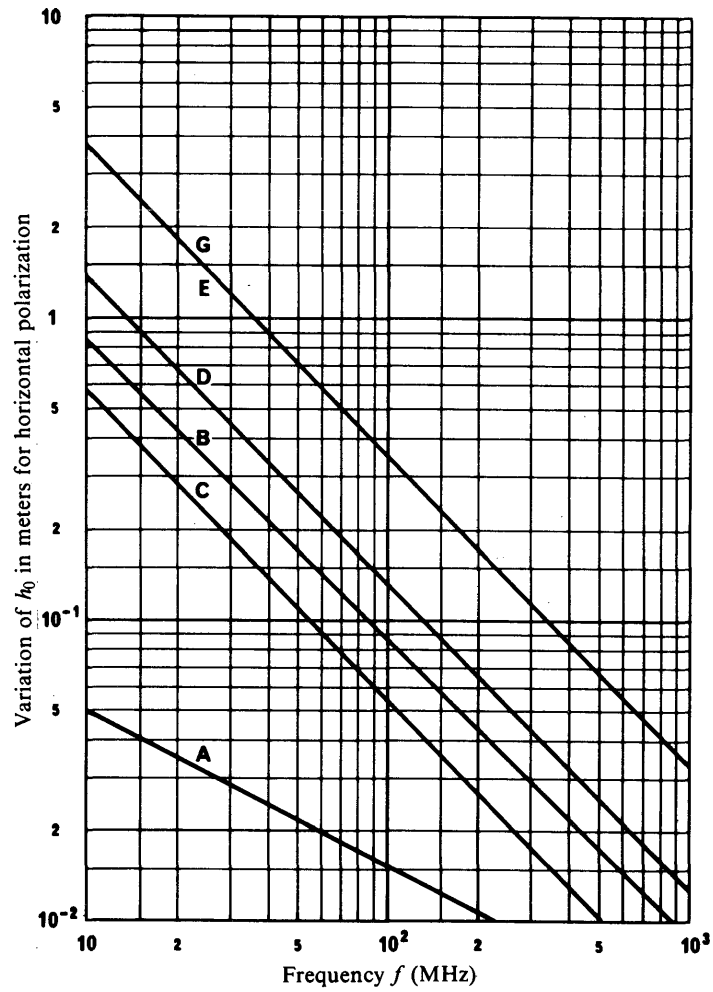


FIGURE 8 — Variation of h_0 in meters with frequency (MHz)
Horizontal polarization

Type of terrain (Recommendation 527)

Curves A: sea water (average salinity) 20° C

B: wet ground

C: fresh water, 20° C

D: medium dry ground

E: very dry ground

4. Depolarization phenomena *

The depolarization factor is defined as the ratio of the amplitude of the orthogonally polarized component, produced by some propagation mechanism, to the amplitude of the original plane polarized wave. For land mobile systems it may be sometimes more convenient to consider the polarization discrimination factor obtained from a receiving antenna in its working environment. This discrimination factor is normally expressed in decibels and is, in practice, of the opposite sign but numerically equal to the depolarization factor provided that the latter is not too small.

Measurements in Sweden of the depolarization effect, with both antennas at a low height (less than 10 m), have shown that the depolarization factor increases with increasing frequency from about -18 dB at 35 MHz to about -7 dB at 950 MHz [Blomquist, 1965].

The depolarization factor is log-normally distributed with a standard deviation somewhat dependent on the frequency. The average value of the difference between the 10% and 90% values (in the frequency range 30 to 1000 MHz) is about 15 dB. Whether the original polarization is vertical or horizontal has been observed to make only a slight difference in this respect.

Two types of time variation of the depolarization effect have been found. The first is a slow variation resulting from the changing electrical properties of the ground with weather conditions. This effect is most pronounced at lower frequencies. The second is due to the motion of trees which gives a depolarization fading phenomenon amounting to several decibels in amplitude at quite moderate wind velocities.

5. Attenuation due to vegetation and buildings

Signals transmitted to and from moving vehicles in urban or forested environments exhibit extreme variations in amplitude due to multiple scattering. Fades of 30 dB or more below the mean level are common. A number of investigators have reported that the instantaneous field strength when measured over distances of a few tens of wavelengths is approximately Rayleigh-distributed [Jakes, 1974; Okumura *et al.*, 1968]. The mean values of these small sector distributions vary widely from area to area, depending on height, density and distribution of trees, buildings and other structures. Studies concerning these variations are described below. Some studies concerning signal attenuation through the walls of buildings are also described.

5.1 Attenuation due to vegetation

A general discussion of signal attenuation in forested terrain appears in Report 236. Report 236 describes the various paths and mechanisms for propagation through an idealized forest environment and presents models giving attenuation as a function of frequency and length of path through the trees. These models cover situations where both antennas are within the forest and where at least one antenna is within or close to the edge of the trees. In the case where both antennas are well clear of a grove of trees, the path can be treated as a diffraction path.

Report 239 discusses the case where both transmitter and receiver are located above the forest as in the broadcast and radio-relay systems. For mobile systems where the base station antenna is located outside or above the trees and mobile stations move in and out of wooded areas, a method described by Kinase [1969] may be useful. This method determines attenuation from median field-strength curves as a function of frequency and percentage of an area covered by clutter, including both trees and buildings.

Measurements were carried out in Washington DC to determine the variation in received signal levels due to changes of season for mobile stations operating in woodland areas [FCC, 1972]. Cumulative statistics for the relative signal levels with trees in full leaf and without leaf were determined for transmission at 459 and 955 MHz. The median seasonal difference for both frequencies was found to be approximately 4.5 dB and the upper decile was approximately 6 dB.

* See Report 722.

5.2 Attenuation due to buildings

According to experimental results in Japan [Kozono and Watanabe, 1977] the median field strength is particularly affected by the buildings around a mobile station, because the mobile station antenna height is almost always lower than these buildings. At 450 MHz these buildings cause a considerable deviation of the median field strength in any small area (of about 0.25 km²) compared with the reference median field strength typical of urban areas, as shown in Fig. 1. This local deviation from the reference value is shown in Fig. 9 as a function of the parameter α , where α is defined as the percentage of the area covered by buildings. Each point in the graph is the deviation of the median field strength for one such small area. The values of median field strength in the 800 MHz band were found to be strongly correlated with those in the 400 MHz band.

Measurements in urban areas in the People's Republic of Poland at frequencies between 34 and 306 MHz show that the spread of field-strength values seems to be almost independent of frequency.

Field-strength measurements at 900 MHz in several metropolitan areas in the United States [Reudink and Black, 1972; FCC, 1971; Jakes, 1974] show significant differences in average signal level from city to city not accounted for by differences in terrain. Variations in small-area (of the order of 0.25 km²) medians about the average level at a given distance show standard deviations of 3 to 12 dB. An attempt is being made to relate these variations in signal level and standard deviation to the distribution of trees and buildings.

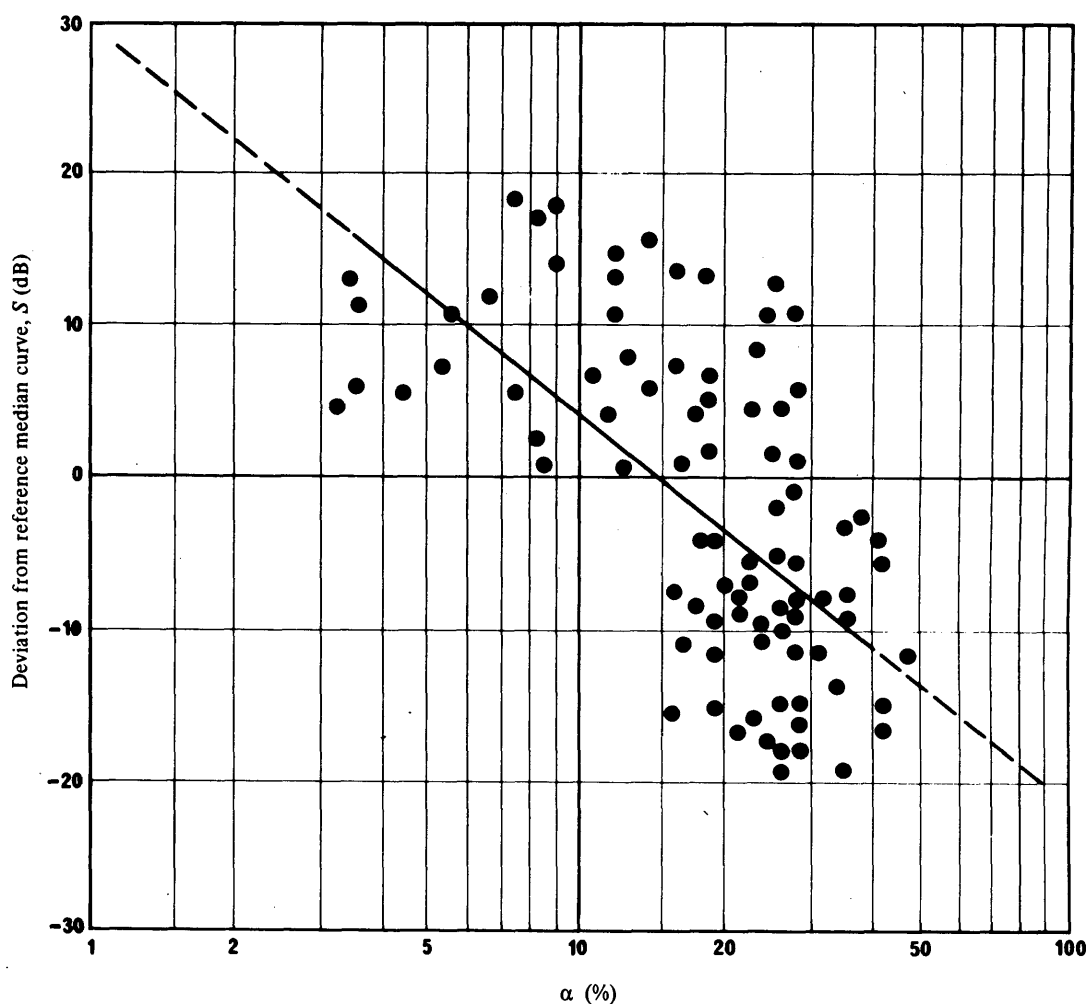


FIGURE 9 — Deviation from median field-strength curve due to buildings surrounding mobile station

Regression curve shown in this figure :

$$S = 30 - 25 \log \alpha$$

$$f = 450 \text{ MHz}$$

$$3\% < \alpha < 50\%$$

α is the percentage of the area covered by buildings

5.3 Building penetration loss

The attenuation of radio-waves through the walls of buildings is a crucial factor in the feasibility and design of portable radio communications and paging systems. Two studies of this attenuation are reported below. The first study involved measurements for several typical buildings in an urban area. The second study was intended to develop statistics for a severe case situation.

Measurements at 940 MHz were carried out in a medium-size city in the United States (Louisville, Kentucky) to determine building penetration losses for hand-held portable radios [CCIR, 1978-82]. These measurements were averaged for 3.7 by 3.7 m areas so as to average the effects of multi-path fading. For typical steel and concrete and stone office buildings these averages were found to be normally distributed between 10 and 90% with a mean of 10 dB and a standard deviation of 7.3 dB. These statistics may be used with the field-strength values determined from Fig. 1 to estimate probable field-strength levels on the ground floor of office buildings comparable in nature to those in the test city.

In order to characterize signal statistics for a severe case, attenuation measurements were carried out in a steel shell building at 900 MHz in the United States. Cumulative statistics of relative signal strengths inside and outside the building for receiver antennas located at heights of 1 to 2 m above the floor were approximately Rayleigh-distributed with a median attenuation of 28.5 dB.

6. Dependence of field strength on time, location and nature of terrain

Recommendation 370 and Report 239 consider problems of the dependence of field strength on time, location and the nature of the terrain.

The parameter Δh is used to define the degree of terrain irregularity. Its derivation and use in correcting median field-strength values for areas where the terrain is smoother or rougher than average is described in Report 239. The range of variation of the log-normal location distribution, i.e., the standard deviation, σ_L , increases with increasing values of Δh and frequency.

For many practical purposes, for instance the evaluation of the probability of interference when preparing frequency plans for mobile radio, the following approximations have been shown to be useful and sufficiently accurate [Rue, 1974]:

- the time and location distributions of field strength are assumed to be Gaussian (dB) in the range of interest (between about 5% and 50% for the time distribution);
- the standard deviations of the location- and time-distributions (σ_L and σ_t) are derived from Recommendation 370, assuming a Gaussian time distribution for time percentages between 5% and 50% (Table III);
- the combined standard deviation is given by $\sigma = \sqrt{\sigma_L^2 + \sigma_t^2}$.

TABLE III - Standard deviations σ_L y σ_t

Band	σ_L (dB)				σ_t (dB)				
VHF	8				d (km)	50	100	150	175
					Land and sea	3	7	9	11
UHF	Δh (m)	50	150	300	Land	2	5	7	
		10	15	18	Sea	9	14	20	

Note. - The values in Table III refer to rural areas. They should be applied with caution when used with Figs. 1 and 2, which are for urban areas.

A recent analysis of a large amount of measurement data in the United States [Longley, 1976] led to the derivation of the following expression relating location variability (standard deviation), σ_L , to the transmission wavelength, λ , and terrain irregularity, Δh , for $\Delta h/\lambda \leq 3000$:

$$\sigma_L = 6 + 0.69 (\Delta h/\lambda)^{1/2} - 0.0063 (\Delta h/\lambda) \quad \text{dB} \quad (8)^*$$

for $\Delta h/\lambda > 3000$, $\sigma_L = 25$ dB.

The data used in this study were spot measurements obtained over paths ranging from 0.5 to 120 km in length, with antenna heights from 0.6 to 15 m, over terrain ranging from plains to rugged mountains and at frequencies from 30 MHz to 10 GHz.

In interference calculations it is sometimes desirable to take into consideration the correlation between signals received at the mobile station from non co-sited transmitters. A recent study [Graziano, 1978] of data at 913 MHz in suburban to urban surroundings in the US found some positive correlation between signals received at a mobile station from base station sites separated by as much as 55° in azimuth. Correlation between signals transmitted over paths with a common transmitting or receiving terminal is also discussed in Report 228, based on measurements at VHF.

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* The coefficients in equation (8) differ from those in the original equation in [Longley, 1976], where Δh is defined as a function of distance rather than for a fixed range of 10 to 50 km.

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REPORT 228-2 *

**MEASUREMENT OF FIELD STRENGTH FOR VHF (METRIC) AND UHF
(DECIMETRIC) BROADCAST SERVICES, INCLUDING TELEVISION**

(Question 7/5)

(1959-1963-1966-1978)

1. Description of coverage

For the purpose of frequency assignment, the description of coverage for VHF (metric) and UHF (decimetric) broadcast services (television broadcasting, frequency-modulation broadcasting, etc.), should be in terms of the extent to which service is provided to potential viewers or listeners. The service may be classified in accordance with the quality of the signal at an individual location. For the purpose of assigning stations, it is probably necessary to consider only one quality of service; however, it may be useful for other purposes to define more than one quality.

Several methods have been proposed for describing the service coverage of broadcast stations in the VHF (metric) and UHF (decimetric) bands.

An acceptable method for describing broadcast service should meet the following criteria [TASO, 1959]:

- 1.1 it should show the location and extent of all areas provided with a given quality of service;
- 1.2 it should take into account significant variations with times;
- 1.3 the method of specifying service should be sufficiently fine-grained to be capable of showing the amount (area or population) and location of service in distinct areas and directions from the transmitter;
- 1.4 it should be capable of showing the effect of interference from one or more stations in terms of the amount and location of service lost;
- 1.5 it should be capable of showing two or more qualities of service;
- 1.6 it should be possible to predict the service area by means of a reasonable number of measurements and/or calculations of field strength;
- 1.7 it should lend itself to simple two-dimensional presentation.

After extensive studies of the various methods for describing VHF (metric) and UHF (decimetric) broadcast services, the location probability has been recommended [TASO, 1959; FCC, 1949 and 1950] as the best statistic for describing services. A brief description of the meaning of this statistic is given for the benefit of those not familiar with the term. Under steady-state laboratory conditions, it has been possible to evaluate statistically the useful signal-to-interfering signal ratios which are required to produce pictures or sound of a quality acceptable to different observers in the presence of various types of interference. The ratio accepted by some percentage of the observers, say 50%, is chosen as the acceptance ratio for each type of interference. At any specific location, the useful signal and/or the interference may vary with time, so that the term "time-availability"

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

is used to indicate the percentage of time for which the acceptance ratio is exceeded. A particular quality of service corresponds to a specified acceptance ratio exceeded for a given percentage of time at an agreed standard receiving installation. The location probability is then defined as the probability of receiving this quality of service, or better. Alternatively, the location probability may be defined as the percentage of locations in a small area, for which this quality of service, or better, is expected. To minimize computations, the single value of 90% time availability may be adopted as the satisfactory level. This figure might be changed as found desirable, or several levels and standard receiving installations might be adopted to show different qualities of service.

Location probability describes, in a satisfactory manner, the location and amount of the service available from the point of view of the station assignment and allocation planner, the operating authority, and the viewer or listener. It is believed that this statistic is the most meaningful and practical for the description of television and frequency-modulation broadcast service and easily meets all the above criteria. Location probability is preferable to the signal-to-interference ratio of the useful signal level as a service index, because it provides a comparable measure of the quality of service which is independent of frequency, distance, etc. Although the signal-to-interference ratio might be easier to comprehend, it has the disadvantage of requiring different numbers at different frequencies and distances to describe the same quality of service. The useful signal level is an unsatisfactory index, in that it varies with frequency and cannot take into account interference other than receiver noise. However, when the interference is receiver noise, then contours of constant location probability will also be contours of constant field strength. Procedures for the computation of location probability are relatively simple and rapid [FCC, 1949 and 1950; Kirby, 1957].

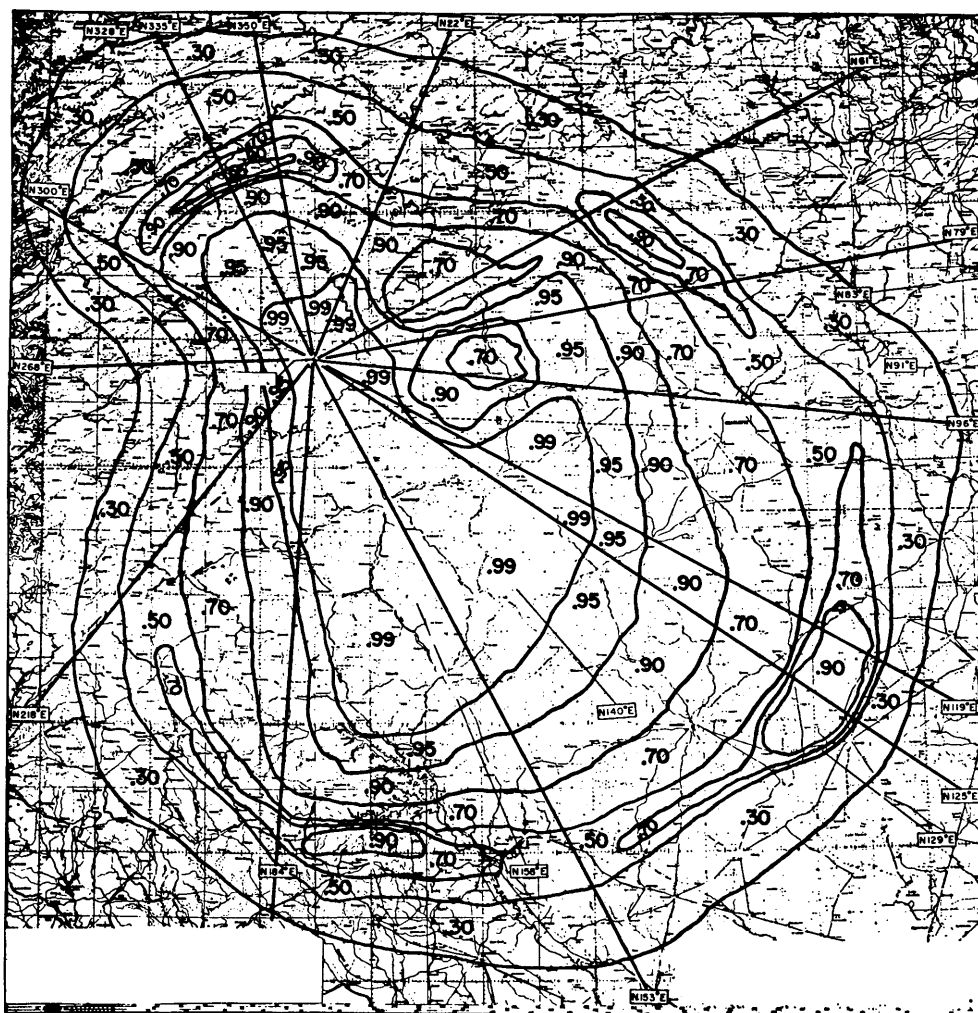


FIGURE 1 – The concept of service probability

The numbers indicate the probability of locations receiving an acceptable service for at least 90 % of the time

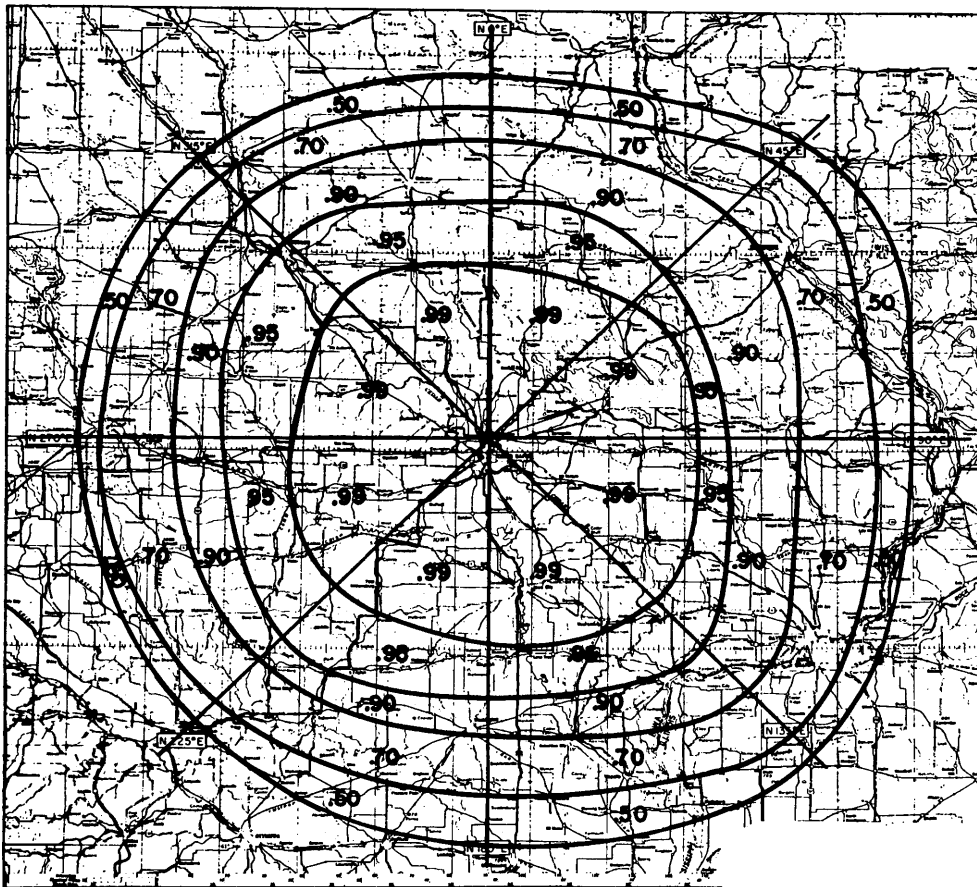


FIGURE 2 – *The concept of service probability*

The numbers indicate the probability of locations receiving an acceptable service for at least 90 % of the time

Two illustrations of the presentation of service by the use of location probability are given in Figs. 1 and 2. The solid curves represent countours of constant service along which the location probability of a given quality of service is constant for a standard installation. Where service is limited by noise, rather than co-channel interference, the location probability, found at a given distance along any radial in Fig. 1, corresponds to some fixed median-time, median-location value of field strength. For example, a location probability of 0.5 in Fig. 1 corresponds to a median field strength of 57 dB relative to 1 $\mu\text{V}/\text{m}$. Fig. 1 shows a great amount of detail, possibly more than could be shown normally with a practical amount of data. However, such detail might be desired for specific sections of a station service area, depending upon the particular problem at hand. Fig. 2 shows what a service map might look like in a more typical case, where the great amount of data for a more detailed map like Fig. 1 is not available.

It is well known, that under practical operating conditions, many people will use an installation just good enough to provide a satisfactory service, but will go to extremes to get the service. Thus, in a strong-signal area many people will use indoor antennae, whereas in weak-signal areas many will employ extremely good installations. Consequently, the number of people receiving a satisfactory signal may well be different than that computed from location probabilities based on a standard receiving installation. However, to provide an objective description of available service, it is desirable to refer always to a fixed quality of service, received on a standard installation. The adoption of a standard receiving installation also makes possible the computation of the combined effects of multiple sources of interference.

Besides meeting all the required criteria, this portrayal of service has several other advantages. The effective service area, or the population served by an individual station, may be computed by adding the products of the location probability, multiplied by the area or the population to which this probability applies [FCC, 1949 and 1950; Kirby, 1957].

This method of portrayal is also convenient for estimating the interference effects of existing, new, or proposed stations in neighbouring areas. Thus, the overall location probability for service in the presence of a number of interfering services, is approximately the product of the individual location probabilities for service of the useful station in the presence of each source of interference acting alone [FCC, 1949 and 1950]. This approximation is fairly good when the resultant overall location probability is 50% or better and improves as the resultant service increases. More accurate methods for computing the effects of multiple interference are also available [FCC, 1949 and 1950; Norton *et al.*, 1952].

2. Method of measurement

Field-strength measurements of VHF (metric) and UHF (decimetric) wave broadcasting stations are made to meet the following objectives:

- 2.1 to provide a basis for assessing the extent of service of any given quality;
- 2.2 to check the directional pattern and power radiated from a transmitting antenna;
- 2.3 to provide data with a view to increasing general knowledge concerning propagation conditions in the bands concerned.

In making measurements, the following conditions should be fulfilled:

- 2.4 measurements should be readily reproducible so that they can be checked subsequently, if required;
- 2.5 the procedure should provide the required information in an efficient manner;
- 2.6 the method should not be hazardous nor too expensive.

Various methods of measurement currently in use fulfil the foregoing criteria with varying degrees of success [EBU, 1973].

It is certainly easier to make the measurements, if the wave collector is about 3 or 4 m above the ground, but a height of 10 m is nearer to the height of the receiving antenna of a typical installation. After obtaining results for a height of 3 m in relatively flat and open terrain, they can be suitably corrected for height, but height correction is difficult for very irregular terrain or built-up areas, more particularly at UHF. Therefore, 10 m would seem to be the best height for the measurement antenna and ideally a great many independent sample observations should be obtained at this standard height.

On the other hand, when the height of the transmitting antenna is such that the field strength varies non-linearly with height above the ground for the frequency band concerned; it is desirable to measure the field strength at various heights up to at least 20 m [Gentile, 1966].

In making measurements of the coverage of television transmitters, the normal practice in all bands is to measure the field strength of the sound channel and to apply the appropriate factor, so obtaining the peak field strength of the picture signal which is expected to correlate closely with the quality of reception as a general rule.

However, when using directional receiving antennas, it is sometimes insufficient to measure only the strength of the sound signal to determine the coverage of a transmitter for both vision and sound.

It is desirable that the recorded results of a survey should relate to the field strength available for 50% of the time. Within 20 to 30 km from the transmitting site, the fading range will generally be very small and no great error will have been introduced by making measurements at any time, irrespective of the prevailing refractivity of the lower atmosphere. At the greater ranges at which survey measurements are made, as for a high-power transmitter, fading effects may lead to a serious error. At these greater ranges, it is desirable, while a survey is in progress, to make continuous field-strength recordings at a fixed reference point, which may, however, need to be changed as the survey proceeds. From examination of these records, it can be decided whether any particular survey measurements should be rejected or whether they could be adjusted for normal conditions.

In the course of a coverage survey, most of the measurements are made in towns and large villages, sometimes supplemented by measurements along radials from the transmitter site.

2.7 Measurements at frequencies below 100 MHz

Normally, below 100 MHz, a continuous record of field strength is made by a travelling vehicle, usually with a suitable chart recorder geared to the road wheels of the vehicle. Ideally, the method of measuring at the full standard receiving antenna height of 10 m is desirable, but there remains the practical consideration of surveying a large area within a reasonable time. A large number of comparative measurements, made at 10 m and at those heights practicable for mobile recording, confirms that a linear correction is of sufficient accuracy at frequencies below 100 MHz. For mobile measurements of this kind, it is clearly convenient to use an omnidirectional antenna.

As a rule, it is not convenient to make measurements at a height of 10 m over long lengths of road, near overhead wires, trees, etc., but short runs (30 to 150 m), or individual spot measurements can be made at this height. As will be described in more detail below, it is possible to use a systematic procedure of statistical sampling for determining the locations at which these short runs or spot measurements should be made. The degree of accuracy, in estimating the area or population provided with a given quality of service, may also be determined. The short distance runs are made along a short section of road, centred on the measurement point selected and the median value of the field measured on this run is referred to this location. As compared with spot measurements made at the given location, the advantage of the short distance runs is that the median value which it gives is more readily reproducible. Spot measurements are more easily made and may also be used to obtain a distribution of the field strength with respect to time over the period involved.

In the presentation of the results, the exact position of the measuring points is plotted on a map and the median or spot value of the field at those points is shown. The following particulars are noted for each point in a separate report; local topography, height and type of vegetation, housing, obstacles, weather conditions, times of day and any other local features likely to affect the received field (if necessary, photographs from measuring sites can be provided). An indication should also be given of the median, maximum and minimum values of field strength for each short mobile run or measurement group and of the direction from which the maximum signal arrives, if other than the direction of the transmitter.

2.8 *Measurements at frequencies above 100 MHz*

At frequencies above 100 MHz, particularly in bands IV and V, field-strength measurements must be made at the required height of 10 m, since linear height-gain between 3 m and 10 m should not be assumed at UHF.

An estimate is made here of the number of independent single-sample measurements required to achieve the desired degree of accuracy. This accuracy is generally required to be greater when measuring field strength within the critical range 46 to 66 dB and 60 to 80 dB relative 1 μ V/m for VHF and UHF respectively. Towns where the median field strength is outside these ranges, can be considered to be either inadequately served or to have good coverage, so that in these cases small errors in measurement of field strength are less important. Figure 3 shows the number of independent sample measurements required to give 95% probability that the probable error ϵ in a median value will be less than 2 dB or 4 dB. In practice, the acceptable sampling error ϵ should not be greater than 2 dB in the critical zone, but may be increased to 4 dB where accuracy is less important. The relationship between the necessary number of samples and the "variation factor", V , defined as the ratio (in decibels) of the field strengths exceeded at 50% and 90% of the locations within the town or other compact area under consideration, is given in Fig. 3; which is derived from the assumption that the distribution of field strength is log-normal.

The value of the variation factor, V , usually lies within the range 5–10 dB at VHF or 5–15 dB at UHF although in a few cases it may reach 20 dB. Figure 4 shows the distribution of V for a number of towns in the United Kingdom at both VHF and UHF. Generally, the median value of V taken for Fig. 4 is used for the determination of the required number of independent samples, but if during a survey, it becomes apparent that V differs appreciably from the median of those values shown in Fig. 4, the number of samples taken is increased. In general, the number of samples should be between 10 and 100, if the above limits are to be maintained.

Another method of deciding the number of sample measurements required, which may have advantages over the method described above, particularly at UHF, is to measure initially the overall range of scatter R of the field strength at a few topographically high and low points. It can be assumed that the range R is equal to 6σ , where σ is the standard deviation. For a log-normal distribution, $V = 0.214R$.

To assess the extent of service, the measurement procedure may be considered a sampling process in which the cumulative distribution of the sample represents an estimate of the variations within a given area of the actual fields. The choice of sampling locations should be free of bias and should as nearly as possible represent typical operating installations. An important factor affecting the choice of sampling location is the tendency for successive measurements made adjacent to each other to be correlated among themselves, that is they are serially correlated. Independent measurements made with sufficient separation to eliminate serial correlation provide an efficient estimate of the variation of the fields. Studies indicate that significant serial correlation between successive measurements will be present at separations normal to the path of propagation up to one or two kilometres [Kirby, 1957; Kirby and Capps, 1956; Kirby *et al.*, 1956]. Serial correlation will be present in radial measurements at even greater separation.

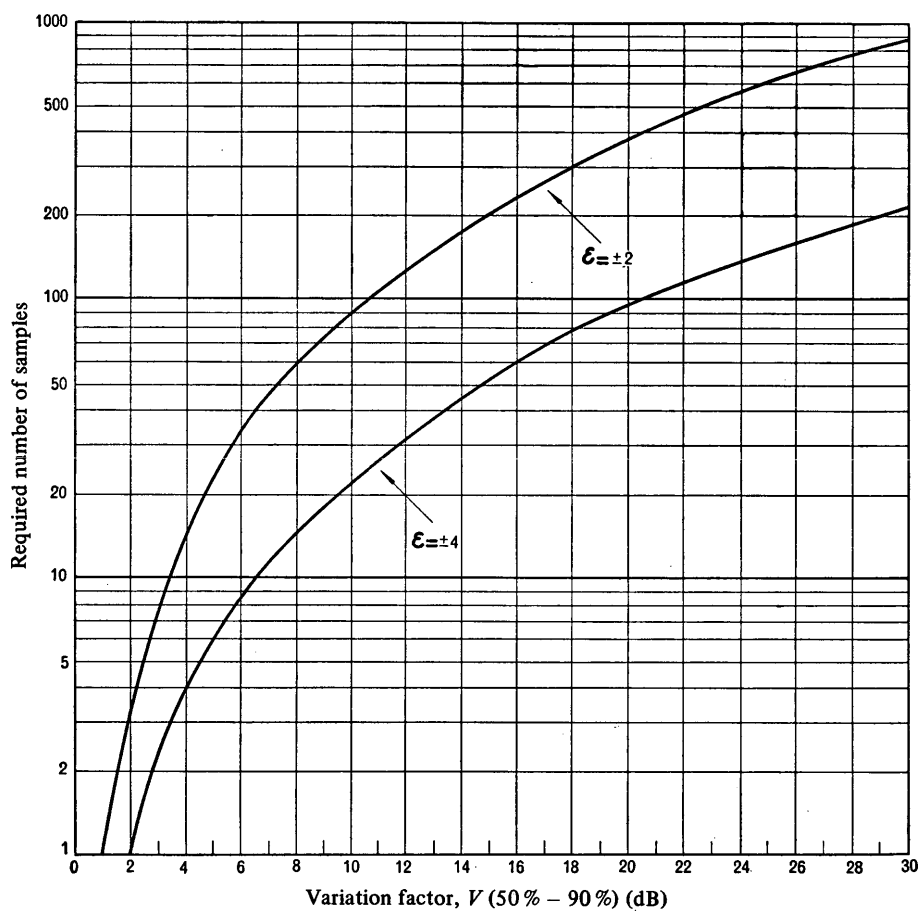


FIGURE 3 – Number of sample measurements required to give 95% probability that the error, ϵ , in the median value will be less than 2 dB or 4 dB

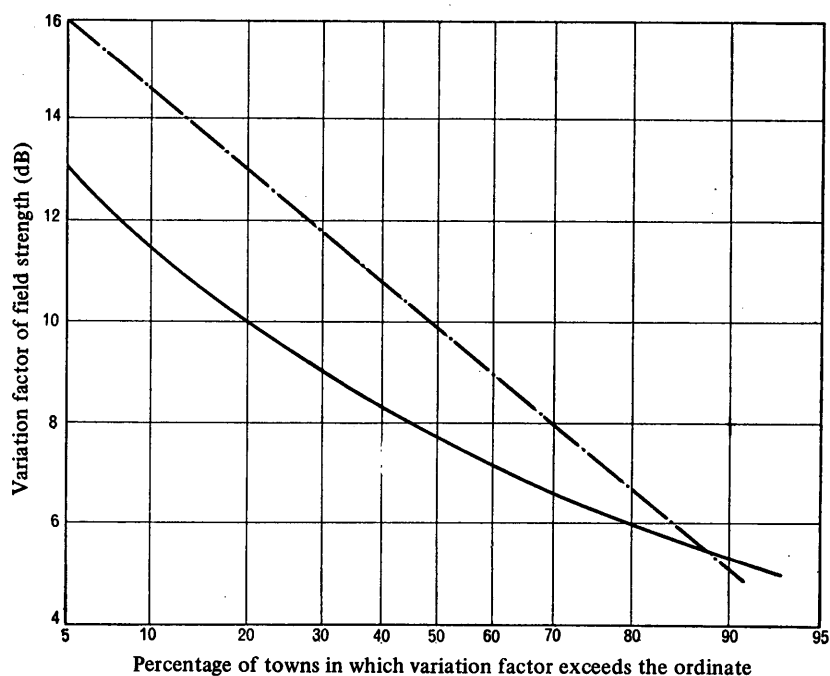


FIGURE 4 – Distribution of values of variation factor for towns in the United Kingdom

All measurements made with the receiving antenna 10 m (30 ft) above ground level

— · — · — Band V measurements in 121 towns
 — Band III measurements in 40 towns

2.9 Selection of sites for measurements

As far as practicable, the urban measuring locations are usually selected at random by reference to a town map, the density of measurements nevertheless being varied according to the population distribution. At each measuring location, a single sample value of field strength may be obtained or, alternatively, a cluster of some four or five measurements may be made at points separated by only a few metres, and the estimated mean of these four or five values recorded as the "sample location" measurement. It is often found that there is substantial correlation between field-strength measurements separated by only a few metres, particularly if a multi-element antenna is employed, but much greater variations between those widely separated, e.g., over different areas of a town. The "single sample" method is often preferred, because of the additional time that may be taken in making "cluster" measurements (due to the frequent raising or lowering of the receiving antenna), or because of the hazard in moving the measuring vehicle while the antenna is fully erected. However, the mean of a cluster is more readily reproduced than a single sample observation, and it can be shown that a given accuracy in assessing the overall variation factor in the area under consideration can be achieved by some 10% to 15% less "cluster" measurements than "single sample" measurements.

All the sample measurements are made using a receiving antenna mounted at the standard height of 10 m. At UHF and at VHF in hilly terrain, typical directional antennas should be used to discriminate against echo signals from surrounding hills and buildings.

For each urban area under consideration, a graph is constructed of the location distribution of field strength from which may be found the percentage of locations at which any given field strength is exceeded.

To arrive at an estimate of the cumulative distribution of field strength in an incremental area within the service area of the transmitter, a sample set of measurements should be obtained in such a way that the propagation characteristics are similar throughout the area of measurement. For example, systematic effects such as large variations of field with distance, should be avoided. One way in which this can be accomplished is to confine each set of sample measurements to an annular area, or segment thereof, centred on the transmitter.

The measurement locations should be laid out on circles or circular arcs centred on the transmitter. The choice of radii for the circles will depend largely upon the location probabilities expected. Therefore, it is extremely helpful to make estimates in advance of the dependence upon distance of the location probabilities for the particular case in question. Figure 5 shows a hypothetical example of this dependence, based on a relationship between field strength and distance for a television station operating in the 54 MHz to 88 MHz frequency band and assuming a log-normal distribution with a standard deviation of 6 dB to represent the dispersion of field-strength values in the incremental areas. Studies of irregular-terrain propagation at these frequencies [FCC, 1949 and 1950; Kirby, 1957; Kirby and Capps, 1956; Kirby *et al.*, 1956; Kühn, 1958], indicate that the logarithm of the field strength has an approximately normal distribution. In this example, the location probabilities indicate the percentage of the areas at the distances shown, that would be expected to have a field strength in excess of 57 dB rel. 1 $\mu\text{V/m}$. Figure 6 illustrates a possible distribution of locations for the measurements. It should be noted that, in this example, the greatest concentration of points is proposed at the distance for which the location probability is 0.5, to provide, in the most efficient manner, information about the total area served. The separations between adjacent measurements should be adequate to eliminate, or at least to minimize, the effects of serial correlation.

2.10 Presentation of results

When the proposed measurement locations, determined in a manner similar to Fig. 6, are transposed to an actual map, it will be found that many of them lie in inaccessible areas. In such cases, the measurement will probably be made nearby at a location which is accessible. The important point to consider in choosing alternate locations is to avoid introducing bias, such as might be the case, for example, if these alternate locations were unduly concentrated along highways.

It would be a relatively simple matter to include other observations along with the basic field-strength measurements. At a selected number of the locations, variations with time could be recorded over a reasonably long period of time. Also the effect of antenna height, antenna directivity, picture or sound quality etc., could be observed. Additional measurements could be made in areas of special interest.

In addition to the method of coverage presentation given in this Report, it is usual to present a field-strength map showing the position of the median contours. The amount of detail that needs to be shown depends upon the degree of irregularity of the terrain and is greater at UHF than at VHF. The supplementary information required with such a map is a table, showing the median field strength and variation factor for 50% to 90% of the locations for each of the more important centres of population.

It may also be useful to present a map similar to Fig. 1, but showing only two or three major demarcations of service zone; for example, the area within which, in any locality, more than 70% or 95% of viewers can obtain a satisfactory service.

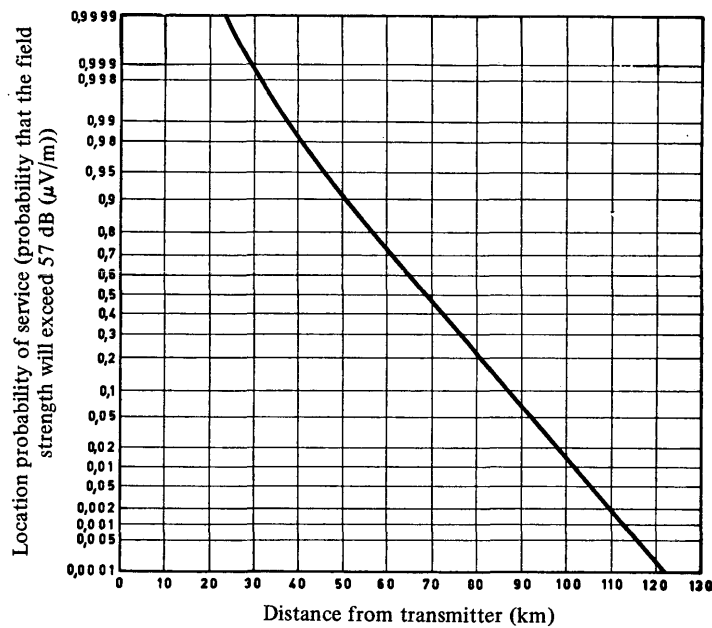


FIGURE 5 – Variation of the location probability of service with distance from the transmitter. Based on typical propagation characteristics of a television station operating at 100 kW e.r.p. in the 54 – 88 MHz band

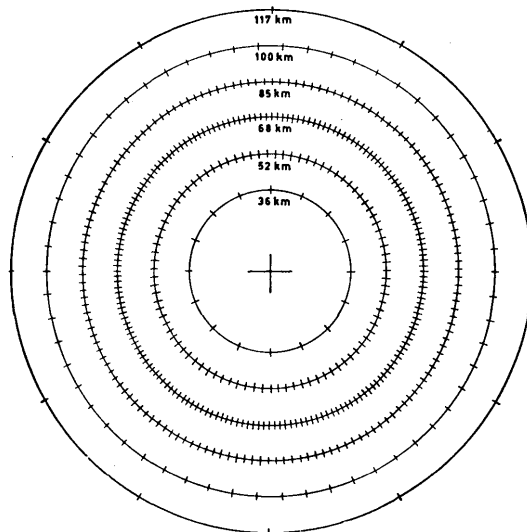


FIGURE 6 – Possible arrangement of measurement sites for a 100 kW station over average terrain
(The transmitter is located at the centre of the diagram)

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REPORT 562-2 *

**PROPAGATION DATA REQUIRED FOR TERRESTRIAL BROADCASTING
IN THE FREQUENCY BANDS ABOVE 10 GHz**

(Study Programme 7B/5)

(1974–1978–1982)

1. Introduction

The increasing demand for broadcasting services in the bands below 1 GHz has required that consideration be given to the use of frequencies above 10 GHz and in particular the 12 GHz band for sound and television broadcasting.

This Report gives a very preliminary description of the propagation effects which are of importance for the planning of networks in the 12 GHz band. Results are given of measurements carried out in the Federal Republic of Germany, in France, in Japan and in Switzerland.

2. General considerations**2.1 Propagation in the service area**

For the planning of a broadcasting system the most important factor to consider is the coverage probability, which is affected by diffraction losses caused by the terrain. In the frequency band above 10 GHz, the losses due to diffraction by buildings are of particular importance.

Consideration should also be given to attenuation due to precipitation and multipath propagation. Measurements in the Federal Republic of Germany indicate that in heavily built-up areas multipath effects caused by reflecting layers in the atmosphere are of minor importance. However, special attention should be given to multipath propagation due to the reflection from large buildings and other terrain features. The relatively high directivity of receiving antennas in this band may alleviate multipath problems of this kind.

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

2.2 *Interference to other service areas*

The propagation characteristics in this frequency band are such that the effective coverage range of each transmitter will be small and hence, to achieve the necessary coverage probability, high transmitter densities may be required. Estimation of the minimum separation distance between co-channel transmitters is therefore of particular importance. This estimation should not be based solely on a calculation of long-term median values of transmission loss, but consideration should also be given to abnormal conditions causing important signal enhancement over long distances for small percentages of the time.

If atmospheric conditions are such that ducting is possible at the transmission frequency, then the interference field strength may be considerably increased, depending on whether the station antenna is located within the duct. Although these effects can be determined for specific cases by various methods [Dougherty and Hart, 1976], a broad probabilistic approach, such as in Report 724, is generally more useful for determining coordination distance, while separation distances between co-channel transmitters may be estimated by means of the methods set out in Report 569.

3. **Propagation data**

3.1 *Propagation in the service area*

Field-strength measurements at about 12 GHz have been carried out by the Federal Republic of Germany [Sakowski, 1970a and b], using an experimental network in Berlin (West) with three transmitters having different effective antenna heights. These measurements show the importance of providing adequate antenna heights to overcome obstruction by buildings. It was found that a more reasonable interpretation of the results in this particular area could be achieved if the receiving antenna heights were not referred to the ground but to the average height of the roof tops near each reception point. Height-gain values for the receiving antenna heights so defined are given in [Sakowski, 1975]. As the relation between field strength and antenna height is highly dependent on the variations in dimensions of the buildings of a town, it is not possible to draw general conclusions from these particular results (the measurements were carried out in a city with relatively standardized roof heights). In a large number of tests [Sakowski, 1977] the influences of single objects were identified. Reflections from buildings turned out to be rather unimportant since the reflection losses were larger than expected. Single trees on the direct path caused attenuations up to several 10 dB, rapidly fluctuating during wind and strongly varying with season in the case of deciduous trees. In comparison to UHF (600 MHz), measured attenuations at 12 GHz in the deep shadow regions were larger by about 10 to 20 dB. Simultaneous measurements with horizontal and vertical polarization showed the difference in attenuation due to obstacles to be generally negligible except that a slight advantage exists (of 4 dB on the average) for horizontally polarized waves in the case of disturbing reflections from vertical surfaces.

The availability of three alternative transmitters in this experiment enabled an assessment to be made of the benefits of threefold coverage of an area. It was concluded that, when using a transmitter height of 200 m in this relatively flat area, single station coverage was only slightly worse than a threefold coverage, the latter being expensive both in transmitter costs and frequency usage.

Similar field-strength measurements, using one 12 GHz transmitter, have been carried out in Switzerland in the urban area of Berne, as well as in flat and mountainous areas of its surroundings [Bärfuss, 1976]. From the results, percentages of coverage within the different areas are derived, based on either a vestigial sideband amplitude modulation system or a frequency modulation system.

In France, propagation measurements were carried out over a period of two years, with 12 GHz broadcasting transmitters situated in central and western France, at path lengths of 74 and 28 km, respectively [CCIR, 1978-82]. The specific attenuations exceeded during 1% and 0.1% of the time were comparable on both paths. However, these attenuations were significantly different for 0.01% of the time.

For an estimation of the attenuation due to precipitation, or due to multipath propagation via atmospheric layers, reference is made to Reports 338 and 720 (worst month attenuation statistics were also obtained in the above-mentioned experiments in Switzerland).

3.2 *Interference to other service areas*

Measurements of interference wave intensities have been carried out in Japan in the different urban areas of Tokyo, using horizontally polarized waves and circularly polarized waves at 12 GHz [Saito *et al.*, 1977]. From the results, transmission loss distributions in the range of 5 to 10 km, in relation to the height and number of buildings around the receiving sites, are derived; and an advantage of using horizontally or vertically polarized transmission over circularly polarized transmission is found by reducing interference to other service areas where the orthogonal polarization is used.

Methods for calculating field strength or transmission loss for the distances which are of interest for assessing long-range interference probabilities are given in Report 569. For network planning at 12 GHz, ranges below about 300 km are of particular interest. Measurements in the Federal Republic of Germany [Abel, 1972] compared with predictions based on [NBS, 1967] showed that the reduction of field strength with increasing distance was less than predicted.

4. Conclusions

This Report summarizes preliminary measurements of field strength in an experimental 12 GHz network.

It is obvious that much additional information is needed to provide a basis for network planning for broadcasting purposes in the frequency bands above 10 GHz.

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CCIR Documents

[1978-82]: 5/113 (France).

SECTION 5E: ASPECTS RELATIVE TO THE TERRESTRIAL FIXED SERVICE

Recommendation and Reports

RECOMMENDATION 530-1 *

**PROPAGATION DATA REQUIRED FOR THE DESIGN OF TROPOSPHERIC-SCATTER
TRANS-HORIZON RADIO-RELAY SYSTEMS, TERRESTRIAL LINE-OF-SIGHT
RADIO-RELAY SYSTEMS, AND EARTH-SPACE TELECOMMUNICATION SYSTEMS**

(1978-1982)

The CCIR,

CONSIDERING

- (a) that for the proper planning of trans-horizon (tropospheric-scatter) and terrestrial line-of-sight radio-relay systems and Earth-space systems it is necessary to have appropriate propagation data that are based on both terrain and atmospheric factors;
- (b) that the data available so far do not allow reliable prediction methods to be developed which would give adequate accuracy in all regions of the world;
- (c) that, however, several methods are available which yield sufficient accuracy in at least some regions,

UNANIMOUSLY RECOMMENDS

1. that the methods set out in Report 238 be adopted for provisional use in the planning of trans-horizon (tropospheric scatter) radio-relay systems;
2. that the methods set out in Report 338 be adopted for provisional use in the planning of terrestrial line-of-sight radio-relay systems;
3. that the methods set out in Report 564 be adopted for provisional use in the planning of Earth-space telecommunication systems;
4. that administrations test these provisional methods and report their findings to the CCIR.

REPORT 338-4 **

PROPAGATION DATA REQUIRED FOR LINE-OF-SIGHT RADIO-RELAY SYSTEMS

(Study Programme 5A/5)

(1966-1970-1974-1978-1982)

1. Introduction

Several propagation problems must be considered in the design of line-of-sight radio-relay systems. These include:

- proximity of the path to obstacles under adverse conditions of refractive index variation with height;
- variability of the apparent angle of arrival of the line-of-sight ray at the receiver terminal;
- signal fading due to multipath effects. This may be overcome partially by the use of diversity systems, dependent on the system employed and the rate of change of fade level.

* This Recommendation is brought to the attention of Study Groups 1, 2, 4, 7, 8, 9, 10 and 11.

** This Report is brought to the attention of Study Group 9.

- the influence of multipath propagation on both analogue and digital modulation systems;
- the effect of multipath propagation and hydrometeors on orthogonal polarization of transmission if this is used to increase the utilization of frequency spectrum;
- attenuation due to rain and other hydrometeors on the path, which also may be overcome partially by the use of path diversity systems;
- attenuation due to gases and due to solid particles in the atmosphere.

Some of the basic physical effects are discussed in Section 5C of this Volume. This Report deals with the propagation data required for system planning.

Although links exist operating at frequencies below 1 GHz, the CCIR does not yet have sufficient data available on the propagation characteristics of these systems, and so typical curves cannot be presented at this time. For this reason the present Report deals mainly with frequencies above 1 GHz.

2. Path clearance

2.1 Variations of k -factor and diffraction loss

Variations in atmospheric conditions cause changes in the effective Earth's radius or k -factor (from its median value of approximately 4/3, see Report 718). When the atmosphere is sufficiently sub-refractive (large positive values of the gradient of refractive index: low k -factor values), the ray paths will be bent in such a way that the Earth appears to obstruct the direct path between transmitter and receiver, giving rise to the kind of fading called diffraction fading. The fade depth (diffraction loss) will depend on the type of terrain and the vegetation. For a given path ray clearance, the diffraction loss will vary from a minimum value for a single knife edge obstruction to a maximum for smooth spherical Earth. Methods for calculating diffraction loss for these two cases, and also for paths with irregular terrain are discussed in Report 715. These upper and lower limits for the diffraction loss are summarized in Fig. 1. Measurements in the United States of America over average terrain [Vigants, 1981; Schiavone, 1981] have shown that diffraction loss may be approximated by the following formula for losses greater than 15 dB:

$$A_d = -20 h/F_1 + 10 \quad \text{dB} \quad (1)$$

where h/F_1 , is the normalized path clearance, as defined in Fig. 1. Note that diffraction fading occurs when h is negative, i.e., the path is obstructed.

Diffraction fading of this type may be alleviated by installing antennas which are sufficiently high, so that the most severe ray bending will not place the receiver in the diffraction region when the effective Earth radius is reduced below its normal value. Diffraction theory indicates that the direct path between the transmitter and the receiver needs a clearance above ground of at least 60% of the radius of the first Fresnel zone (Annex I) to achieve free-space propagation conditions. Minimum effective values of k for a range of path lengths in a continental temperate climate are shown in Fig. 2 [Boithias and Battesti, 1967]. Examples of measurements of refractive-index gradient carried out in a number of countries may be found in Reports 563 and 718. These gradients need to be averaged over horizontal distances of the order of the path length in order to obtain effective values of k .

2.2 Planning criteria for path clearance

When the statistics of sub-refractive conditions are known, it may be possible to devise an accurate procedure which takes into account the actual expected sub-refraction occurring in various regions. See, for example, [Nadenenko, 1971; Schiavone, 1981; Vigants, 1981]. In the absence of such a procedure, examples of planning rules used by various administrations are given in Table III. If excessive path clearance is used, multipath fading and signal distortion may occur on paths with significant surface reflections (§ 4.3). In areas where atmospheric layers or ducts are prevalent, prolonged depressions of median signal may occur if the antenna heights are significantly different (§ 4.1).

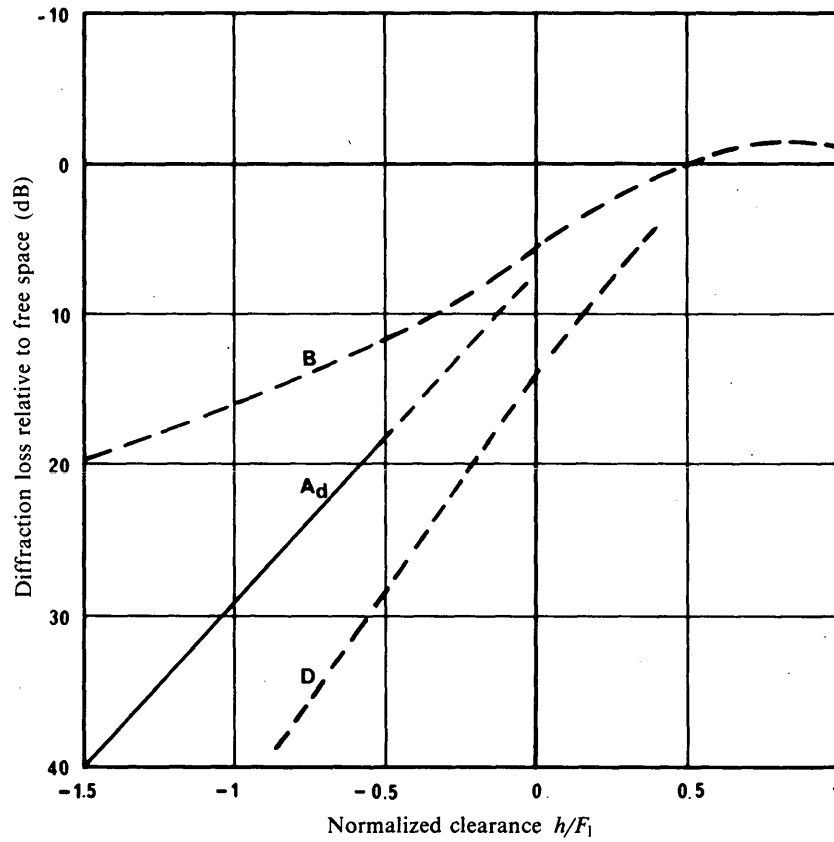


FIGURE 1 — Diffraction loss for obstructed line-of-sight microwave radio paths

B: the theoretical knife-edge loss curve,
 D: the theoretical smooth spherical Earth loss curve,
 A_d : an empirical diffraction loss derived in the United States for intermediate terrain,
 h : the amount by which the radio path clears the Earth's surface and
 F_1 : the radius of the first Fresnel zone

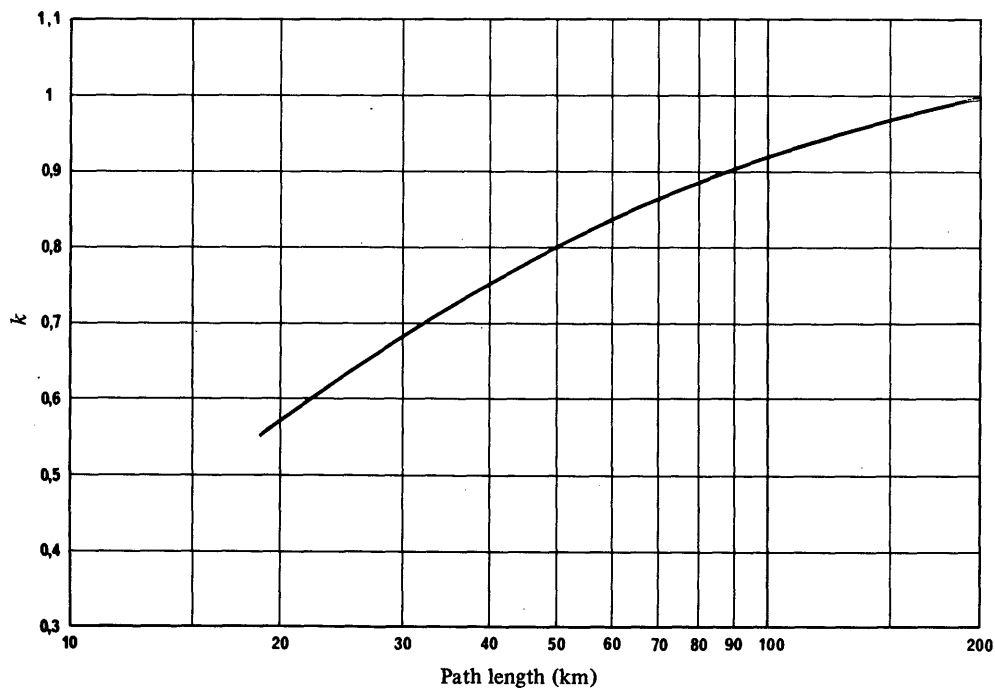


FIGURE 2 — Minimum effective value of k exceeded for approximately 99.9% of the time (Continental temperate climate)

3. Angles-of-arrival

3.1 Variation during single path propagation

The range of variation of angle-of-arrival in the vertical plane is approximately proportional to the path length. The variations are caused by changes of the mean refractive index gradient. The expected range of angle-of-arrival is greater in humid coastal regions than in dry inland areas. Examples of measured data are given in Table IV.

Variations measured on several paths in Japan showed fairly good agreement with those predicted by the statistics of ΔN and $\sigma_{\Delta N}$ in the first 1 km layer, and the layer thickness of ΔH over which the radio waves were propagated [Ikegami *et al.*, 1968].

Mild antenna decoupling due to angle-of-arrival movements has been measured in Canada [Webster and Ueno, 1980; Webster and Lam, 1980] and similar effects have been observed in the U.S.S.R., where the narrow beamwidths employed were thought to be responsible for slow variations in signal strength [CCIR, 1978-82a; Nadenenko *et al.*, 1978]. This is consistent with descriptions presented elsewhere [Dougherty, 1968].

Since, under given conditions, the deviation in angle-of-arrival is expected to be proportional to path length, a useful parameter might be defined, namely, specific change in angle-of-arrival (that is, change in degrees/path length in km). Theoretical and experimental evidence suggests that, as a guide, the range of specific change in angle-of-arrival covering 99.8% of the time may be taken as $\pm 2 \times 10^{-3}$ degrees/km for dry inland paths, and $+14$ to -5×10^{-3} degrees/km for humid coastal regions: the larger upward movements in the latter case should be noted. For humid coastal regions therefore it may be advantageous to elevate the antenna beams slightly from the normal boresight setting under well-mixed atmospheric conditions, provided that this does not cause unacceptable degradation of the cross-polar discrimination.

Variations of angle-of-arrival in the horizontal plane are usually very much less than those in the vertical plane (e.g. less than $\pm 0.1^\circ$ [Sharpless, 1946]).

3.2 Variation during multipath propagation

Deviations from the normal angle-of-arrival vary widely under multipath conditions and do not exhibit a strong dependence on path length. On two paths on the eastern seaboard of North America a high degree of variability was observed, with individual paths elevated up to 0.75° above normal and component separations from 0.7° down to unresolvable values [Crawford and Sharpless, 1946; Crawford and Jakes, 1952]. Rapid changes with time were also noted. Similar results have been found for the Great Lakes area of North America [Webster and Ueno, 1980] with elevated angles-of-arrival up to 0.7° and component separations of the order of 0.4° ; variability with time in these angles was also observed. Very large excursions seemed to be predominantly in an upward direction. Examples of measured data are given in Table IV.

4. Ducting and multipath fading

4.1 Introduction

Under normal conditions there should be only one propagation path between the two antennas on a line-of-sight radio-relay link. In practice, for some of the time, more than one propagation path may exist and interference between the signals received over these paths may give rise to significant fading. The additional paths are generally due to either reflections from the ground or from surface structures or from one or more tropospheric layers with rapid vertical variations or discontinuities in the refractive index. (See Report 718 for details of tropospheric layers.)

The physical and statistical characteristics of tropospheric multipath fading are very different from those which are caused by reflection from the ground. Fading caused chiefly by the troposphere will therefore be studied first. The influence of reflections from the ground will be studied in § 4.3.

In line-of-sight links where deep multipath fading does not occur, small amplitude fluctuations are observed which are referred to as scintillation. Although the phenomenon of scintillation occurs at all frequencies, it is particularly marked above 10 GHz. Information is given in Report 881. At the frequencies of interest, the amplitude of these rapid fluctuations is normally less than a few dB peak-to-peak, and they are not therefore considered of interest to the system designer.

During stratified atmospheric conditions on a line-of-sight radio-relay system, various height configurations between the transmitting and receiving antennas, and ducting layers can give rise to different fading effects. A particularly severe condition is found if, because of a large difference between the transmitting and receiving antenna heights, the transmission path is intersected at a shallow angle by the ducting layer. In this case the radio-wave energy can be trapped and diverted away from the receiving antenna, which therefore lies in a "shadow" region. This condition can persist for hours, and is known to be especially marked over water and coastal areas. It will not be treated further but its occurrence should be avoided by the system designer.

Multipath fading occurs when stratified layers form, resulting in the reflection/refraction of additional ray paths between transmitter and receiver.

Experiments in the Federal Republic of Germany have revealed that total reflection can occur in an atmospheric layer near the ground. Such situations are dealt with in § 4.3. A model has also been developed [Fehlhaber, 1976a] to show how the use of terminals with a sufficient difference in their heights can prevent significant multipath fading.

4.2 *Tropospheric fading on paths without significant reflections*

Apart from diffraction fading and significant surface reflections (§ 4.3), fading on these paths can generally be separated into shallow fading, or scintillation, which occurs for the major proportion, P_0 , of the time and the deep fading multipath mode, occurring for a small proportion, P_M , of the time.

Tropospheric multipath fading exhibits a frequency and duration of fading which are related to the variation of the structure of the refractive index in time. On overland paths and in temperature climates, these variations normally occur during the night and early morning hours of summer days.

Measurements carried out in various countries have shown that the number of multipaths can at times be very high. In Japan, measurements have shown [Nomura *et al.*, 1967] that most of the deep fades are caused by destructive interference between two dominant rays and that the path-length difference between these rays varies to a considerable extent with propagation path conditions. The relative amplitude ratio of multiple rays showed a rapid variation over a wide range resulting in an almost uniformly distributed probability density. Delays can sometimes correspond to extremely high path differences, even on short paths [Cartwright and Tattersall, 1977].

4.2.1 *Prediction methods*

For designing radio-relay systems conforming to CCIR Recommendations, it is necessary to predict the probability of deep fades for very small percentages of the time.

The overall probability of fading below a certain signal level, W (watt), is given by:

$$p_r(W) = p_0 p_0^1(W) + p_M p_M^1(W) \quad (2)$$

where p_0^1 and p_M^1 are the probability distributions of the instantaneous signal level associated with the shallow and deep fading processes respectively. These distributions may be modelled by separate Nakagami-m distributions. Their composite distribution, p_r , is approximately Nakagami-m if the mean signal levels during shallow and deep fading periods are approximately the same [Nakagami, 1960]. The parameters of the composite distribution can be determined by fitting the distribution to measured data.

The results of fitting a Nakagami-Rice distribution to data measured over average rolling terrain in North-west Europe are given in Fig. 3 for a frequency of 4 GHz [Boithias, 1981]. The curves in Fig. 3 corresponding to shorter distances (less than 50 km) are an extrapolation of a statistical model obtained from fitting the distributions to the measurements above 50 km. First order empirical adjustments for frequency are as follows: At 2 GHz, the fading depth exceeded for 1% of the time is less than that given in Fig. 3 by an amount varying from 0.5 dB for 50 km to 5 dB for 250 km. At 6 GHz, the fading depth exceeded for 1% of the time is greater than that given in Fig. 3 by an amount varying from about 1 dB for 50 km to 6 dB for 250 km. Measurements carried out in Italy over a mixed overland and sea 300 km path at 2 GHz have given results in good agreement with Fig. 3 taking into account frequency and path length corrections.

For low signal levels (fades greater than about 15 dB) the Nakagami-m distribution can be approximated by a Rayleigh-type distribution [Morita, 1970]. Adjusting for the probability that deep fading occurs, p_M , the overall probability is given by:

$$p_r(W) = p_M \cdot K \cdot Q \cdot \frac{W}{W_0} \cdot f^B \cdot d^C \quad (3)$$

where

d : path length (km)

f : frequency (GHz)

K : factor for climatic conditions

Q : factor for terrain conditions

W : received power (W)

W_0 : received power (W) in non-fading conditions.

This formula applies only to fading depths exceeding about 15 dB; it may not be applicable for very short distances.

Figures have been proposed by various administrations for the values of $(p_M K Q)$, B and C for estimating cumulative deep fading time in an average worst month (for a definition of average worst month, see Report 723), see Table I (see Note below). Note that the values given for these parameters may be distorted by the inclusion of paths with surface reflections and/or diffraction fading.

For frequencies greater than 12 GHz, it is necessary to include an allowance for the attenuation by water vapour and oxygen.

Note. — Administrations are urged to present additional measured data on the statistics of multipath fading during the worst month to support or oppose Table I. In order to increase the usefulness of the individual contributions, and to ensure compatibility between the various contributions, these should, as a minimum, contain the information indicated in Annex III for each path. Administrations which have already submitted results are requested to re-submit them in this form. It is urged that data from paths which may suffer from surface reflections should be excluded from these submissions.

4.2.2 Results of measurements

Fading depths on more than 40 paths at various frequencies and of various lengths over rolling terrain in France, the Federal Republic of Germany and the United Kingdom can be represented by a common set of distributions [Battesti and Boithias, 1964]. Over paths up to about 100 km the fading depth seems not to be very dependent on frequency but above that distance frequency dependence becomes more marked.

Measurements carried out in the People's Republic of China at 4 GHz on five terrestrial paths between 54 and 123 km in length showed that the probability of multipath fading was not sensitive to path length. This may be associated with a large difference in the heights of the terminals [CCIR, 1978-82b]. Results of measurements of multipath propagation may also be found in other papers [Tattersall and Cartwright, 1977; Stephansen and Mogensen, 1979].

Measurements at 11 GHz on one of the two adjacent 16 km paths in Canada are in approximate agreement with calculations based on equation (3), while measurements on the other path were an order of magnitude lower, suggesting that local effects are very important. The predicted frequency dependence was not observed, measurements at 17 GHz being more than an order of magnitude lower than those at 11 GHz rather than somewhat higher [Butler, 1981].

From Fig. 3 the attenuation value (A dB) which is not exceeded for 80% of the worst month, is represented for N.W. Europe by the following semi-empirical formula [CCIR, 1978-82c]:

$$A = 3 \times 10^{-2} d \sqrt{f} \quad (4)$$

4.2.3 Dynamic aspects of tropospheric multipath fades

4.2.3.1 Number and duration of fades

The duration and number of fades over a certain period of time (for example, a month) affect transmission quality. These quantities also influence the choice of the diversity system required to reduce the degradation of quality. They are of particular importance for digital radio-relay systems, where the performance may be expressed in terms of error-free seconds (see Report 378).

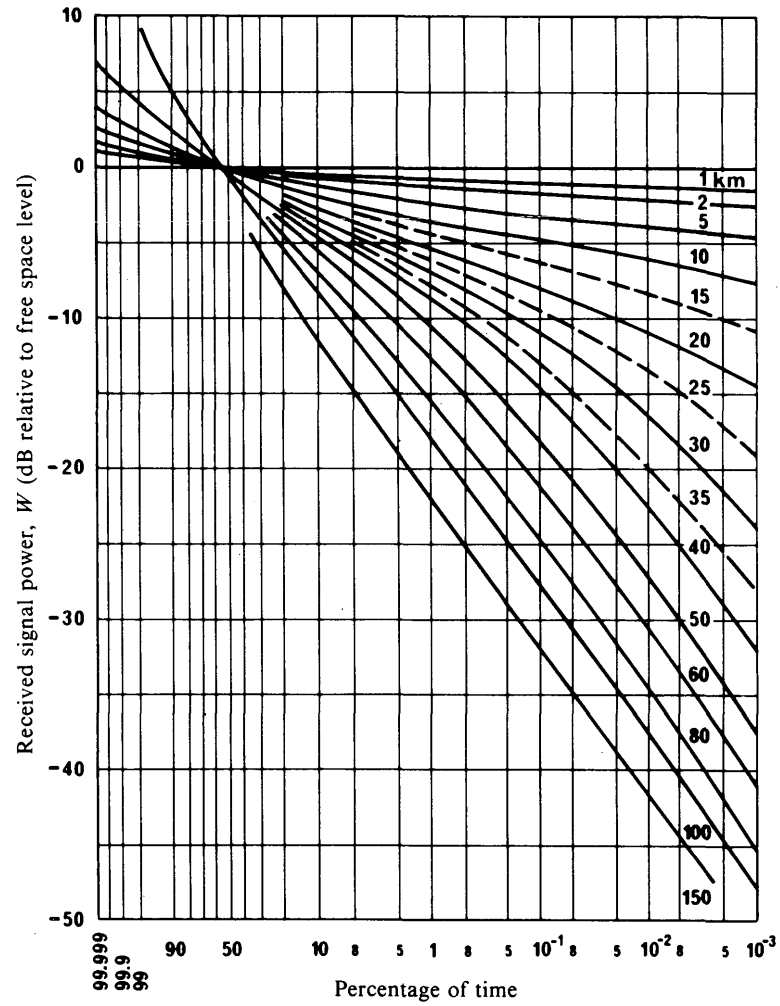
FIGURE 3 — *Atmosphere multipath fading* $f = 4$ GHz — temperate climateProbability ordinate is not exceeded, $p_r(W)$ (for time percentage)

TABLE I - Comparison of parameters for equation (3)

Proposed for	Japan ⁽¹⁾	N.W. Europe	United Kingdom	United States	U.S.S.R.
Reference	[Morita, 1970]		[Doble, 1979]	[Barnett, 1972; Vigants, 1975]	[Nadenenko, 1980]
<i>B</i>	1.2	1.0	0.85	1.0	1.5
<i>C</i>	3.5	3.5	3.5	3.0	2.0
$p_M \cdot K \cdot Q$ for maritime temperate, mediterranean, coastal or high-humidity-and-temperature climatic regions				$\frac{4.1 \times 10^{-5}}{S_1^{1.3}}$	2×10^{-5}
$p_M \cdot K \cdot Q$ for maritime sub-tropical climatic regions				$\frac{3.1 \times 10^{-5}}{S_1^{1.3}}$	
$p_M \cdot K \cdot Q$ or continental temperate climates or mid-latitude inland climatic regions with average rolling terrain	10^{-9}	1.4×10^{-8}	$\frac{8.1 \times 10^{-7}}{S_2^{1.4}}$ to $\frac{4.0 \times 10^{-6}}{S_2^{1.4}}$	$\frac{2.1 \times 10^{-5}}{S_1^{1.3}}$	4.1×10^{-6}
$p_M \cdot K \cdot Q$ or temperate climates, coastal regions with fairly flat terrain	$\frac{9.9 \times 10^{-8}}{\sqrt{h_1 + h_2}}$				2.3×10^{-5} to 4.9×10^{-5}
$p_M \cdot K \cdot Q$ or high dry mountainous climatic regions	3.9×10^{-10}			$\frac{10^{-5}}{S_1^{1.3}}$	
$p_M \cdot K \cdot Q$ or temperate climates, inland regions with fairly flat terrain					7.6×10^{-6} to 2×10^{-5}
Standard deviation of measured results			2.6 dB, 29 links, 2-37 GHz, 7.5-75 km		1 dB, 33 links at 4 GHz

(¹) The Japanese data applies for the worst season.

Note. - h_1 and h_2 are antenna heights in metres.

S_1 is the terrain roughness measured in metres by the standard deviation of terrain elevations at 1 km intervals ($6 \text{ m} \leq S_1 \leq 42 \text{ m}$). The height of the radio sites has to be excluded.

S_2 is defined as the r.m.s. value of the slopes (in milli-radians) measured between points separated by 1 km along the path, but excluding the first and the last complete km interval ($1 < S_2 < 80$).

It is possible that some of these parameters may be distorted by the inclusion of data from paths which experience surface reflection problems and/or diffraction fading.

Measurements of the number and of the duration of fades have been carried out by several administrations [Barnett, 1972] at frequencies between 4 and 15 GHz. Except where noted the results generally agree on the following points [Boithias, 1981]:

- if the ratio between the power under consideration and the power under free space conditions is designated by W/W_0 , and if only fades deeper than 15 dB approximately are considered, the number of fades per hour, N , is given by the following expression:

$$N = C_1 \left(\frac{W}{W_0} \right)^{\alpha_1} f^{\beta_1} \quad (5)$$

N tends to increase with path length;

- for a given depth of fading, the fade duration is distributed according to a log-normal law whose average value, $\bar{t}$ (s) is given by:

$$\bar{t} = C_2 \left(\frac{W}{W_0} \right)^{\alpha_2} f^{\beta_2} \quad (6)$$

The constants of proportionality C_1 and C_2 depend on the period under consideration, path length, climate, etc.; α_1 , α_2 , β_1 , β_2 , C_1 , and C_2 have been calculated by several experimental workers. The results are shown in Table II.

TABLE II - Parameters for calculation of fade dynamics

Location	α_1	α_2	β_1	β_2	$\beta_1 + \beta_2$	C_1	C_2
France	0.5	0.5	1.4	-1	0.4	-	-
Denmark	0.67	0.33	-	-	-	$\sim 0.7^{(1)}$	-
United States	0.5	0.5	1.32	-0.50	0.82	-	$56.6\sqrt{d}$
Switzerland	0.41	0.59	1.38	-1.38	0	-	-

(¹) Based on an assumed value of β_1 of 1.4.

The United States data were measured at 4 and 6 GHz [Lin, 1971; Vigants, 1971; Bullington, 1971]. Measurements in the U.S.S.R. have shown, however, that $\bar{t}$ decreases with path length (without obstacle fading) and with relative path clearance.

In each case the sum of the exponents α_1 and α_2 is equal to 1, as the product $N \cdot \bar{t}$ represents the total fade duration which, for deep fades, is proportional to the received power (see equation (3)).

The standard deviation of fade duration decreases with fade depth [Nadenenko and Sviatogor, 1972; Stephansen and Mogensen, 1979] for 13.5 to 15 GHz and increases somewhat with frequency. It depends only slightly on the geometrical characteristics of the path and the climatic conditions [Nadenenko and Sviatogor, 1972].

4.2.3.2 Rate of change of signal level

The rate of change of signal level can be measured in one of two ways, either as a change in signal level in a specified small time interval, or as a time interval associated with a specified small change in level.

In general, experimental data have shown that this rate increases with frequency and fade depth (consistent with the behaviour of $\bar{t}$ in equation (6)) and increases with path length.

Measurements carried out in France over one year on a 53 km path at 13 GHz have shown that the rates of change in level had log-normal distributions with the same standard deviation for average attenuations of 20 dB and 30 dB. The measurements were carried out over a 10 dB interval. The median values were 5 dB/s around 20 dB and 20 dB/s around 30 dB. The ratio of the rates of change over a standard deviation interval was 5.4 [Derrennes, 1979].

4.3 *Paths with significant reflection from the ground*

If the radio-relay path passes over very reflective ground, fading is more dependent on reflections from the ground than on tropospheric multipaths especially on short paths. High ground reflections could occur over such areas as sea, lake, flat and humid areas, wet ground and moist river valleys or moors where total reflection can occur in an atmospheric layer near the ground when mist or ground fog occurs. The fade characteristics are then different from those described above. In particular the curves in Fig. 3 are no longer directly applicable, and smaller or greater fade depths occur, depending on the height of antennas above the reflective surface (see Annex I).

A method has been proposed [Morita, 1972] for calculating the probability of "equivalent Rayleigh fading" from a reflective ground, on the basis of fading in non-reflective conditions, taking the equivalent reflection coefficient as a parameter. However, Rayleigh's distribution is not necessarily a good model if there are stable reflections.

In such cases the antennas could be used to discriminate against the reflected signal and hence reduce the severity of fading. If the beamwidth is narrow enough, the antennas could be pointed slightly upwards. Alternatively, space diversity (§ 4.4) or a vertical array of the two receiving antennas coupled by means of a phase shifter could be employed. The vertical spacing required between the antennas is dependent on path length, antennas heights and frequency [CCIR, 1978-82d]. It has been found that if the path can be so arranged that the geometrical point of reflection on the water is screened from one or the other of the terminals by the terrain, even if some of the water is still visible from both terminals, the fading can be reduced considerably. However, experience on one over-water path 80 km long [Giugliarelli, 1965] showed that it was very difficult to transmit complex signals, such as colour television, if the water was visible from at least one terminal.

Studies carried out in the Federal Republic of Germany [Giloi, 1979] suggest that in some instances the interference fading pattern can be modified by the presence of a knife-edge which is well below the direct path.

Over sufficiently flat paths, the number of fades (except sub-refractive) also rises with increased path clearance. On coastal paths, the number of fades is substantially higher than over land paths. For example, at 4 GHz in the summer months, over a sea path of 43.3 km with a clearance of 86 m ($k = 1$), 1350 fades with a depth of 30 dB were observed, compared with only 260 fades of the same depth over a fairly flat land path of 48.7 km with a clearance of 16 m [Nadenenko and Sviatogor, 1972].

4.3.1 *"Single" frequency results*

Under normal conditions and over moderately irregular sea or terrain, a portion of the ground reflected wave can be scattered away from the propagation path [NBS, 1967]. However, when the atmosphere is super-refractive and the Earth appears concave, the reflected wave can be enhanced by the convergence of the associated rays. Enhancements of 12 dB above free space have been observed on several occasions [Stephansen and Mogensen, 1979].

Measurements on a 22 km overseas path off the west coast of France showed a decrease in the median value of fade durations as well as in the standard deviation, with an increase in frequency from 2 to 15 GHz. Furthermore fading rates of 5 dB/s at 2 GHz were measured and values above 100 dB/s were attained at 15 GHz in a 10 dB interval [CCIR, 1978-82e].

4.4 *Diversity reception*

Frequency and vertically-spaced antenna diversity are the main methods used to alleviate the effects of multipath fading. Significant benefits can be obtained even if the correlation between the signals is high. Several methods based on the effects of variation of refractive index gradient on a two-ray model have been published [Lewin, 1962; Norton *et al.*, 1965]. Models have been developed [Vigants, 1975; Makino and Morita, 1967] for predicting the correlation coefficient and hence the diversity improvement factor.

Studies carried out in France and Italy show that a vertical spacing of 150 wavelengths is desirable for space diversity to be effective. However, measurements conducted in the Federal Republic of Germany show that the correlation between signals does not decline uniformly with the antenna spacing in wavelengths. These measurements also show that by taking account of diffraction phenomena during multipath fading it is possible to reduce the clearance of the lower space diversity antenna [Giloi, 1979].

The available improvement from a pair of vertically spaced antennas can be defined in terms of a ratio I ; where

$$I = \frac{p_r(W)}{p_{rd}(W)}$$

and $p_{rd}(W)$ represent the fraction of the month during which the received power is less than or equal to W on paths with diversity.

The expression for the available improvement on an overland link which has been engineered to have negligible ground reflections, is given in [Vigants, 1975] as:

$$I = S^2 (f/d) 10^{(F-V)/10} \cdot 1.2 \times 10^{-3} \cdot \eta \quad (7)$$

where

F : fade margin, dB

S : vertical separation of receiving antennas, in metres centre-to-centre

V : difference of the two antenna gains, dB

η : efficiency of the protection switching arrangement.

This equation for I applies only for the following ranges of parameters:

$$2 \leq f \leq 11 \text{ GHz}$$

$$24 \leq d \leq 70 \text{ km}$$

$$5 \leq S \leq 15 \text{ m.}$$

Extrapolation beyond these limits will lead to errors. Furthermore, antenna separations for which the available improvement I is less than 10 should not be used.

This formula is based on experience in the United States of America [Vigants, 1968, 1970, 1971, and 1975; White, 1968; Barnett, 1970], under particular conditions of climate and terrain.

The design of diversity systems on paths with significant surface reflections differs slightly from that above. Annex I gives formulae for the calculation of the path geometry. These formulae can be used to calculate an optimum frequency or antenna spacing in order to achieve maximum protection against ground reflected waves [Vigants, 1975].

Frequency diversity measurements have been made at 2.5 GHz in the Federal Republic of Germany and at 2 GHz in Italy, where it has been found that on paths of length 50 to 70 km, a frequency separation of 150 to 200 MHz is required for efficient diversity, but that on paths of length 120 km, the frequency separation may be reduced to 80 MHz. Measurements made in the German Democratic Republic on a 56 km path (near Dresden) indicated that frequency diversity at 11 GHz with frequencies separated by 240 MHz resulted only in an improvement of 5 dB for 99.9% of the time. A method to quantify the diversity improvement has been published [Barnett, 1970].

Other diversity techniques and methods suitable for adverse conditions have been proposed to alleviate the effects of multipath fading. Measurements made on a 6 GHz, 106 km path in the Federal Republic of Cameroon have shown that it is possible to reduce the correlation between received signals on two antennas arranged so that one antenna was pointed slightly upwards from the direct path, creating in effect an angle diversity system. In areas where ducting is prevalent, e.g. in Senegal [Hautefeuille *et al.*, 1980; CCIR, 1978-82f], measurements indicate that diversity using parallel radio paths properly spaced above the ground could lead to significant improvement in reception [Boithias, 1979].

As a result of numerous experimental measurements carried out by several administrations, it was possible to plot the curves shown in Fig. 4 [Boithias and Battesti, 1967] indicating the improvement obtained with space or frequency diversity. These curves are valid for the worst month on links seriously affected by fading, for frequencies between about 2 and 10 GHz. The improvement would probably be slightly better for lower frequencies. With space diversity, it is assumed that the vertical spacing between the antennas is greater than about 150 wavelengths. Measurements in the United States [McGavin *et al.*, 1970; Dougherty, 1968] have compared the effectiveness of frequency diversity and space diversity performance under adverse conditions.

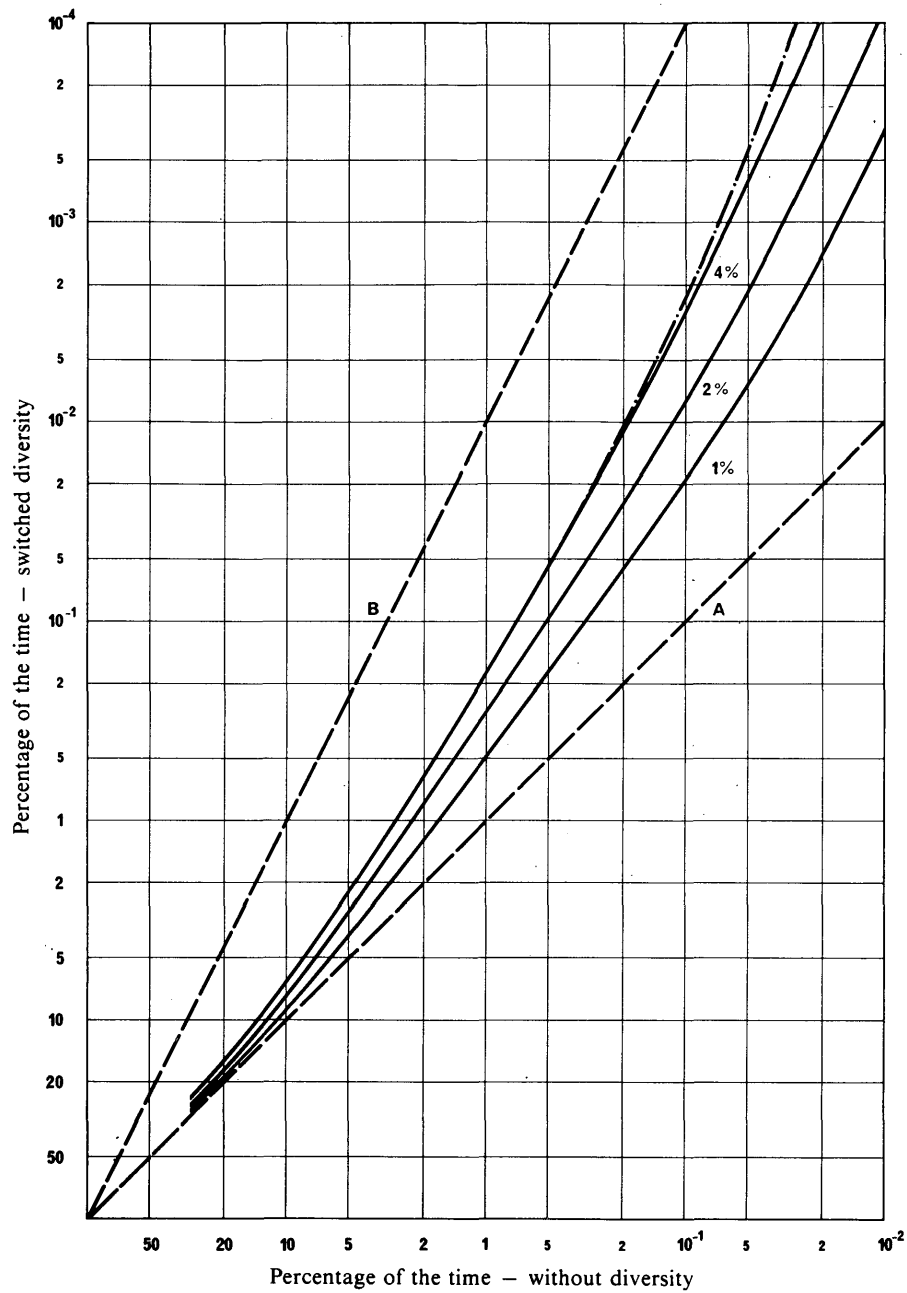


FIGURE 4

Curves A: limiting curve without diversity

B: limiting curve with switched diversity

— Frequency diversity with $\Delta F/F = 1\%$, 2% and 4%

- · - Space diversity greater than 150 wavelengths vertical spacing between antennas

5. Attenuation due to hydrometeors

5.1 General

Microwave radio propagation through the atmosphere shows attenuation due to absorption and scattering by hydrometeors (rain, hail, snow and fog). This attenuation is usually negligible at frequencies below 5 GHz but may become considerable at higher frequencies. Therefore, in planning radio-relay systems to operate in such bands, attenuation due to hydrometeors is a consideration whose importance increases with rising frequency, since this may constitute the source of the highest attenuation. Report 563 gives a description of the characteristics and extent of rainfall. For a general discussion of attenuation due to rainfall reference is made to Report 721.

For frequencies where attenuation due to rain is not negligible, there exists a percentage of the time, depending on the climate and frequency, for which the attenuation due to rain is greater than that due to multipath. For percentages of the time of practical interest in the United Kingdom and the Netherlands [Turner *et al.*, 1966; Bell, 1967; Harden and Turner, 1973; Hewitt and Norbury, 1973; Morita, 1971] attenuation due to rainfall at 11 and 12 GHz respectively is not a preponderant factor, either on a monthly or on an annual basis; in a United Kingdom experiment, multipath propagation was the dominant cause of deep fades at 11 GHz on the longer links while heavy rain was the major influence at 37 GHz on the shorter links, at 20 GHz multipath fading and attenuation due to rain were of comparable importance. In Japan attenuation due to rainfall is the preponderant factor above 10 GHz. In the Federal Republic of Germany it was found that for frequencies between 9 and 12 GHz and path lengths between 25 and 70 km either type of fading could be dominant.

Since multipath propagation occurs mainly when the atmosphere is stratified, i.e. when there is no heavy rainfall, it will suffice to add the percentages of time corresponding to these two causes of fading.

5.2 Long-term statistics of rain attenuation

5.2.1 Prediction method

Modelling of attenuation due to rain on terrestrial links for frequencies above 10 GHz is examined in Report 721, which also summarizes the methods presently available for predicting attenuation statistics.

From an examination of these methods the following simple technique appears to yield reasonable agreement with available data. It can be applied when detailed information on rain structure is not available.

The methods consists of the following steps:

- obtain the rain intensity exceeded for 0.01% of the time (with an integration time of 1 minute). If this information cannot be obtained from local data sources, an estimate can be obtained from the maps of rain climates given in Report 563, Figs. 11 to 13;
- knowing the frequency and polarization, the specific attenuation γ_R (dB/km) for the rain intensity of interest can be obtained from Report 721;
- the effective path length l_{eff} of the link is obtained by multiplying the actual path length l by a reduction factor r . A first estimate of this coefficient is given by:

$$r = \frac{90}{90 + 4l} \quad (8)$$

- the attenuation exceeded for 0.01% of time is found from:

$$A_{0.01} = \gamma_R l_{eff} = \gamma_R \cdot l \cdot r \quad (9)$$

- attenuation exceeded for other percentages P is deduced from the following power law:

$$A_P = A_{0.01} (P/0.01)^{-a} \quad (10)$$

The coefficient a is given by [Fedi, 1981]:

$$a = 0.33 \text{ for } 0.001 \leq P \leq 0.01\%$$

$$a = 0.41 \text{ for } 0.01 < P \leq 0.1\%.$$

By applying the procedure for testing the prediction accuracy set out in Report 721, this prediction method appears to be in agreement with available experimental attenuation data to within some 20% when used with simultaneous rain rate measurements. When used with rain climatic information from Report 563, the errors may be expected to be larger, in general. Note that this method provides an estimate of the long-term statistics of attenuation due to rain. When comparing measured statistics with the prediction, allowance should be given for the rather large year-to-year variability in both rain and attenuation statistics [Crane, 1980].

Some observations in Canada suggest somewhat higher values of the coefficient a in a continental climate, while some observations in tropical and equatorial climates (Congo) would suggest somewhat lower values. However, due to the scarcity of data no general conclusions can be drawn at this instant.

This method is a first step, requiring updating and revision as more detailed information, especially for non-European climates becomes available. Administrations are invited to furnish additional information in the format of Annex IV and to investigate possible improvements to the method.

System planning often requires attenuation statistics for the time percentages P_w of the "worst month". Worst month statistics can be derived from average annual statistics by the use of the following relationship between P_w and P (see Report 723):

$$P = 0.29 P_w^{1.15} \quad (11)$$

5.2.2 Results of attenuation measurements

Many administrations have carried out attenuation measurements at various frequencies and distances. Measurements have shown that the year-to-year variability is large, especially for small percentages of the time.

Annex IV gives a summary of the presently available statistics of rain attenuation below 60 GHz.

Fading due to cloud, fog, snow and hail is usually of less importance than fading due to rain (Report 721). However, attenuation due to wet snow may be notable, deep fades have been observed [CCIR, 1974-78; Mogensen, 1977], but snow on the antenna may be a complicating factor.

5.3 Polarization effects

An estimate of the dependence of attenuation on polarization can be obtained from Report 721.

Some experimental results are summarized below.

Experiments carried out in France at 13 GHz on a 53 km path and at 20.5 GHz on a 23.5 km path [Fimbel *et al.*, 1976; Fimbel and Juy, 1977] and in Italy at 17.8 GHz on a 9.5 km path [Fedi *et al.*, 1977, 1978] have shown that horizontally-polarized waves are attenuated considerably more by rain than are vertically-polarized waves. Results are generally in agreement with estimates derived from Report 721.

From long-term observations in France it was concluded that the following simple equation produces a useful approximation for the relation between attenuation at horizontal and vertical polarization:

$$A_v = \frac{300 A_H}{335 + A_H} \quad (12)$$

5.4 Measurements at frequencies above 50 GHz

There have been fewer studies at frequencies above 50 GHz. Calculations based on work in the United States [Weibel and Dressel, 1967] show that, in the United Kingdom [Lane, 1968] at a frequency of 100 GHz on a pulse-code modulation link 2 km long, 20 μ W would be adequate, except for rain heavier than 25 mm/h, which occurs for 0.008% of the time. For a link 6 km long, however, a reliability of 99.99% would require a transmitter power of about 5 W assuming the same receiver characteristics. Similarly, measurements conducted for a year at 110 GHz over a distance of 2.6 km [Llewellyn-Jones and Závody, 1972] show that such frequencies can be used to establish short radio-relay systems of acceptable reliability.

5.5 Frequency scaling

Report 721 summarizes methods available for frequency scaling.

Measurements in Sweden over a 15 km path at 11, 18 and 36 GHz show good agreement to a scaling formula which employs the power law relationship between specific attenuation and rain rate given in Report 721 [Rue, 1980; CCIR, 1978-82g].

If only attenuation data measured at one frequency are available, the following empirical formula may be applied in the frequency range 7 to 50 GHz for attenuation values of interest [Battesti, 1981]:

$$\frac{A_1}{A_2} = \frac{g(f_1)}{g(f_2)} \quad (13)$$

where:

$$g(f) = \frac{f^{1.72}}{1 + 3 \times 10^{-7} (f^{1.72})^2}$$

A_1 and A_2 are the values of attenuation in dB at frequencies f_1 and f_2 (in GHz) exceeded with equal probability.

5.6 Duration and rate of fading

Measurements carried out during one year in France at 13 GHz on a 53 km path have shown that the cumulative distribution of duration of fading can be represented by a log-normal law [Rooryck, 1973], and that the rate of fading due to rain is much less than the rate of fading due to multipath [Rooryck and Juy, 1977].

Measurements carried out in Denmark at 14 GHz on a 45 km path showed that the rate of fading exceeded about 3 dB/s for less than 0.0001% of the time. The rate of the precipitation fading did not show any clear level dependence [Mogensen, 1977].

Data collected in the United Kingdom at 10 to 40 GHz on links up to 60 km [Harden *et al.*, 1978] have indicated that the duration of precipitation fades varies considerably. Moreover, the average and median values of duration differ. The former depend mainly on the gross structure of the rain and its mean velocity over the path, whilst the latter depend on short-term changes in the number, size distribution, and rate of fall of drops.

Statistics on fade duration and rate of fading are too scarce to enable general conclusions to be drawn or reliable models to be made. In view of the importance of a knowledge of these factors for the design of digital systems, more information is urgently needed.

5.7 Tandem paths and convergent paths

5.7.1 General aspects

The overall transmission performances of tandem systems are influenced by propagation characteristics of each individual link. It is necessary to investigate the propagation effects on tandem paths, together with the single-hop propagation characteristics. Increasing the hop length means increasing the probability of outage in an individual hop. On the other hand, increasing the hop length means fewer hops in a tandem system whereby the outage probability assigned to each hop may be larger.

5.7.2 Tandem paths

When the hop length is larger or much larger than the rain cell size and the probability of occurrence of rain cells is the same for all points in the area of interest, the probability that the rain attenuation exceeds the receiver dynamic range, i.e. that there is an interruption in adjacent paths simultaneously, may be disregarded [Rue, 1977; Peroni and Fedi, 1974]. This means that the overall circuit interruption probability is equal to the sum of interruption probabilities on the individual links.

In severe rain climates, in the higher frequency bands, for extremely small allowable interruption probability and/or when the available fade margin is relatively small, the hop length may become comparable with or smaller than the rain cell size. Then the rain attenuation may exceed the receiver dynamic range in adjacent rain or separated paths simultaneously. This simultaneous interruption in adjacent or separated links results in the reduction of overall circuit interruption time, which means that the overall circuit interruption probability is less than the sum of interruption probabilities on the individual links. This reduction was studied in Japan [Sasaki *et al.*, 1976; Morita and Higuti, 1977].

It was found that the joint interruption probabilities for pairs of separated paths may be disregarded compared to the joint interruption probability for adjacent paths (average path length 4.5 km).

5.7.3 *Convergent paths*

Where two or more radio paths converge to one radio-relay station, the correlation coefficient of attenuation between pairs of paths is dependent on the angle between the paths. This dependence, together with the differential attenuation on the converging paths and the interference between paths, was studied in Japan [Morita and Higuti, 1977] for the case when the path length is smaller or comparable in size with the rain cell. As an example it was found theoretically that for a path length of 4 km, the correlation coefficient increased from 0.8 to 0.97 when the angle between the paths decreased from 180° to 20°.

5.8 *Path diversity*

Whereas fading due to multipath propagation can be corrected by a vertical separation of several metres between the antennas, a choice of paths with a separation of several kilometres may reduce fading due to precipitation.

Experimental data obtained in the United Kingdom in the 20-40 GHz range [Harden *et al.*, 1978] give an indication of the improvement in link reliability which can be obtained by the use of switched-path route diversity. The diversity gain (i.e. the difference between the attenuation (in dB) exceeded for a specific percentage of time on a single link and that simultaneously on two parallel links):

- tends to decrease as the path length increases from 12 km for a given percentage of time, and for a given lateral path separation,
- is generally greater for a spacing of 8 km than for 4 km, though an increase to 12 km does not provide further improvement,
- is not significantly dependent on frequency in the range 20-40 GHz, for a given geometry, and
- ranges from about 2.8 dB at 0.1% of the time to 4.0 dB at 0.001% of the time, for a spacing of 8 km, and path lengths of about the same value. Values for a 4 km spacing are about 1.8 to 2.0 dB.

6. **Attenuation due to atmospheric gases**

Microwave radio propagation through the atmosphere shows attenuation due to absorption by oxygen and water vapour. This attenuation is usually negligible at frequencies below 10 GHz but may become considerable at higher frequencies. Means of computing attenuation due to atmospheric gases for frequencies above 1 GHz are given in Report 719.

7. **Attenuation due to sand and dust storms**

Sand and dust particles (for example during intense storms in desert areas) may absorb or scatter electromagnetic radiation at higher frequencies. However, significant propagation effects have not been reported up to the present time. Further information on attenuation by solid particles is given in Report 721.

8. **Reduction of orthogonal polarization discrimination due to propagation**

The possibility of increasing channel capacity by using orthogonally polarized waves of the same frequency on the same path is restricted by propagation phenomena that transfer energy from waves of one polarization to waves of the orthogonal polarization. Both clear-air and precipitation phenomena are important.

8.1 *Effects during clear-air conditions*

8.1.1 *General*

Various mechanisms can produce cross-polarization during clear-air conditions. These are discussed in Report 722 along with prediction procedures in the process of development. This section concentrates on the results of measurements and some of the tentative conclusions that can be drawn from them. A provisional technique for estimating the unconditional cumulative distribution of the cross-polarization discrimination (*XPD*) from a cumulative distribution of the co-polarized attenuation (*CPA*) (i.e., fade depth) is provided on the basis of information contained in Report 722.

8.1.2 Prediction techniques

In estimating the joint distribution of XPD and CPA , experimental measurements on the actual links involved should be used as far as possible. If such measurements are not available, a rough estimate of the unconditional distribution of XPD can be obtained from a cumulative distribution of fade depth using the equi-probability relation:

$$XPD = -CPA + XPD_0 + Q \quad (14)$$

$$CPA \geq 15 \text{ dB}$$

that applies for sufficiently large fade depths. In this relation, XPD_0 is the static XPD during unfaded conditions and Q is an improvement factor that shows a strong dependence on the slope of the cross-polarized antenna patterns in the vertical plane (see Report 722).

In equation (14), a value of $Q = 0$ would provide a worst-case estimate of the unconditional distribution of XPD . A less conservative estimate, but one which still provides a lower bound to existing data, can be obtained from Table I and equation (12) of Report 722.

Equation (14) is provisional and should be employed with extreme caution. Particular care should be taken when the path is over water or when the path clearance is small. Caution should also be exercised in using equation (14) for space-diversity systems.

8.1.3 Measurements

Various experiments on long paths have demonstrated that XPD can deteriorate significantly during clear-air conditions. For example, experiments carried out in France at 6 and 7 GHz [Lefrançois *et al.*, 1973] and at 13 GHz [Battesti and Constantinidis, 1975], in Japan at 6 GHz [Morita, 1971], and in the Federal Republic of Germany at 7 GHz [Valentin, 1974], for path lengths of 50 km or more, have shown that the XPD between horizontal and vertical polarization could decrease to less than 15 dB for 0.01% of the time; whereas the XPD caused by antennas was greater than 40 dB during normal propagation conditions. Experiments conducted in the U.S.S.R. at 4 GHz on a 55.7 km path showed that the XPD could decrease to 7 dB for 0.01% of the time in the summer months, whereas in the absence of fading the XPD was equal to 27 dB [Nadenenko and Sviatogor, 1981].

In Canada, measurements at 11 and 17 GHz on a 16 km path [Butler, 1981] showed that the XPD for horizontal and vertical polarizations could fall below 23 dB for 0.01% of the time, with a value greater than 34 dB during normal conditions. On an adjacent 16 km path, the deterioration in XPD was not nearly as great for the same percentage of time, suggesting that local effects are important.

The results of experiments conducted in France at 7 GHz [Rooryck and Martin, 1977] and in Japan at 4 GHz [Sakagami and Morita, 1979; Morita *et al.*, 1979] using antennas with different cross-polarized patterns have shown the importance of interaction between multipath mechanisms and cross-polar antenna patterns. Both these experiments showed the XPD degradation to be smaller for antennas with relatively flat cross-polar patterns than for antennas with sharp minima near boresight. A more complete description of the effects of the antennas is given in Report 722.

All observations have shown a considerable variability in XPD for a given fade depth. For constant fade depths greater than about 20 dB, three sets of measurements [Martin, 1977; Lin, 1977; Morita *et al.*, 1979] show the standard deviation in XPD to be of the order of 5 dB.

The advantage of using vertically-spaced receiving antennas to combat the effects of clear-air cross-polarization in addition to fading has been demonstrated from measurements on a 7 GHz, 50 km link in France [Martin, 1977], on an 8 GHz, 51 km link in Canada [Barber, 1981] and for a 4 GHz, 56 km link in the U.S.S.R. [Nadenenko and Sviatogor, 1981].

A review of these and other measurements during clear-air conditions has recently been given [Olsen, 1981a]. For application in systems design and in further improvement to the prediction technique discussed in § 8.1.2, statistical measurements of XPD and fade depth are tabulated in Table VI.

8.2 Precipitation effects

8.2.1 General

A review of various measurements leads to the conclusion that rain is the most significant form of precipitation causing the reductions in *XPD* observed for small percentages of the time [Olsen, 1981b]. The physical mechanism involved and the effects of other hydrometeors such as snow are discussed in Report 722.

8.2.2 Prediction techniques

In predicting cumulative statistics of *XPD* from statistics of *CPA*, Report 722 advises the use of a semi-empirical equation of the form:

$$XPD = U - V(f) \log(CPA) \quad \text{dB} \quad (15)$$

for both linear and circular polarizations. The coefficients U and $V(f)$ are in general dependent on a number of variables and empirical parameters, including frequency, f . For line-of-sight paths with small elevation angles and horizontal or vertical polarization, these coefficients may be approximated by:

$$U = U_0 + 30 \log f \quad (16)$$

$$V(f) = 20 \quad (17)$$

in the frequency range $8 \leq f \leq 20$ GHz. A value of $U_0 = 9$ appears to provide a lower bound for all measurements of *XPD* for attenuations greater than about 15 dB (see Report 722).

Note. — It is suggested that administrations interpret experimental data in terms of models such as that in equations (15) to (17). Additional information on the parameter U_0 is urgently needed.

The prediction method expressed by equations (15) to (17) is provisional and should be used with caution. The relationship between *XPD* and *CPA* is influenced by many factors, including the residual antenna *XPD*, that may not yet be adequately taken into account.

From measurements conducted at 20 GHz on six paths in Japan, an empirical equi-probability relationship between *XPD* and *CPA* was derived to take into account the influence of various factors, including the elevation angle, length of the path and residual antenna *XPD* [Morita, 1976].

8.2.3 Frequency scaling

Long-term *XPD* statistics obtained at one frequency can be scaled to another frequency using the semi-empirical formula:

$$XPD_2 = XPD_1 - 20 \log(f_2/f_1) \quad 4 \leq f_1, f_2 \leq 30 \text{ GHz} \quad (18)$$

where XPD_1 and XPD_2 are the *XPD* values not exceeded for the same percentage of time at frequencies f_1 and f_2 , respectively (see Report 722).

Equation (18) is provisional and must be used with particular caution for large differences between the respective frequencies. It is most accurate if XPD_1 and XPD_2 correspond to the same polarization (horizontal or vertical).

8.2.4 Measurements

Various early measurements were directed towards obtaining cumulative statistics of *XPD* under various conditions [Oguchi, 1975]. As a result of these measurements, it has been concluded that vertical and horizontal polarization results in less deterioration of *XPD* than circular polarization [Possenti, 1975; Zufferey, 1976; Inoue, 1975; Dilworth and Evans, 1980]. Improvements of vertical and horizontal polarization over circular polarization range from 9 dB [Dilworth and Evans, 1980] to as much as 15 dB [Possenti, 1975]. It has also been found that there is a strong correlation between *XPD* and *CPA* [Tirro, 1975; Zufferey, 1976]. This has led to a prediction relation involving *XPD* and *CPA* as discussed in § 8.2.2, and also to the interpretation of most recent experimental data in terms of the semi-empirical parameters of this prediction relation [Olsen, 1981b].

Recent measurements at 11 and 17 GHz on two adjacent 16 km paths in Canada [Butler, 1981] were found to be in agreement with the logarithmic form of the prediction relation (15) in § 8.2.2. However, the effective value of coefficient V was significantly lower than the predicted value of 20. A similar effect is evident in at least one other set of data taken in Japan [Morita *et al.*, 1973]. The physical explanation of this behaviour is discussed in Report 722.

Although a considerable amount of information is available on cumulative statistics of *XPD* for terrestrial paths, little, if any, information is available on other cross-polarization statistics such as fading rate and duration. (Administrations are urged to provide such additional information.)

A collection of experimental data is contained in Table VII.

8.3 *Relative importance of cross-polarization during clear-air and precipitation conditions*

For dual horizontally and vertically polarized systems, with or without diversity, the dominant cause of outages (that are due primarily to cross-polarization interference) is rain on short links and multipath on long links. The smallest path length for which multipath effects dominate depends on the frequency, climate, path clearance, and whether the link is over land or water and whether diversity is employed. In the non-diversity case, for example, measurements in the 10 to 12 GHz range in Europe for paths shorter than 20 km [Watson, 1976; Dilworth and Evans, 1980] show that rain is more significant. Measurements in the 6 to 13 GHz range for paths longer than 50 km [Rooryck and Battesti, 1975; Rooryck and Martin, 1977] show that multipath effects are more important. They also show that *XPD* degradation due to rain does not increase significantly the outage time, because reduction of *XPD* tends to occur at the same time as does severe attenuation [Battesti and Constantinidis, 1975]. On two adjacent 16 km links operated at 11 and 17 GHz in Canada [Butler, 1981], multipath fading and depolarization were dominant on one, while rain attenuation and depolarization were dominant on the other. However, even though one effect may be dominant, both multipath and rain effects will normally have to be accounted for in any system design.

9. **Effect of multipath fading on system performance**

9.1 *General*

System performance impairment due to multipath fading depends on the basic RF bandwidth occupancy of the information bearing signal. For narrowband signals, the statistics of single frequency amplitude fading are adequate for characterizing system outage statistics and frequency selectivity of multipath is relatively unimportant. For broadband signals, on the other hand, both frequency selectivity and power fading influence system performance.

The relationship between fade depths measured at a single frequency and those measured as an integrated power over a wideband system is complex and depends on system bandwidth, path length and antenna beamwidth.

Comments on physical aspects of modelling multipath transfer functions may be found in Report 881.

In this section models are presented to aid the designer in system performance prediction. The validity of the physical models on which these approximations are based needs to be verified in order to allow their extrapolation to different terrains and climates.

Multipath fading is frequency-selective, causing variations of attenuation within a channel bandwidth. Measurements in the United Kingdom have shown evidence of frequency-selective fading of 20 dB over an 80 MHz spacing on an 11 GHz, 36 km path [CCIR, 1978-82d]. The phenomenon is accompanied by group-delay distortions, which may be positive or negative. Inversions of the sign of the group delay are usually accompanied by slight variations of maximum attenuation. With an attenuation of 40 dB, a group-delay distortion of 30 ns has been recorded over a 400 MHz band at 11 GHz on a 50 km path. The greatest speed of variation in group delay, measured at a given frequency, was 108 ns per second [Martin, 1980].

9.2 *Mathematical modelling of the broadband multipath channel*

The performance of any radio system on a line-of-sight path can be evaluated when the complex transfer function of the channel during multipath propagation is known; however, the complete transfer function is generally not known. Various simplified models of the transfer function have been proposed with the purpose of estimating the bit error ratio on digital radio links under multipath conditions [Stephansen, 1981].

The simplest model for the multipath transfer function (MTF) is the two-ray model with various assumptions on the distributions of amplitude and delay of the second ray relative to the first.

A slightly more complex, modified three-ray model for the MTF has been proposed [Rummler, 1979] (Report 718) and the statistics of the model parameters obtained by fitting the amplitude predictions of the model to observed frequency selective amplitude characteristics of a 29 MHz RF channel in the 6 GHz band. Variations of the multipath amplitudes with delay were measured at 11.7 GHz [Turner *et al.*, 1966].

Polynomial representations for the complex MTF have also been proposed [Greenstein, 1978; Greenstein and Czejak, 1980]. In another approach, a polynomial representation is used to model only the amplitude variations due to frequency selectivity [Babler, 1972]. Studies conducted with such polynomial representations conclude that it is necessary to use terms of at least the third order to represent frequency selective fading in broadband channels adequately.

The dependence of MTF model parameters and their statistics on link characteristics and climatic factors is not known. Also, no attempt has been made yet to model the statistical aspects of the broadband MTF of a space diversity channel.

9.3 Analogue systems

In analogue FM-FDM systems multipath transmission contributes to an increase in the thermal noise (due to power fading) and in the intermodulation noise (due to frequency selectivity).

Measurements in the United Kingdom on a 55 km, 600 channel, 4 GHz path [Meadows *et al.*, 1966] and on a 58 km, 600 channel, 11 GHz path [Turner *et al.*, 1966] show that the intermodulation noise contributed by multipath propagation was not important compared with thermal noise.

The same result was obtained in France over a 95 km, 1800 channel, 6 GHz path and in Denmark over a 45 km, 2700 channel, 14 GHz path [Mogensen, 1977].

However, measurements on two — a 138 km and a 182 km — 1800 channel, 6 GHz paths in the Federal Republic of Germany showed significant increases in intermodulation noise as well as considerable variations in the baseband levels for low percentages of the time. This was due to multipath propagation caused by reflection from atmospheric layers [Fehlhaber, 1971, 1973 and 1976b].

Measurements made in Japan at 4 and 6 GHz [Nishino *et al.*, 1975] on a long oversea path, with sections about 120 km long have shown that 960 telephone channels can be transmitted which satisfy the CCIR Recommendations for noise performance. Even on an all sea section, where a reflected wave from the sea surface was possible, the use of space diversity greatly reduced the thermal and intermodulation noise.

Another experiment [Inoue and Akiyama, 1974] which was conducted on a 37.2 km maritime path at 4 GHz with a sea-reflected wave, showed that the cumulative distribution of the duration of noise level increases (measured with a time constant below one second) can be represented by a log-normal law. The circuit noise in a simple receiver shows very marked seasonal variations but, space diversity reception, with an antenna spacing equal to one-half of the distance between two interference maxima, helps greatly to reduce both thermal and intermodulation noise.

Similar results have been obtained in the Federal Republic of Germany using switching diversity reception.

Theoretical methods for calculation of multipath transmission effects upon analogue systems have been obtained in the Federal Republic of Germany [Fehlhaber, 1971 and 1976b] and in France [Azoulay, 1975] for confirmation of these effects. In Sweden [Rue, 1971] a method was developed to calculate the distortion when several or a large number of wave components are present simultaneously in the received signal, with phases of equal probability (0-2 π).

Theoretical and experimental studies carried out in Japan [Nomura *et al.*, 1967] have shown that ground reflections can give a distribution of total noise more unfavourable than that for thermal noise alone, even on propagation paths having relatively weak reflections.

In microwave FDM-FM (analogue) radio-relay systems, the thermal noise variation due to multipath fading are accumulated at the circuit end. This accumulation characteristic was investigated in Japan, both theoretically and experimentally. From these investigations, the relationship between the thermal noise power distribution on the single link and that on multi-relay links of arbitrary length was made clear [Morita *et al.*, 1971].

9.4 Digital systems

The impact of multipath propagation on digital radio systems depends on, *inter alia*, the method of modulation including number of levels and bandwidth. In-band amplitude and phase distortion due to propagation effects causes more system impairment than does signal fading in the absence of such distortion, especially for high capacity systems that have high signalling rates and therefore large bandwidths.

A variation of amplitude of 5 to 6 dB across the signal passband would in many systems give an unacceptably high error rate, even when the signal-to-noise ratio is adequate. Also transient ripples of amplitude and phase across the signal band tend to degrade the performance of a system.

Measurements have been carried out in France on 4-phase digital links, at 6 GHz on a 95 km path, and at 11.7 GHz on a 58 km path, with a capacity of 40 and 200 Mbit/s respectively. The degradation caused by the frequency-selectivity of fading due to multiple paths dominated the system performance for the higher bit rate. From this experiment the parameters of an equivalent two-ray model were determined. The median value of time delay of the indirect ray due to a layer about 0.4 ns [Rooryck, 1979].

Using this two-ray model as the basis, the performance of 4-PSK digital systems operating in a temperate climate in France at 11 to 12 GHz and having path lengths of 50 to 60 km, over rolling terrain, were determined analytically for a number of bit rates. The technique uses a concept that has proved useful to system designers, but that does not in fact have any direct propagation significance. This concept is, in this Report, called the "net" fade margin and for the purpose of this section is defined as the equivalent single frequency fade depth that is exceeded for the same percentage of time (calculated using the method of § 4.2) that the system threshold error rate is exceeded. It follows therefore that the net fade margin would not be the same for radically different equipments, e.g. reduced bandwidth systems, operating under the same propagation conditions.

Figure 5 shows the relationship between the flat fade margin (defined as the fade depth without frequency selectivity at which the specified threshold error rate is exceeded) and the net fade margin. The curves show that the digital system performance cannot necessarily be improved merely by increasing the system flat fade margin.

It has been observed in France that for a given link the value of net margin is practically equal to the value of the actual attenuation for which the threshold error rate is exceeded during about 50% of time. In a two-ray model, this value is given by the attenuation for which the time delay between the two rays is equal to its median value [Rooryck, 1981].

A 34 Mbit/s QPSK link, 73 km long in Sweden, operating at 2.2 GHz had an apparent fade margin of 34 dB, but exhibited loss of synchronization in 50% of fades exceeding 20 dB [Blomquist *et al.*, 1980].

Extremely severe degradation in performance has been observed in an experimental study with 4-phase, 400 Mbit/s systems; this study was carried out at 13.3 and 14.9 GHz on a 22.8 km path in the USA [Dougherty and Hartman, 1977]. Almost all of this degradation was attributed to two-component multipath (terrain/atmospheric) which produced inter-symbol interference. It was concluded that space or frequency diversity reception would have been an effective remedy.

When crossed polarizations are used at the same frequency on a digital link, cross-polarization interference limits the performance of each radio channel. In France [Rooryck and Martin, 1977] the degradation in performance on a QDPSK link was calculated using the distribution of polarization discrimination measured during multipath fading. Then, switched space-diversity reception gives each channel a better performance than that of one channel operating with a single polarization without diversity [Martin, 1977].

In Canada, experiments on an 8 GHz, long-haul digital radio-relay system have indicated that an adaptive amplitude equalizer that compensates for slope distortions of the channel during multipath fading, when used in conjunction with a space-diversity receiver using an in-phase combiner, reduces the probability of outage (due to multipath) of the digital system to very low values [Anderson *et al.*, 1979]. Measurements on the deterioration of cross-polarization discrimination during multipath fading events show that a space-diversity system with an in-phase combiner provides adequate cross-polar discrimination for co-frequency dual-polarized operation of the 8 GHz digital radio-relay system [Barber, 1981].

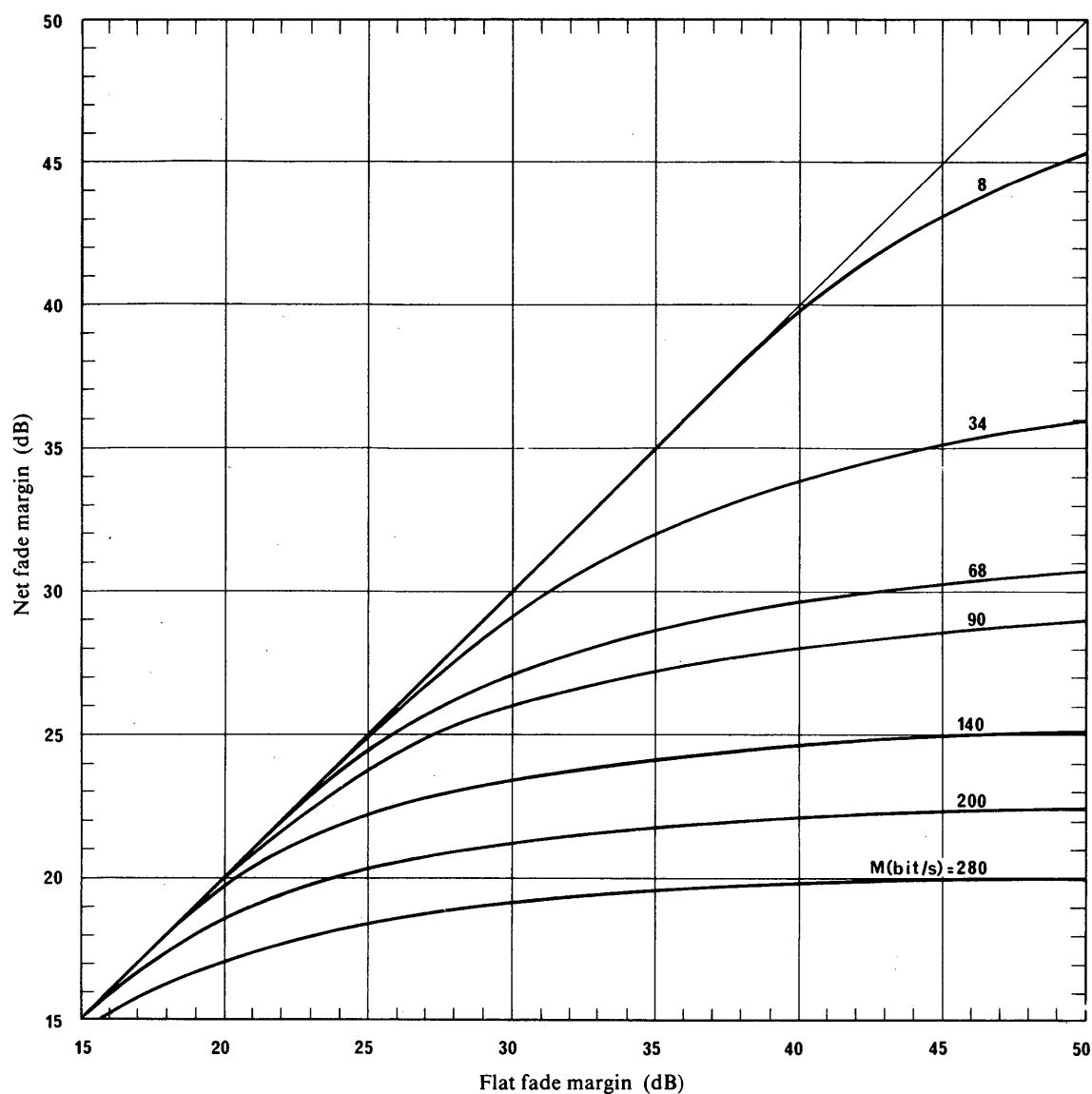


FIGURE 5 — Net margin as a function of flat margin for QPSK system ($BER=10^{-5}$) operating without diversity or equalization at 11 to 12 GHz over 50 to 60 km paths

(The curves were derived from measurement at these frequencies and distances using an experimentally determined 2-ray model)

Note. — Bandwidth = $1.2 \times$ symbol rate
5-pole Butterworth filter

10. Propagation tests for radio links

Path propagation tests are occasionally required to identify or locate sources of fading. While investigating fading phenomena, distinction must be made between multipath fading due to reflection from the ground or water or other surfaces, reflection from atmospheric discontinuities and diffraction by the Earth's bulge (low k -values) or extreme refraction. The observer may distinguish between these fading phenomena by impulse transmission techniques, which permit direct amplitude and delay measurements to resolve received signal components [Lindfield *et al.*, 1976].

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ANNEX I

PATH GEOMETRY

For line-of-sight paths with reflection from the ground, a two-ray model of the propagation is used as shown in Fig. 6. An effective Earth radius, $a_e (= ka)$, rather than the real radius, a , is used to allow for average refraction of radio rays. For effects of atmospheric refraction see Report 718.

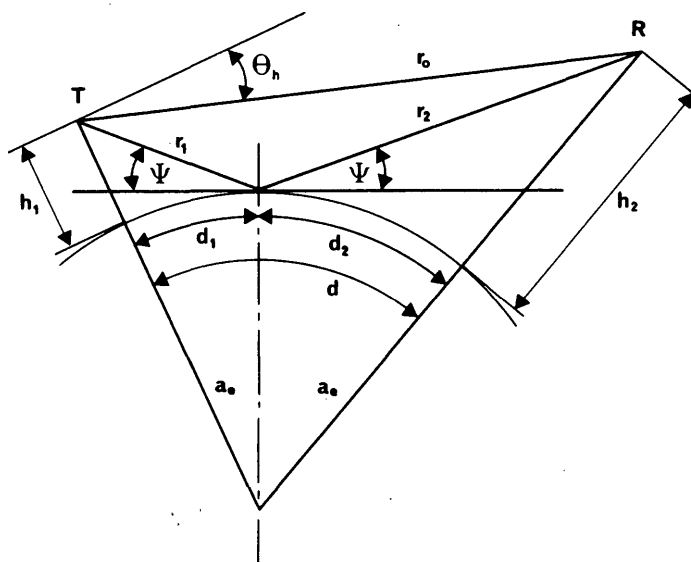


FIGURE 6 — Geometrical relationships for within-the-horizon paths

For a smooth, perfectly conducting surface, the additional path loss relative to free space of the received signal, as a result of the sum of the direct and ground reflected waves is

$$A = -6 - 10 \log \sin^2 (\pi \Delta r / \lambda) \quad \text{dB} \quad (19)$$

where λ is the radio wavelength and $\Delta r = r_1 + r_2 - r_0$ is the difference between the ray paths.

For small grazing angles, ψ , and with antennas h_1 and h_2 (km) above the Earth,

$$\Delta r \approx 2h'_1 h'_2 / d \quad (20)$$

where h'_1 and h'_2 are the heights of the antennas above a plane tangent to the Earth at the point of reflection.

$$\Delta r = \frac{n\lambda}{2} \quad \text{corresponds to the } n\text{th Fresnel zone.}$$

For equal antenna heights over a spherical earth of effective radius, a_e :

$$\Delta r = d(\sec \psi - 1) \quad (21)$$

The greatest distance $d = d_0$ for which $A = 0$ may be obtained graphically from the relation

$$2h_1^2/d_0 - h_1 d_0/(2a_e) + d_0^3/(32a_e^2) = \lambda/6 \quad (22)$$

ANNEX II

TABLE III - Radio-link path clearance measurement data (in terms of Fresnel zone radius) and design criteria

Location	Fresnel zone radius factor	k-factor	Comments
USA ⁽¹⁾	0.6	1.0	Good propagation conditions
USA ⁽¹⁾	all others > 0	0.66	
	the larger combination of: 0.3 and 1.0 and	0.66, or 1.33	Average propagation conditions
USA ⁽¹⁾	> 0	0.5	
France ⁽²⁾	0	$k_{min.}$	$k_{min.}$ determined from Fig. 2
	1	1.33	
United Kingdom	0.6	0.7	No diffraction fading observed from 300000 hours of records from 21 radio-relay stations Protection against diffraction fading for $d > 100$ km (50% of the time) (99% of the time)
Germany (Federal Republic of)	1.0	1.33	
Germany (Federal Republic of)	1.0	1.0	
Various	1.0	1.33	

⁽¹⁾ [Vigants, 1975].

⁽²⁾ [Boithias and Battesti, 1967]

Note. - When two clearance criteria are given, the higher value of the calculated clearances should be adopted.

TABLE IV - Angle of arrival data

Path location	Frequency (GHz)	Path length (km)	Angle-of-arrival variations (degrees)	References
1. <i>Single path propagation</i>				
(a) <i>Inland</i>				
England	11	55	± 0.12	[Bell, 1967]
Germany (Federal Republic of)	0.52	70	similar	
(b) <i>Coastal</i>				
Japan	11	29	+ 0.4 to - 0.1	[Ikegami <i>et al.</i> , 1968]
North America (Great Lakes)	9	35	± 0.4	[Webster and Ueno, 1980; Webster and Lam, 1980]
North America (East Coast)		38	± 0.46	[Sharpless, 1946; Crawford and Sharpless, 1946]
2. <i>Multipath propagation</i>				
North America (Great Lakes)	9	35	up to 0.7	[Webster and Ueno, 1980]
North America (East Coast)	4.24	28	up to 0.75	[Crawford and Sharpless, 1946; Crawford and Jakes, 1952]

During multipath propagation large and rapid variations in the angle-of-arrival were observed. Vertical separations between individual multipath components up to 0.7° [Crawford and Jakes, 1952] and up to 0.4° [Webster and Ueno, 1980] were measured.

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ANNEX III

PROPOSED FORMAT FOR PRESENTING INFORMATION
RELATING TO RESULTS ON MULTIPATH FADING

1. Country
2. Location: approximate longitude and latitude
3. Description of the geographic conditions (over-sea, coastal area, mountain, etc.)
4. Frequency
5. Bandwidth of system
6. Path length (km)
7. Terrain roughness (m) expressed as the standard deviation of terrain elevation at 1 km intervals about the mean slope of the path (excluding terminals)
8. Path clearance (number of Fresnel zones for $k = 2/3$)
9. Slope of path and slope of major part of terrain (mrad)
10. Beamwidths of antennas at the half-power points (-3 dB)
11. Height of antennas (m)
12. Number of years represented in measured data
13. Recording technique (integration time constants, data sampling time interval)
14. Supporting meteorological measurements
15. Standard deviation in measured data at specific levels, year-to-year
16. Standard deviation with respect to a specified model if data have been statistically processed.

ANNEX IV

RAIN ATTENUATION BELOW 60 GHz

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TABLE V

Location	Frequency (GHz)	Polar- ization	Length (km)	Period	Years	References	Rain attenuation in dB (rainfall intensity in mm/h) exceeded for various percentages of time										
									10 ⁻³ %	2 × 10 ⁻³ %	3 × 10 ⁻³ %	6 × 10 ⁻³ %	10 ⁻² %	2 × 10 ⁻² %	3 × 10 ⁻² %	6 × 10 ⁻² %	10 ⁻¹ %
Mendlesham									(50)	(39)	(32)	(23)	(18)	(13)	(10)	(6)	(4-5)
(United Kingdom)	19.4	V	7.4	73-75	3	[Fedi, 1979]			18.6	14.7	12.9	9.9	8.1	6.0	5.2	4.2	3.2
	20.1	V	16.6	73-75	3	[Fedi, 1979]			34.8	29.4	25.8	20.2	16.8	12.2	9.6	6.8	5.5
	20.7	V	22.7	73-75	3	[Fedi, 1979]			36.0	30.0	26.7	22.6	18.4	15.0	13.5	10.8	8.6
	22.1	V	2.9	73-75	3	[Fedi, 1979]			13.9	11.0	9.8	7.2	5.7	4.1	3.7	3.1	2.3
	22.3	V	4.0	73-75	3	[Fedi, 1979]			17.9	16.0	14.9	12.1	9.0	6.1	5.3	4.3	3.6
	22.1	V	7.0	73-75	3	[Fedi, 1979]			24.0	20.0	18.6	15.2	12.0	8.0	6.5	5.0	4.1
	36.6	V	2.8	73-75	3	[Fedi, 1979]			24.9	19.6	15.4	12.0	10.3	9.0	8.0	6.3	4.2
	36.1	V	7.4	73-75	3	[Fedi, 1979]			-	32.2	31.0	27.0	22.7	18.0	15.7	13.3	11.9
	36.6	V	8.8	73-75	3	[Fedi, 1979]			-	38.7	36.0	29.0	25.8	20.8	18.0	12.8	9.8
	37.4	V	3.7	73-75	3	[Fedi, 1979]			30.0	26.0	21.8	16.4	12.6	9.6	8.4	6.8	5.9
	37.4	V	7.7	73-75	3	[Fedi, 1979]			-	-	-	28.5	25.6	18.0	14.1	10.6	8.5
Kjeller									(53)	(40)	(34)	(25)	(20)	(14)	(11)	(7)	(5)
(Norway)	18.0	V	21.3	75-76	2	[Fedi, 1979]			26.6	24.8	23.7	20.0	15.0	11.8	9.8	7.4	6.0
Stockholm									(70)	(52)	(43)	(30)	(23)	(17)	(14)	(9)	(6)
(Sweden)	10.8	H	15.0	76-77	2	[Fedi, 1979]			15.2	12.0	10.4	9.1	8.4	6.8	-	-	-
	17.9	H	15.0	76-77	2	[Fedi, 1979]			-	30.0	27.2	22.8	19.2	14.0	12.2	10.0	9.0
	36.0	H	15.0	76-77	2	[Fedi, 1979]						56.0	47.0	36.0	30.0	24.0	21.0

TABLE V - (Continued)

Location	Frequency (GHz)	Polar- ization	Length (km)	Period	Years	References	Rain attenuation in dB (rainfall intensity in mm/h) exceeded for various percentages of time										
									10 ⁻³ %	2 × 10 ⁻³ %	3 × 10 ⁻³ %	6 × 10 ⁻³ %	10 ⁻² %	2 × 10 ⁻² %	3 × 10 ⁻² %	6 × 10 ⁻² %	10 ⁻¹ %
Darmstadt									(50)	(43)	(38)	(28)	(22)	(16)	(12)	(8)	(5.5)
(Germany (Federal Republic of))	12.4	H	20.0	76	1	[Fedi, 1979]			19.6	16.8	14.8	11.6	9.2	6.8	5.4	3.7	2.8
	15.0	H	20.0	76	1	[Fedi, 1979]			28.4	23.0	20.9	16.8	14.1	10.4	9.0	5.6	4.6
	29.0	H	20.0	76	1	[Fedi, 1979]			–	–	–	46.0	39.0	32.0	27.4	22.0	18.0
	39.0	H	20.0	76	1	[Fedi, 1979]			–	–	–	–	–	–	–	36.0	27.5
Leidschendam									(62)	(48)	(40)	(28)	(20)	(18)	(16)	(8)	(6)
(Netherlands)	35.5	H	12.4	73-74	1	[Fedi, 1979]			–	–	–	–	42.4	32.7	28.4	22.0	16.8
Paris									(90)	(68)	(58)	(42)	(35)	(22)	(17)	(11)	(8)
(France)	13.0	H	12.0	75-77	3	[Fedi, 1979]			29.4	22.6	18.7	14.1	11.6	8.4	7.0	–	–
	13.0	H	15.4	75-77	3	[Fedi, 1979]			37.8	30.0	26.5	19.7	16.1	11.1	9.2	6.8	–
	11.7	H	58.0	75-77	3	[Fedi, 1979]			45.7	41.0	37.0	29.6	23.6	18.9	16.3	12.8	10.6
Dijon									(–)	(75)	(66)	(53)	(40)	(28)	(22)	(14)	(10)
(France)	13.0	H	53.0	72-79	5	[Fedi, 1979]			54.0	47.2	44.1	39.6	35.0	27.2	23.6	17.4	13.6
	20.0	H	22.0	79	1	[Fedi, 1979]			–	59.5	54.4	45.1	39.7	30.6	25.0	17.1	13.6
Fucino									(100)	(75)	(64)	(47)	(35)	(25)	(20)	(14)	(9)
(Italy)	11.0	V	9.5	75-77	2	[Fedi, 1979]			16.0	14.0	12.7	9.2	7.6	6.0	4.8	4.1	3.0
	17.8	V	9.5	75-77	2	[Fedi, 1979]			29.8	25.6	23.3	19.1	15.6	12.1	10.7	8.1	6.3
	17.8	H	9.5	75-77	2	[Fedi, 1979]			39.8	33.4	29.7	23.8	20.0	14.0	12.1	9.4	7.2
Rome									(–)	(110)	(97)	(75)	(62)	(46)	(37)	(22)	(15)
(Italy)	11.0	V	25.0	69	1	[Fedi, 1979]			–	38.4	34.0	29.4	25.0	20.5	18.3	15.2	13.8

TABLE V - (Continued)

Location	Frequency (GHz)	Polar- ization	Length (km)	Period	Years	References	Rain attenuation in dB (rainfall intensity in mm/h) exceeded for various percentages of time										
									10 ⁻³ %	2 × 10 ⁻³ %	3 × 10 ⁻³ %	6 × 10 ⁻³ %	10 ⁻² %	2 × 10 ⁻² %	3 × 10 ⁻² %	6 × 10 ⁻² %	10 ⁻¹ %
Turin									(110)	(90)	(80)	(62)	(50)	(35)	(27)	(15)	(8)
(Italy)	11.45	V	22.5	74-75	2	[Damoso <i>et al.</i> , 1980]			48.7	42.2	39.2	28.0	20.8	15.8	13.8	9.8	7.7
Merrimack Valley									(120)	(92)	(78)	(60)	(48)	(16)	(12)	(8)	(6)
(USA)	18.0	V	4.3	71-73	3	[Lin, 1975]			36.3	29.0	24.2	19.0	14.5	-	-	-	-
Palmetto									(170)	(136)	(120)	(92)	(76)	(56)	(48)	(36)	(28)
(USA)	17.7	H	5.1	70-74	2	[Lin, 1975]						39.0	31.0	23.0	19.0	13.5	-
Holmdel									(-)	(120)	(104)	(76)	(60)	(44)	(36)	(22)	(-)
(USA)	18.5	V	6.4	68-69	2	[Lin, 1975]			-	44.0	41.8	32.8	27.0	19.0	13.0	-	-
Tokyo									(109)	(98)	(94)	(83)	(66)	(42)	(33)	(22)	(17)
(Japan)	11.5	C	1.3	79-80	1	[Ihara and Furuhama, 1981]			6.3	5.5	5.0	3.4	3.1	1.8	1.3	0.9	0.8
	34.5	C	1.3	79-80	1	[Ihara and Furuhama, 1981]			-	-	-	19.3	16.3	11.3	9.9	6.6	5.0
	81.8	C	1.3	79-80	1	[Ihara and Furuhama, 1981]			-	-	-	33.8	29.3	24.5	21.7	17.4	14.6
Brazzaville									(-)	(-)	(-)	(144)	(120)	(97)	(91)	(53)	(37)
(Congo)	7.0	H	33.5	80-81	1	[Moupfouma, 1981]			-	-	-	21.8	20.0	18.0	16.0	11.0	9.0
Rio de Janeiro	10.9	H	8.6	-	3	[CCIR, 1978-82]			(230)	(179)	(140)	(105)	(90)	(75)	(65)	(-)	(-)
(Brazil)									-	19.5	18.5	16.5	14.5	11.0	9.0	7.0	6.0

ANNEX V

MEASURED CROSS POLARIZATION DISCRIMINATION (XPD) DATA

TABLE VI - Measured XPD and CPA statistics during clear-air conditions

Location (height above mean sea level) (m)	Frequency (GHz)	Path length (km)	Transmission polarization	XPD ₀ (dB)	Time period	0.001%	0.01%	0.1%	Additional information	References
						XPD (dB) CPA (dB)	XPD CPA	XPD CPA		
Rhine Valley	7.7	63.5	Vertical		Aug. 1974			16		[Valentin, 1977]
Lannion (225)	7.15	50	Vertical	40	5 Aug.- 5 Sept. 1973		16.5 36	26 26	Antenna with relatively sharp cross-polar pattern.	[Martin and Casanova, 1974]
			Vertical Horizontal	41	5 Aug.- 5 Sept. 1973		21 36	31 26	Antenna with relatively flat cross-polar pattern.	[Martin and Casanova, 1974]
Dijon	6	95	Horizontal	45	Dec. 1971			>14 31	Propagation conditions were very bad during this month.	[Lefrançois <i>et al.</i> , 1973]
Yokosuka (410)	4.15	44.1	Horizontal	45	May-Oct. 1978	23 23	31 15	37 7		[Sakagami and Morita, 1979]
Yokosuka (410)	4.15	44.1	Horizontal	42	May-Oct. 1978	31 23	34 13	35 6		[Sakagami and Morita, 1979]
Yokosuka (410)	4.15	44.1	Horizontal	37	May-Oct. 1978	27 25	36 15	39 6		[Sakagami and Morita, 1979]
Atlanta	4.2	42.5	Vertical		Aug. 1971		12	19		[Barnett, 1974]
Atlanta	6	42.24	Vertical	25.9	15 Aug. 1974- 28 Feb. 1975	≈7 42	16 32	22 22	r.m.s. values of XPD	[Lin, 1977]
	11.46	25.44	Vertical	42.7	15 Aug. 1974- 28 Feb. 1975	15 42	20.5 22	30 12		
	11.6	42.24	Vertical	19.5	15 Aug. 1974- 28 Feb. 1975	- 48	-1.5 38.5	7 28		
Ottawa	11.1	16	Horizontal	33	May-Sept. 1979	5 33	21 16.5	26 8.7		[Butler, 1981]
	16.8	16	Horizontal	40	May-Sept. 1979	-	23	27		[Butler, 1981]

TABLE VII - Measured XPD statistics due to precipitation

Location (height above mean sea level) (m)	Frequency (GHz)	Path length (km)	Transmission polarization H, V	Time period	0.001%	0.01%	0.1%	XPD ₀	References
					XPD/CPA (R)	XPD/CPA (R)	XPD/CPA (R)		
Musashino (80)	19.1	4.3	H	Jan. 1972-Dec. 1972	15/53 (140)	25/32 (75)	36/12 (20)	40	[Morita <i>et al.</i> , 1974]
Owase (235)	19.3	4.0	H	Jul. 1972-Oct. 1972	14/>70 (270)	21/>70 (200)	26/35 (100)	45	[Morita <i>et al.</i> , 1974]
Owase (235)	19.4	4.0	V	Jul. 1972-Oct. 1972	15/>70 (270)	18/68 (200)	20/32 (100)	45	[Morita <i>et al.</i> , 1974]
Bradford	10.7	13.6	V	May 1971-April 1972	-	18/11.5	22.5/8	32	[Watson, 1976]
	10.7	13.6	H	May 1972-April 1973	-	19/17	22.5/7	25	
	10.7	13.6	V	May 1972-April 1973	-	24/11.5	26.5/7.5	32	
	10.7	13.6	H	May 1973-April 1974	-	22.5/20	25.5/8	25	
Rhine Valley	29	20	V	1 year	20/>40	23/34	27/17	35	
Ottawa	11.4	16	H	May-Sept. 1979	-	26/26	31/5.4	>33	[Butler, 1981]
	17.7	16	H	May-Sept. 1979	-	-	24/14	-	[Butler, 1981]

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REPORT 238-4 *

PROPAGATION DATA REQUIRED FOR TRANS-HORIZON RADIO-RELAY SYSTEMS

(Study Programme 5B/5)

(1959-1963-1970-1974-1978-1982)

1. Introduction

This Report relates to the design of radio-relay systems **. It is based on an analysis of observations made at frequencies between 200 MHz and 4 GHz and has not been validated outside this range.

The only mechanisms for radio propagation beyond the horizon which occur permanently for frequencies greater than 30 MHz are those of diffraction at the Earth's surface and scatter from atmospheric irregularities. Attenuation for diffracted signals increases very rapidly with distance and with frequency, and eventually the principal mechanism is that of tropospheric scatter. This mechanism may be used to establish "trans-horizon" radio communication.

Signals received by the tropospheric scatter mechanism show both slow and rapid variations. The slow fades are ascribed to overall changes in refractive conditions in the atmosphere. The hourly median values below the long-term median are distributed approximately log-normally with a standard deviation which generally lies between 4 and 8 dB, depending on the climate. The largest variations of transmission loss are often seen on paths for which the receiver is located just beyond the diffraction region, whilst at extreme ranges the variations are less. The slow fading is not strongly dependent on the radio frequency. The rapid fading has a frequency of a few fades per minute at lower frequencies and a few hertz at UHF. The superposition of a number of variable incoherent components would give a signal whose amplitude was Rayleigh distributed and this is found to be nearly true when the distribution is analysed over periods of up to five minutes. If other types of signal form a significant part of that received, there is a modification of this distribution. Sudden, deep and rapid fading has been noted when a frontal disturbance passes over a link. Reflections from aircraft can give pronounced rapid fading.

* This Report is brought to the attention of Study Group 9.

** See Recommendation 452 for interference problems related to propagation.

For radio paths extending only slightly over the horizon, or for paths extending over an obstacle or over mountainous terrain, diffraction will generally be the propagation mode determining the field strength. In these cases, the methods described in Recommendation 526 should be applied.

2. General method for calculating the long-term median transmission loss of tropospheric scatter paths

The long-term median transmission loss due to tropospheric scatter is approximately:

$$L(50) = 30 \log f - 20 \log d + F(\theta d) - G_t - G_r + L_c - V(d_e) \quad \text{dB} \quad (1)$$

where f is the radio frequency in MHz, G_t and G_r are the antenna gains and L_c is the aperture-to-medium coupling loss. $F(\theta d)$ is shown in Fig. 1 as a function of the product θd . The angular distance, θ (in radians) is the angle between radio horizon rays in the great circle plane containing the antennas for median atmospheric conditions, and d (in km) is the distance between antennas [NBS, 1967].

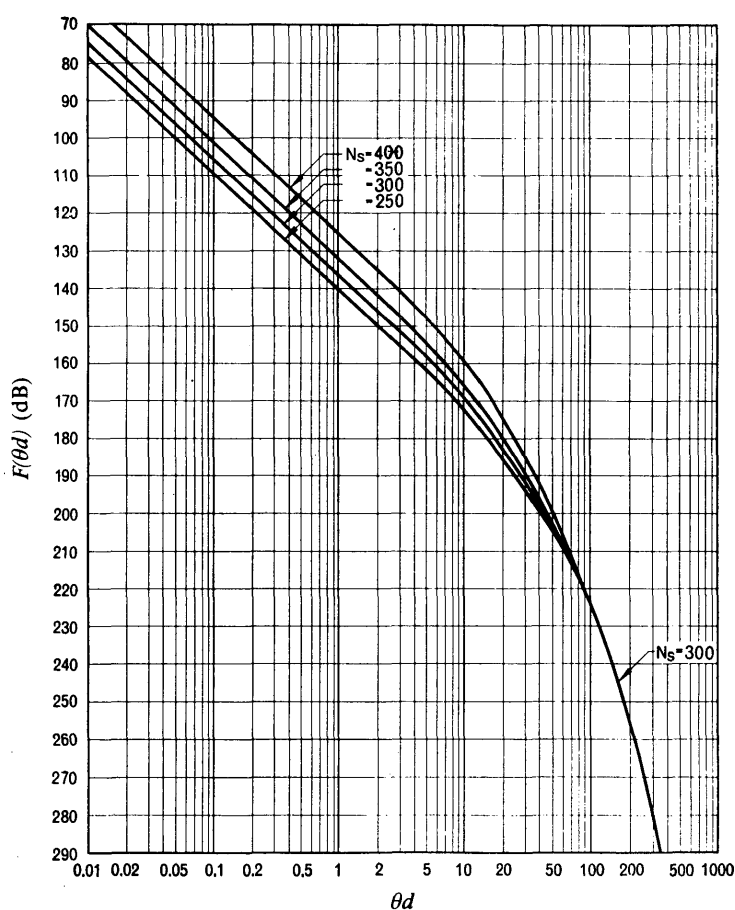


FIGURE 1 — The attenuation function, $F(\theta d)$, where d is in km and θ is in radians

A semi-empirical estimate of L_c is provided by the formula

$$L_c = 0.07 \exp [0.055 (G_t + G_r)] \quad \text{dB} \quad (2)$$

for values of G_t and G_r each less than 50 dB (see also § 9).

$V(d_e)$ is a correction for various types of climate (see § 3) and is shown in Fig. 2, as a function of distance d_e and climate. The "effective distance" d_e , is defined as a function of the propagation path length d , effective antenna heights h_{te} and h_{re} (m) above the foreground terrain, and the radio frequency, f in MHz, in the following way:

Define θ_{sl} as the angular distance where diffraction and forward scatter transmission loss are approximately equal over a smooth earth of effective radius $a = 9000$ km, and define d_{sl} as $a \cdot \theta_{sl}$. Then:

$$d_{sl} = 302 f^{-1/3} \quad \text{km} \quad (3)$$

The path length, d , is compared with the sum of d_{sl} and the smooth-earth distances to the radio horizons:

$$d_L = \sqrt{2 ah_{te}/1000} + \sqrt{2 ah_{re}/1000} \quad \text{km} \quad (4)$$

It has been observed that the long-term variability of hourly median transmission loss (see also § 4) is greatest on the average for values of d only slightly greater than the sum of d_{sl} and d_L ; the effective distance d_e is arbitrarily defined as:

$$\text{for } d \leq d_L + d_{sl}, \quad d_e = 130 d / (d_L + d_{sl}) \quad \text{km} \quad (5a)$$

$$\text{for } d > d_L + d_{sl}, \quad d_e = 130 + d - (d_L + d_{sl}) \quad \text{km} \quad (5b)$$

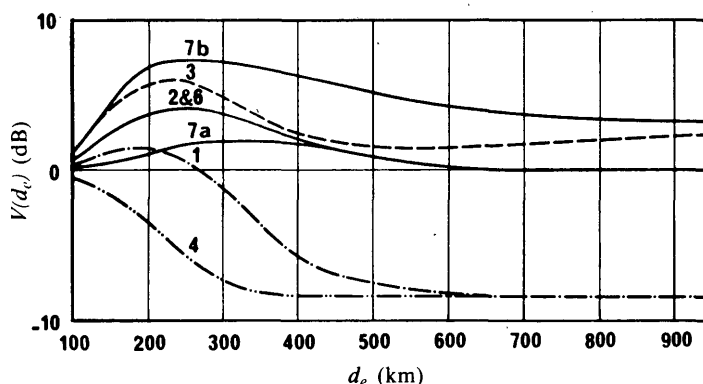


FIGURE 2 — The function $V(d_e)$ for the types of climate indicated on the curves (see § 3)

3. Effects of climate (see Annex I for climate descriptions)

The types of climate listed below are to be used for the correction of propagation data in § 2, 4 and 5. The corrections are supported by measured data.

Type 1: equatorial (data from Congo and Ivory Coast);

Type 2: continental sub-tropical (Sudan);

Type 3: maritime sub-tropical (data from West Coast of Africa);

Type 4: desert (Sahara);

Type 5: Mediterranean (no curves available);

Type 6: continental temperate (data from France, Federal Republic of Germany and United States);

Type 7a: maritime temperate, over land (data from United Kingdom and France);

Type 7b: maritime temperate, over sea (data from United Kingdom);

Type 8: polar (no curves available).

This division is, of course, rather crude, and local geographical conditions may require substantial modifications.

In temperate climates, monthly median transmission losses tend to be higher in winter than in summer but the difference diminishes as the distance increases. Measurements made in the European parts of the U.S.S.R. on a 920 km path at 800 MHz show a difference of only 2 dB between summer and winter medians. For medium-distance links the difference is about 15 dB. Diurnal variations also occur. The transmission loss is generally at a maximum in the afternoon. Oversea paths are more likely to be affected by super-refraction and elevated layers than land paths, and so give greater variation. This may also apply to low, flat coastal regions in maritime zones.

In dry, hot desert climates attenuation reaches a maximum in the summer. The annual variations of the monthly medians for medium-distance paths exceed 20 dB, while the diurnal variations are very large.

In equatorial climates, the annual and diurnal variations are generally small.

In monsoon climates where measurements have been carried out (Senegal, Barbados), the maximum values of N_s occur during the wet season, but the minimum attenuation is between the wet and dry seasons.

Based on measurements that have been made for a long period of time in the People's Republic of China it has been found that the following empirical formula for long-term median transmission loss due to tropospheric scatter applies:

$$L(50) = 124.6 + 30 \log f + 30 \log \theta + 10 \log d - G_t - G_r + L_c + N(H) - 0.08(N_s - 320) \text{ dB} \quad (6a)$$

where the last two terms take account of variations of refractive index with height and climate.

$$N(H) = 20 \log (5 + 0.3H) + 0.65H \quad \text{dB} \quad (6b)$$

where

$$H = \frac{\theta d_1 d_2}{d}$$

d_1 and d_2 are the distances from the crossing-point of radio-horizon rays in the great circle plane containing the transmitting and receiving antennas, to the transmitting and receiving points, respectively, and N_s is the annual mean value of refractivity at the ground.

4. Long-term variability of hourly median transmission loss in various climates

The performance of a radio service depends on the signal-to-noise ratio. As a general rule, adequate service over a radio path requires protection against noise when propagation conditions are poor. The minimum acceptable ratio depends on the particular types of fading exhibited by the signal, on the one hand and by the noise, on the other, as well as upon the demodulation and coding schemes used. Signal-to-noise ratios depend upon the strength of available signals and noise, and vary with time. A distinction is made between the "rapid fading" (see § 1 and 10) and the slow diurnal and seasonal changes, or "long-term power fading", associated with changes in average refraction, turbulence, or stratification in the atmosphere.

It is convenient to divide the instantaneous envelope power, expressed in dBW, into two additive components, one associated with rapid fading, and one associated with long-term power fading. This section deals only with long-term hourly median transmission losses and their variability with time throughout a year.

One may estimate $P(q)$, the value of the received power (P) exceeded for $q\%$ of the time, or $L(q)$, the value of L exceeded $(100 - q)\%$ of the time, where $P(q)$ and the corresponding transmission loss $L(q)$ are referred to long-term median values $P(50)$ and $L(50)$.

Thus:

$$P(q) = P(50) + Y(q) \quad \text{dBW} \quad (7a)$$

or

$$L(q) = L(50) - Y(q) \quad \text{dB} \quad (7b)$$

Where empirical estimates of $Y(q)$ are shown in Figs. 3 to 9 for the various climates. For overland paths, curves for 10% and 1% of the time may be achieved by symmetry. For overseas paths, see Report 569.

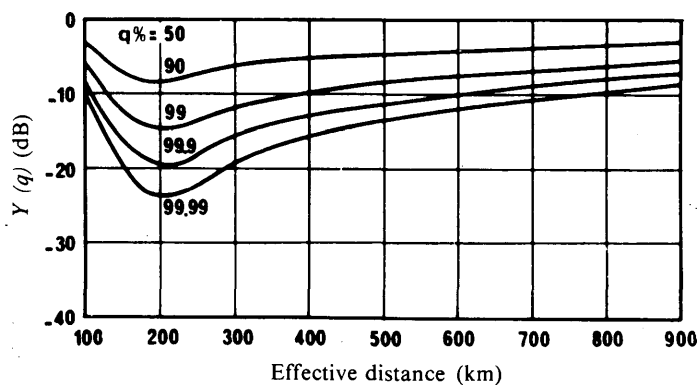


FIGURE 3 — Variation of transmission loss with effective distance for an equatorial climate (Type 1)

(The values of q are indicated on the curves)

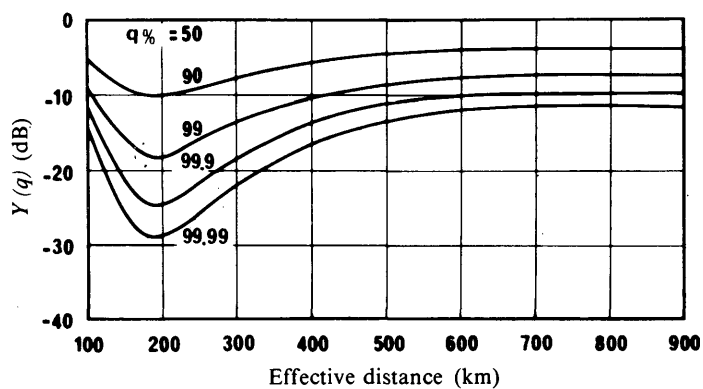


FIGURE 4 — Variation of transmission loss with effective distance for a continental sub-tropical climate, Sudan (Type 2)

(The values of q are indicated on the curves)

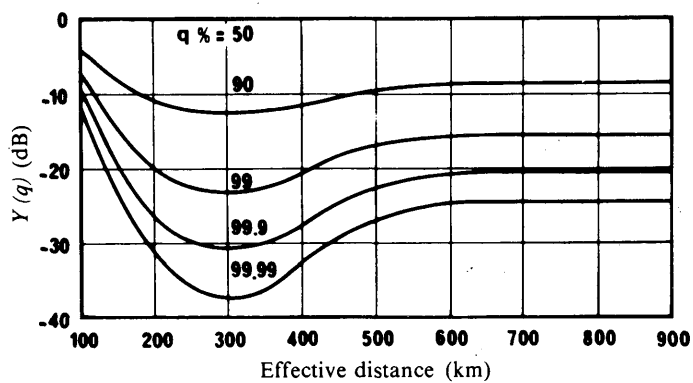


FIGURE 5 — Variation of transmission loss with effective distance in a maritime sub-tropical climate (Type 3)

(The values of q are indicated on the curves)

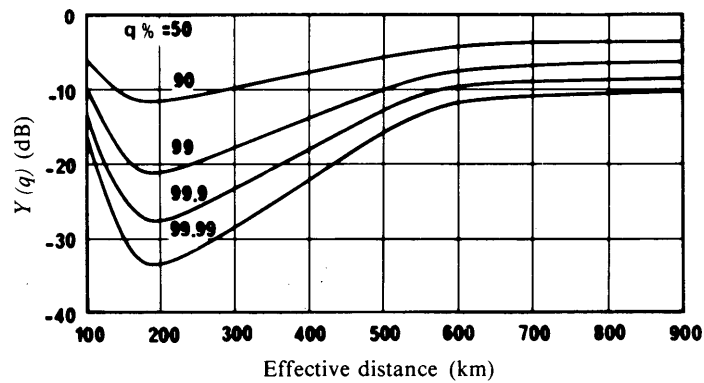


FIGURE 6 — Variation of transmission loss with effective distance for a desert climate, Sahara (Type 4)

(The values of q are indicated on the curves)

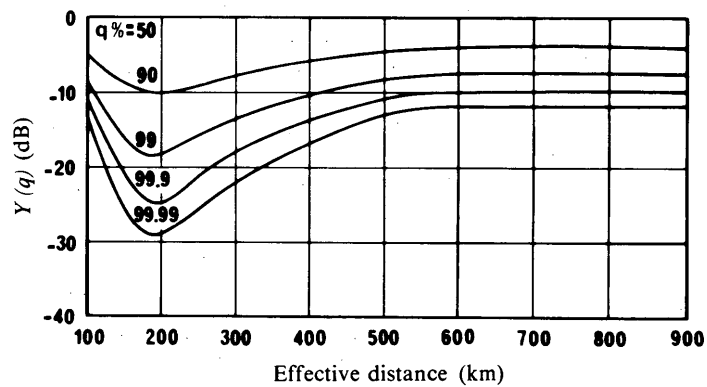


FIGURE 7 — Variation of transmission loss with effective distance for a continental temperate climate (Type 6)

(The values of q are indicated on the curves)

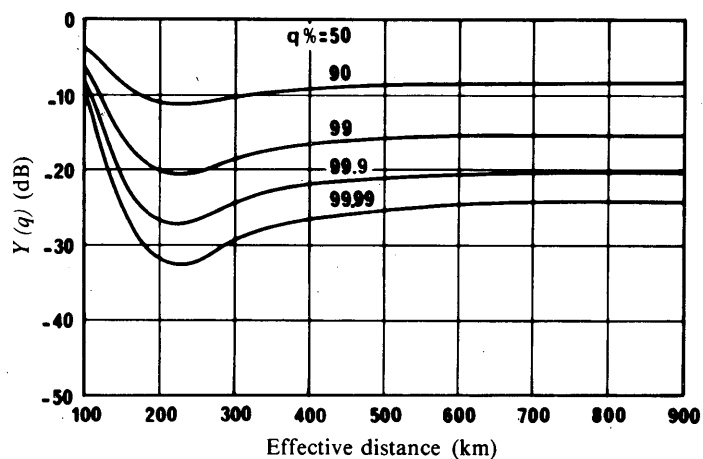


FIGURE 8 — Variation of transmission loss with effective distance for an overland path in a maritime temperate climate (Type 7a)

(The values of q are indicated on the curves)

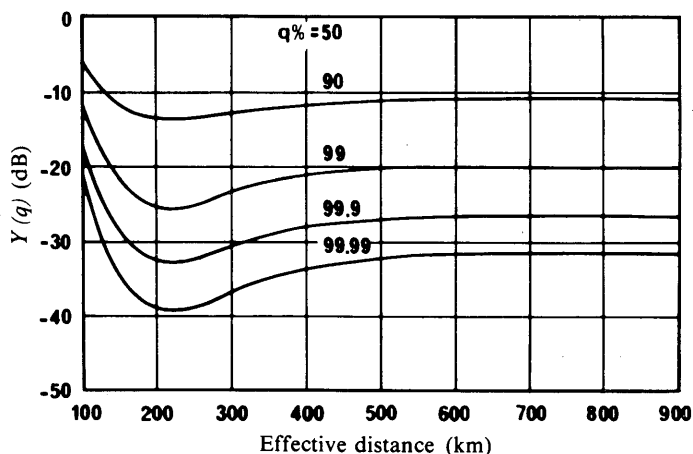


FIGURE 9 – Variation of transmission loss with effective distance for an oversea path in a maritime temperate climate (Type 7b)

(The values of q are indicated on the curves)

An estimate of the standard error of prediction for any given percentage of the time is given by the formula:

$$\sigma(q) = \sqrt{13 + 0.12 Y^2(q)} \quad \text{dB} \quad (8)$$

In the People's Republic of China, analysis of the measured data indicates that the long-term (annual) variability of the hourly median transmission losses distributes log-normally and its standard deviation can be calculated as follows:

$$\delta \begin{cases} = 7 + 0.09 \Delta N_s e^{-0.003 d_s} & \text{dB} & \text{(in plain area)} \\ = 4.6 + 0.06 \Delta N_s e^{-0.003 d_s} & \text{dB} & \text{(in mountain area)} \\ = 8.8 + 0.11 \Delta N_s e^{-0.003 d_s} & \text{dB} & \text{(over sea)} \end{cases}$$

where ΔN_s is the difference between the mean value of refractivity on the ground in winter, and that in summer, d_s (km) is the difference between the path length and the sum of the distances in the great circle plane from the transmitting point and the receiving point to their respective radio-horizons.

5. Transmission loss for the worst month

From measurements made in Europe and in Africa, the French Administration has plotted sets of curves for climate types 1, 3, 4, 6 and 7a (Figs. 10 to 13). Curves for climate type 5 (Mediterranean) lie between those for climate types 3 and 6. These curves show statistics for the worst month of the loss between isotropic antennas at 1 GHz for a number of time percentages which may be applied in designing radio-relay systems [Boithias and Battesti, 1965]. For frequencies other than 1 GHz the correction factor is $30 \log(f/1000)$ dB, where f is expressed in megahertz.

These curves assume that the horizon is seen from each end of the link at a zero angle of elevation. If the angles of elevation are equal respectively to θ_1 and θ_2 , the real distance d should be replaced by an equivalent distance d_q given by the relation:

$$d_q = d + 8.5 (\theta_1 + \theta_2) \quad (9)$$

the distances d and d_q being expressed in kilometres and θ_1 and θ_2 in milliradians. Furthermore, the following quantity must be added to the loss thus calculated:

$$20 \log \frac{d}{d_q}$$

Further methods are described [Wvedensky, 1965; Kalinin *et al.*, 1975; Kalinin, 1979].

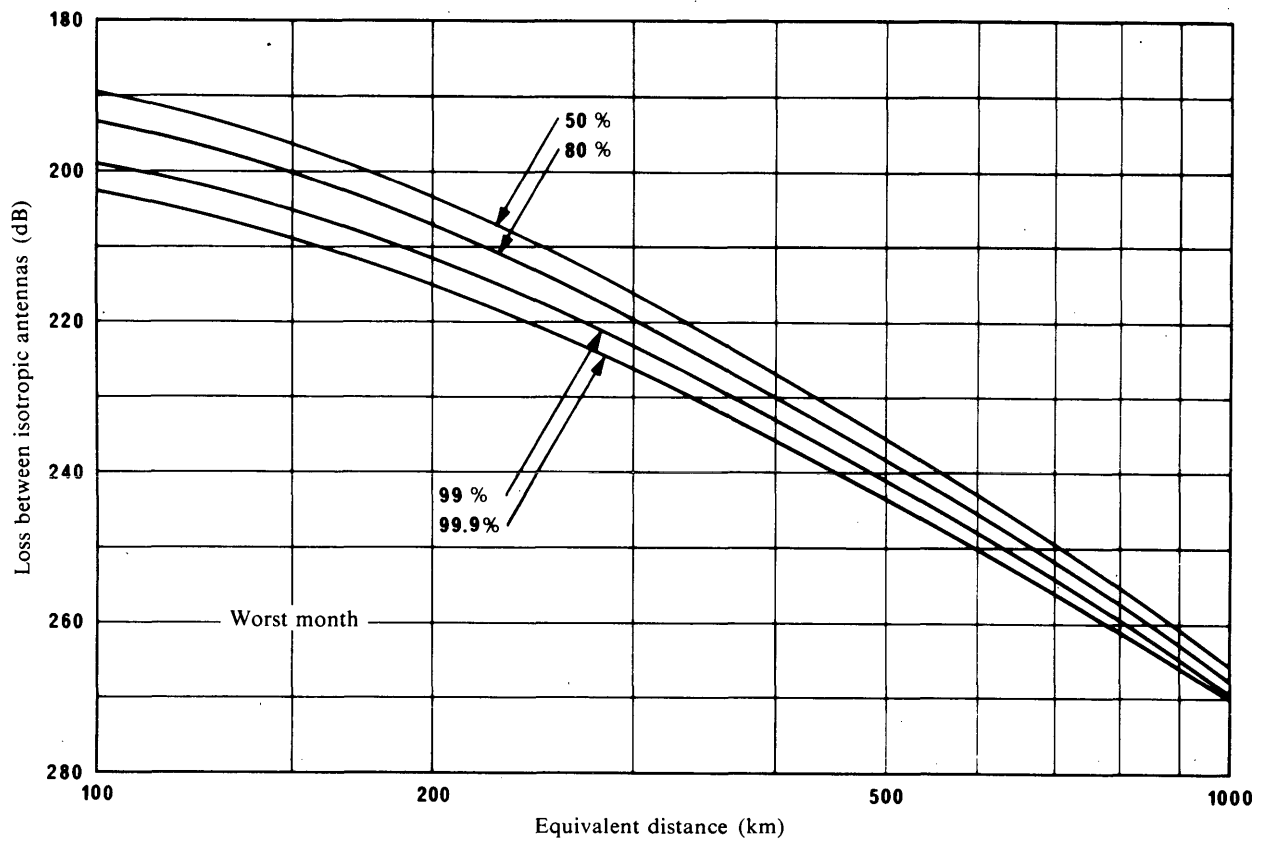


FIGURE 10 — Mean loss with tropospheric scatter
1 GHz — Land paths — Equatorial climate (Type 1)

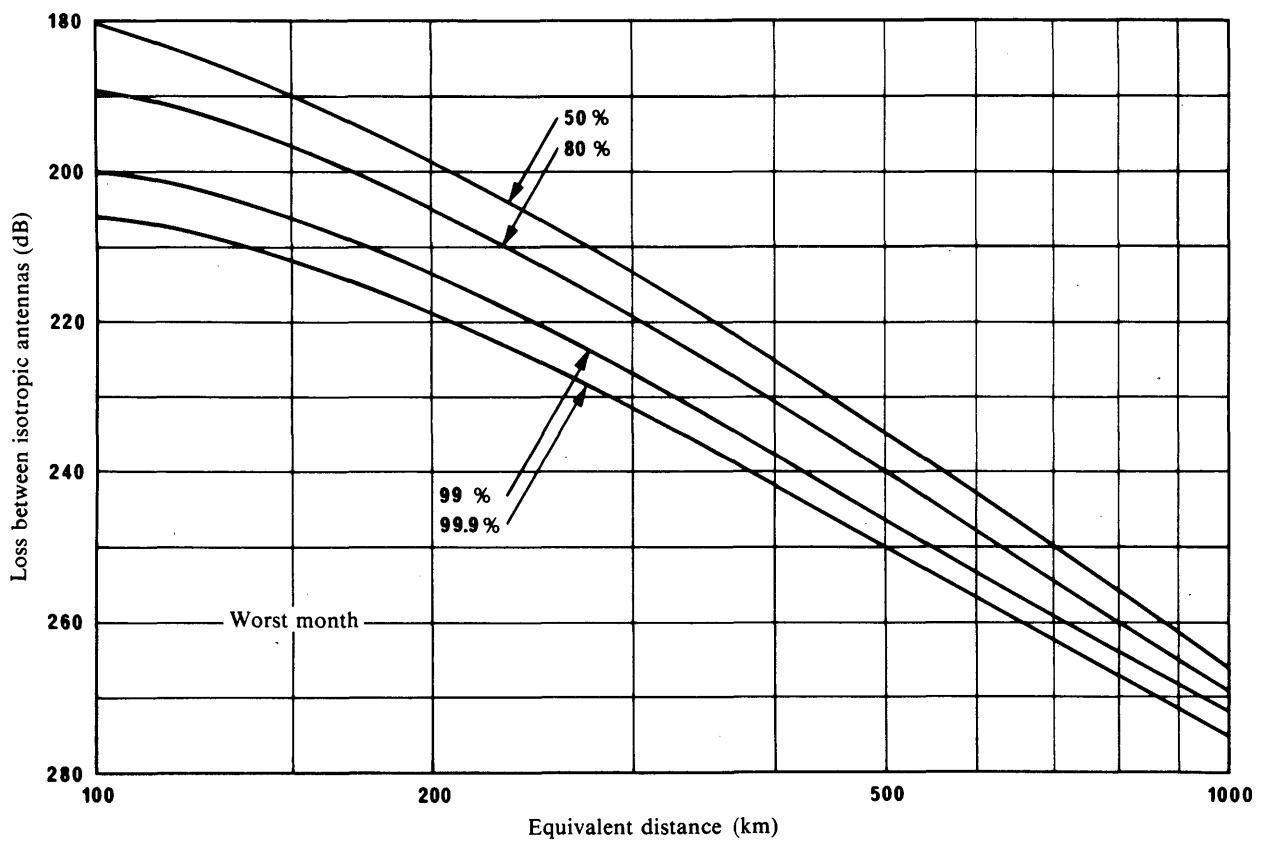


FIGURE 11 — Mean loss with tropospheric scatter
1 GHz — Land paths — Maritime sub-tropical climate (Type 3)

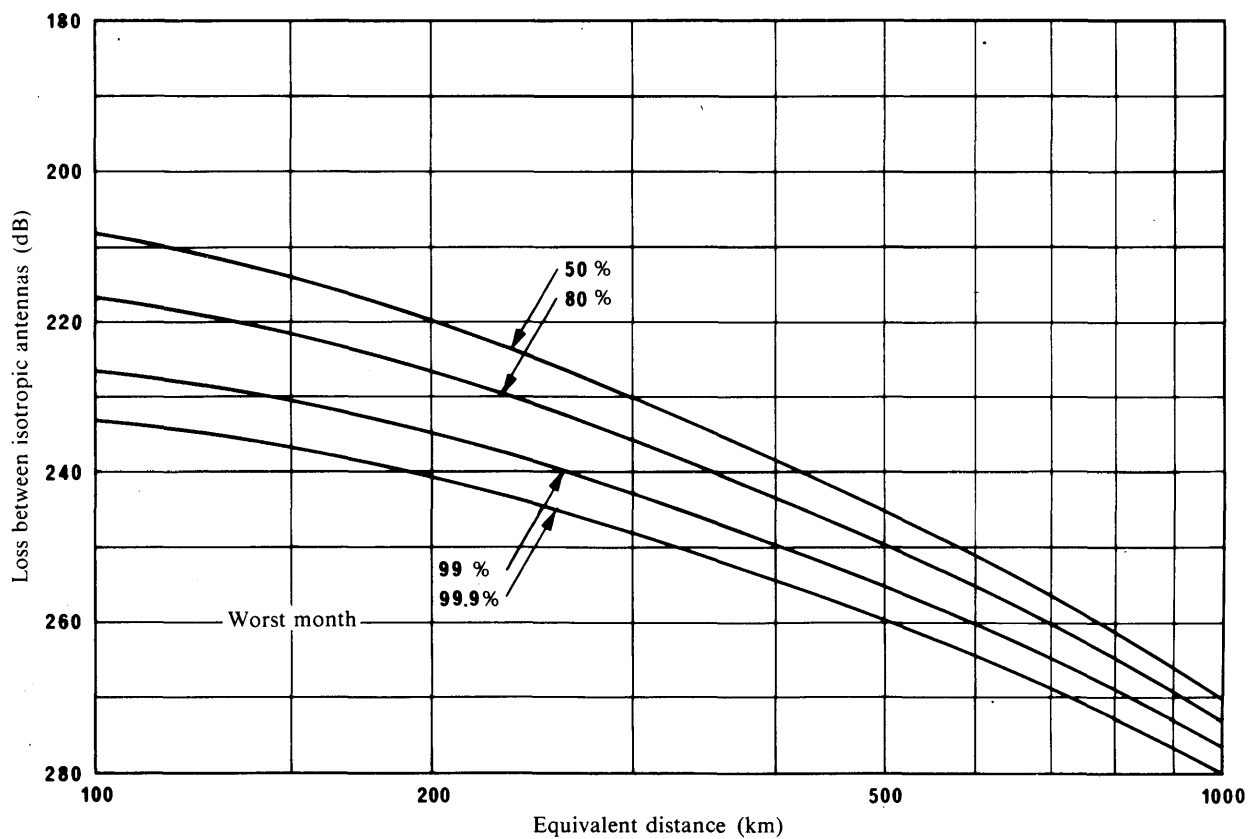


FIGURE 12 — Mean loss with tropospheric scatter
1 GHz — Land paths — Desert climate (Type 4)

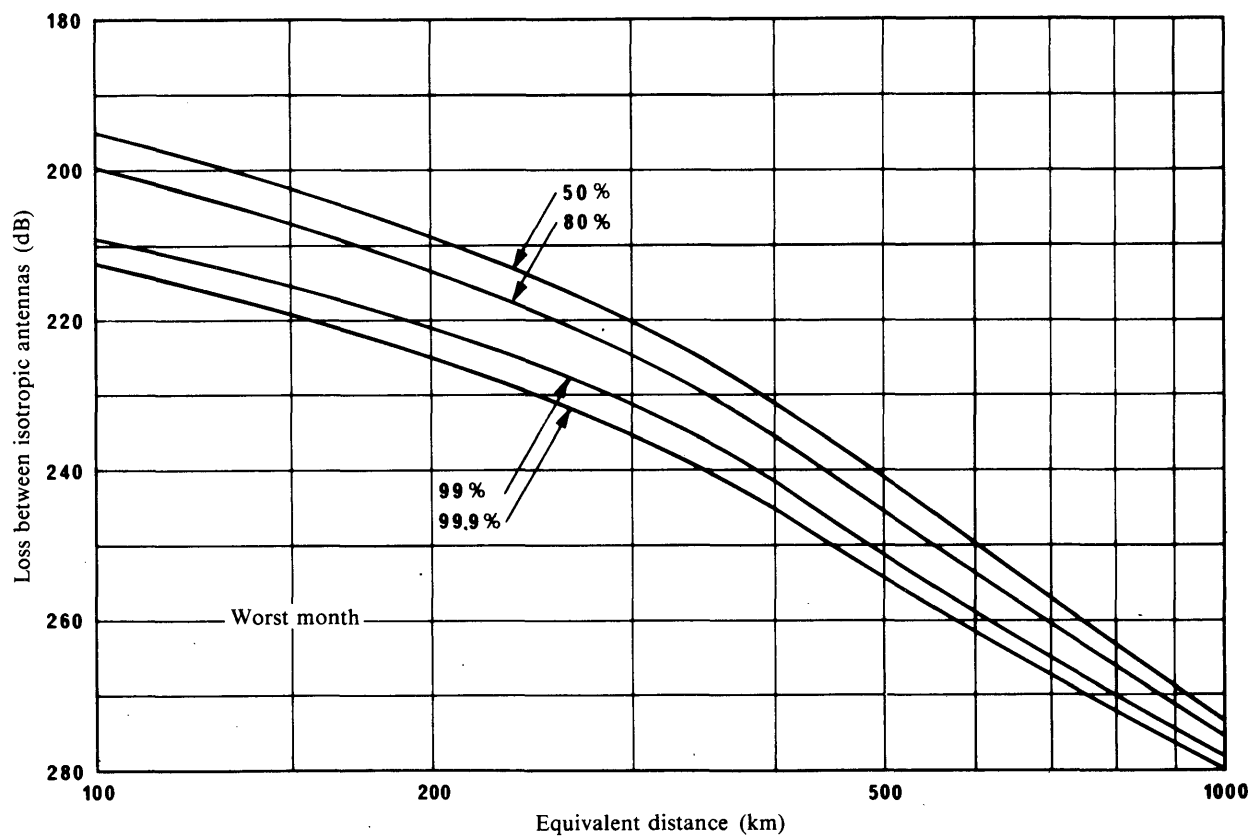


FIGURE 13 — Mean loss with tropospheric scatter
1 GHz — Land paths — Temperate climate (Types 6 and 7a)

6. Calculating loss when the radiometeorological parameters are known

Studies conducted by the French Administration [Battesti and Boithias, 1971] have shown that loss between isotropic antennas could be represented by a formula, which seems valid for all climates. This formula applies the refractive index gradient near the base of the common volume, as explained in Report 718.

The following semi-empirical formula is obtained:

$$L_b(p) = 102 + 30 \log d + 30 \log f + 1.5 G_c \quad (\text{dB}) \quad (10)$$

where:

- $L_b(p)$: basic transmission loss for the time percentage p , in decibels,
- d : distance (km),
- f : frequency (MHz),
- G_c : index gradient near the base of the common volume (which can often be replaced by the difference between the value of N at 1 km above and at the base of the common volume).

The time percentage, p , to which the value of $L_b(p)$ corresponds depends on the times at which the soundings used to determine G_c were carried out, as explained in Battesti *et al.* [1968].

The values of G_c are usually obtained from radiosonde measurements made at fixed times of day. Because of the local diurnal variations in G_c , the timing of measurements may introduce bias in the measured statistics of G_c . If the soundings are available at 12-hour intervals, the measured median of the statistics may correspond to the median that would be measured if hourly measurements were available. However, if soundings are available at (for example) 1600 h local time, the measured median value corresponds to a true time percentage of 90 to 99%, since large values of G_c and low values of $L_b(p)$ do not occur at this time. Further details are given in [Battesti *et al.*, 1968].

7. Effect of frequency

It is generally agreed that the long-term median transmission loss, between isotropic antennas, increases as the third power of the frequency f (see also § 2), up to about 3 GHz, and as the first power for free space.

For measurements, the sampling period of which is less than 1 hour, the frequency dependence of the attenuation relative to free space has been found to vary between f^2 and $f^{-1/3}$ [Ecklund and Wickerts, 1968]. Measurements made in France at 460 and 2220 MHz over two distances, 325 and 165 km, show that the increase of attenuation relative to free space as a function of the frequency:

- is greater on the long link, where the dependence is f^2 for 1% of the time and f for 99% of the time, than on the short link, where the dependence is $f^{1.5}$ for 1% of the time and $f^{0.5}$ for 99% of the time;
- is slightly greater in summer than in winter; this difference is more marked on the short link;
- falls, on the average, when the received level falls.

Measurements made in India [Majumdar and Sarkar] at 120 MHz and 2 GHz indicated that the transmission loss relative to free space increased as the first power of the frequency for most of the period (refractivity gradients being between -40 and -157 N unit/km). For small percentages of the time the exponent decreased below 1 and even became negative.

Above 10 GHz, the absorption by atmospheric oxygen and water vapour on trans-horizon links is not negligible. The attenuations in an atmosphere with average absolute humidity can be determined from Report 720. Measurements in the Federal Republic of Germany [Abel, 1972] at 12 GHz on a 210 km link have shown that, during small percentages of the time, precipitation either increases the transmission loss by attenuation, or decreases it by scattering, depending on the position of precipitation cells on the path.

8. Diversity reception

The deep fading occurring with scatter propagation severely reduces the performance of systems using this propagation mode. The effect of fading can be reduced by diversity reception, using two or more signals which fade more or less independently owing to differences in path, frequency, or time interval. The effect of space diversity has been studied in the Federal Republic of Germany [Fehlhaber and Grosskopf, 1967] by measuring the space correlation function and its scale length l , using simultaneous recording of the transmission loss at several horizontally and vertically spaced antennas (usually three).

Adequate spacing of two receiving antennas in a space diversity system depends on the scale length, $l(m)$, as defined by the space correlation function and on the antenna diameter, $D(m)$, of the receiving antennas. Because of the statistical character of l , its value exceeded in 1% of time, denoted by l_y in the horizontal and l_z in the vertical direction should be used. Adequate diversity spacings, $\Delta_y(m)$, and, $\Delta_z(m)$, are then given for frequencies greater than 1000 MHz by the relations.

$$\Delta_y = 0.36 (D^2 + 4l_y^2)^{1/2} \quad (11)$$

$$\Delta_z = 0.36 (D^2 + l_z^2)^{1/2}$$

Measurements yielded the values:

$$l_y \approx 20 \text{ m}, l_z \approx 15 \text{ m}.$$

The use of quadruple space diversity in tropospheric scatter systems has been studied theoretically by Larsen [1980] in an analysis which extends earlier work by Hirai [1961]. The recent work evaluates the 6 correlation coefficients for the 4 paths of a quadruple system of Fig. 14. The predictions were found to be in fair agreement with available measured data. Significant correlation can sometimes occur, especially on the crossing paths and this can degrade system performance. The recent analysis shows how the various correlations are affected by antenna beamwidth, horizontal spacing of antennas and path geometry. The correlations can be reduced by suitable choice of antenna spacing. For some path profiles, the optimum performance may be achieved with unequal spacings at the two terminals. In general, the performance is improved by increasing the antenna spacing.

In such quadruple space diversity, the two transmissions use the same frequency, but are on orthogonal polarizations (to allow separation of the received signals). It is found that the signal polarization is well preserved during transmission, and that transmission loss and signal fading do not depend on which polarization is used. Hence polarization diversity is unlikely to be of practical use.

It is also possible to use frequency diversity. An adequate frequency separation, Δf (MHz) has been found [Fehlhaber, 1967] to be

$$\Delta f = (1.44 f / \delta d) (D^2 + l_z^2)^{1/2} \quad (12)$$

where f in MHz is the carrier frequency, δ in mrad the angle of scattering in the centre of the common volume, and d in km, the distance between transmitter and receiver. Some caution is needed using these formulae with frequencies well below 1000 MHz. The variation in the frequency correlation coefficient with path length has been studied in the Federal Republic of Germany [Fehlhaber, 1967].

It is also possible to have angle diversity using multiple feeds and a common reflector. A simple system of this kind, employed at the receiver end, may provide a performance capability comparable to and considerably more economical than that of space diversity, particularly as one approaches the SHF range [Surenian, 1965]. Another measurement on angle diversity conducted in Japan [Iwasa and Kurobe, 1974] on a 256 km path over the sea at 1.8 GHz shows that a beam separation of more than about 6 mrad gives a sufficiently low correlation coefficient (less than 0.4). Therefore, the performance of angle diversity is considered to be comparable to that of frequency diversity, although there is a slight increase in transmission loss.

9. Path antenna gain

In a trans-horizon radio-relay system, the transmission of radio energy is due to the sum of re-radiations from all the atmospheric inhomogeneities illuminated by the transmitting antenna. Hence a wave arriving at the receiving station is not a plane wave, so that the apparent gain of the receiving antenna is less than the free-space gain (which is defined with a plane wave). For the same reason, the antenna beamwidth seems bigger than in the case of a plane wave. This reduction in gain is known as "aperture-to-medium coupling loss" or "gain degradation".

A theoretical analysis of the phenomenon [NBS, 1967] shows that the drop in gain should depend on the antenna gain and on distance. In reality it has been observed experimentally to be practically independent of distance between about 150 and 500 km [Boithias and Battesti, 1964]. Furthermore, the total effective gain, shown in Fig. 15, may be assumed to depend only on the sum of the free-space antenna gains, without large corrections, provided that neither of the free-space gains exceeds about 55 dB, and that the gains of the two antennas are not too different.

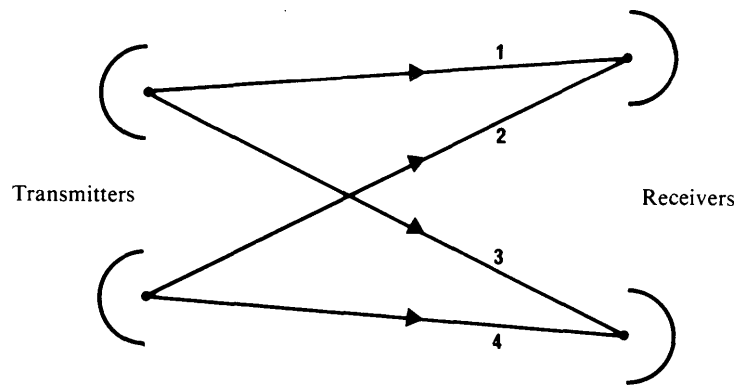


FIGURE 14 — Correlations involved in quadruple space diversity

Convergent paths : ρ_{12}, ρ_{34}
 Divergent paths : ρ_{13}, ρ_{24}
 Near-parallel paths : ρ_{14}
 Crossed paths : ρ_{23}

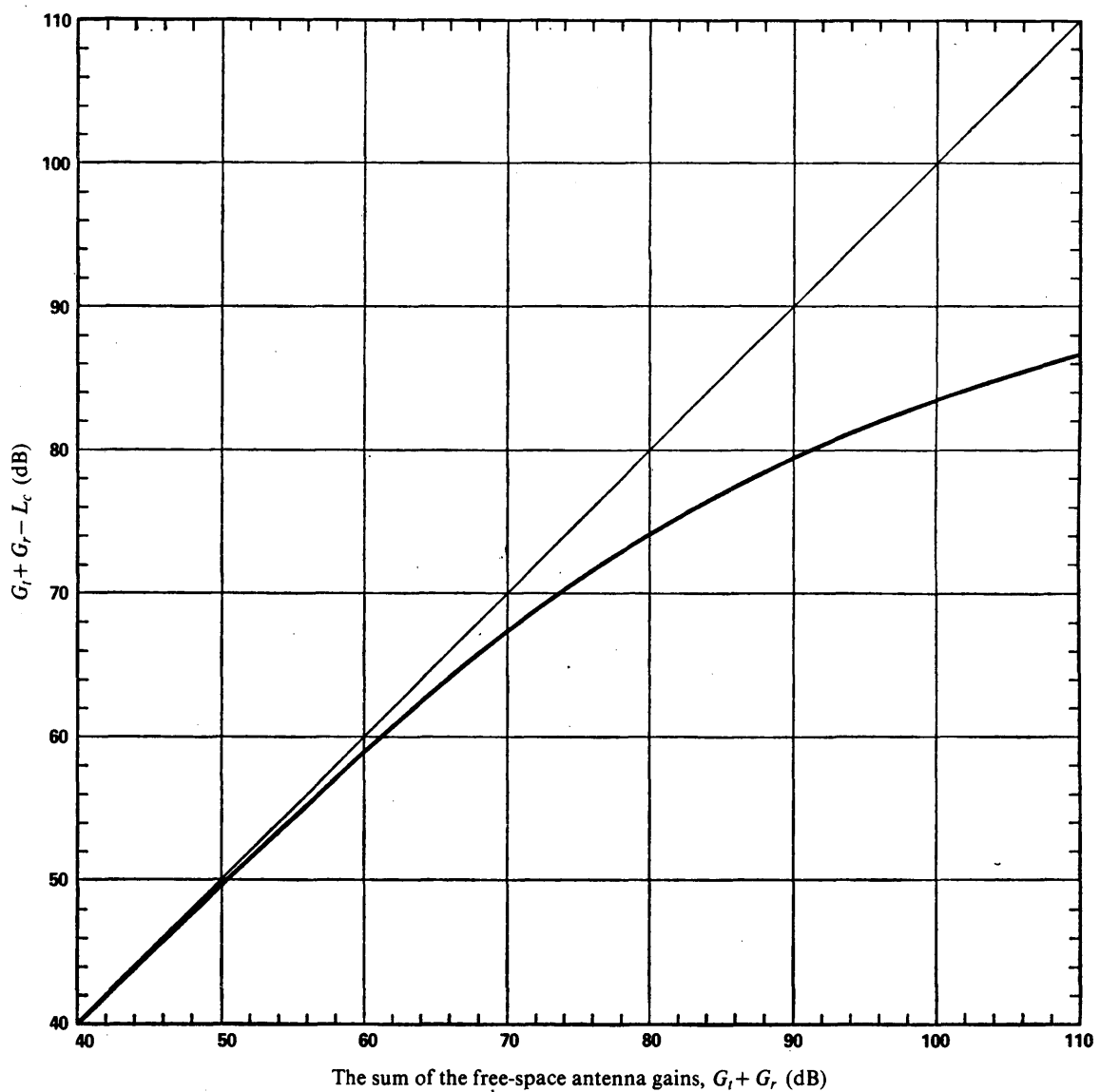


FIGURE 15

This result can be explained [Battesti and Boithias, 1971] if account is taken of the varying number of atmospheric inhomogeneities contained in the common volume, with increasing distance, i.e. when the altitude of the common volume increases. It can also be deduced from this that if very high gain antennas are used, the total effective antenna gain (path antenna gain) increases by only a quarter of the increase given by the sum of the two free-space gains. For distances longer than 500 km, the antennas-to-medium coupling loss appears to decrease and become very small at about 1000 km.

Measurements made in the United Kingdom [Hall and Misme, 1975] on two 300 km radio paths at 2 GHz showed a variability of gain degradation for an antenna of 53 dB gain; for the important conditions of low received power (99% levels) Fig. 15 was found to be optimistic by several dB. This variability may be expected to be less with antennas of lower gain.

Studies conducted in the U.S.S.R. [Troitsky, 1970 and 1971; Petrushko and Troitsky, 1975; Troitsky and Shur, 1977] have shown that for the general case of asymmetrical antennas and/or antennas with widely divergent gain coefficients, aperture-to-medium loss L_c can be calculated from the formula:

$$L_c = -5 \log \left[1 + \left(\frac{\theta_v}{\alpha_{v1}} \right)^2 \right] - 5 \log \left[1 + \left(\frac{\theta_v}{\alpha_{v2}} \right)^2 \right] - 5 \log \left[1 + \left(\frac{\theta_h}{\alpha_h} \right)^2 \right] \quad \text{dB} \quad (13)$$

with:

$$\alpha_h = \frac{\alpha_{h1} \cdot \alpha_{h2}}{\sqrt{\alpha_{h1}^2 + \alpha_{h2}^2}} \quad (14)$$

where

α_{v1}, α_{h1} : are the beamwidth of the transmitting antenna in the vertical and horizontal planes respectively (3 dB level);

α_{v2}, α_{h2} : are the same values for the receiving antenna;

θ_h, θ_v : are the angular width of tropospheric scatter volume in the horizontal and vertical planes respectively.

The values of θ_h and θ_v are derived from experiments with pencilbeam scanning antennas. According to references [Troitsky, 1971; Petrushko and Troitsky, 1975] $\theta_h \approx 1^\circ$ and $\theta_v \approx 1.7^\circ$. Calculation of the antenna gain degradation for identical symmetrical antennas, using formula (13) and the above values of θ_h and θ_v , yields L_c values which coincide with those derived from Fig. 15.

The People's Republic of China have presented a calculation method which can reflect the physical relation between the path antenna gain and the path parameters [CCIR, 1974-78].

10. Fading frequency

The rapidity of fading is important particularly in communicating digital signals. It has been studied in the Federal Republic of Germany [Fehlhaber and Grosskopf, 1966 and 1967; Grosskopf and Fehlhaber, 1962] in terms of the time auto-correlation function, which provides a "mean fading frequency". This mean fading frequency is a measure of fading rapidity (or fading rate). Its median value increases nearly proportionally to distance and carrier frequency, and decreases slightly as the antenna diameter increases. At 12 GHz, during the influence of rainfall, fading frequencies up to about 20 Hz have been observed [Abel, 1972].

Measurements made at 2 GHz in the United Kingdom [Hall, 1973] on two radio paths of 300 km demonstrated the way in which the distribution of fade rate changed as the hourly median level itself changed. With hourly median levels of path attenuation exceeded for less than 0.2% of the time, fades were not observed more frequently than three times per minute; with hourly median levels of path attenuation greater than the long-term median value, the median fade-rate was about 30 fades per minute, and the range of fade rate was from 6 per minute to 120 per minute.

Similarly, measurements were conducted over a 13-month period in the United States of America at 186 MHz on overland paths of 376 and 633 km [Dougherty *et al.*, 1970]. When the signal approximated the long-term hourly median level (65 dB below the free-space level), it exhibited the rapid fading (fade durations of tens of seconds) usually associated with troposcatter. When the hourly median signal exceeded the long-term median level by 15 dB or more (5% of all hours), the fading rate decreased, and the fade durations increased to minutes. When the hourly median signal exceeded the long-term median level by 25 dB or more (1% of all hours) the fading virtually disappeared. These signal levels were within the predicted 90 percentile range [NBS, 1967].

11. Transmissible bandwidth

The various discontinuities which give rise to scatter propagation create propagation paths which may vary in number and in transmission time. Accordingly, the transmission coefficients for two adjacent frequencies are not entirely correlated, thus leading to a distortion of the transmitted signal. The transmissible bandwidth is the bandwidth within which the distortion caused by this phenomenon is acceptable for the transmitted signal. This bandwidth therefore depends both on the nature of the transmitted signal (multiplex telephony, television picture, etc.) and on the acceptable distortion for this signal. Studies carried out in France [Battesti and Boithias, 1971] show that:

- increase in the antenna gain widens the transmissible bandwidth to the extent to which the gain degradation also increases (i.e., for gains exceeding approximately 30 dB);
- all other things being equal, the transmissible bandwidth depends on the atmospheric structure and hence on the climatic zone in question;
- the transmissible bandwidth becomes narrower as the distance increases, but this is governed by a law which is not the same for all climates;
- the transmissible bandwidth becomes narrower when there are positive angles of departure, and wider, when these angles are negative.

12. Effect of the siting of stations

The siting of transmission links requires some care. The antenna beams must not be obstructed by nearby objects and the antennas should be directed slightly above the horizon. The precise optimum elevation is a function of the path and atmospheric conditions, but it lies within about 0.2 to 0.6 beamwidths above the horizon [Hirai *et al.*, 1963]. Measurements made in the United Kingdom [Hall, 1973] by moving the beam of a 53 dB gain antenna away from the great circle horizon direction of two 2 GHz transmitters, each 300 km distant, demonstrated an apparent rate-of-decrease of power received of 9 dB per degree. This occurred with increases of scattering angle over the first three degrees, in both azimuth and elevation, for each path, and for a wide range of time percentages.

ANNEX I

The climates, considered in the present Report are described below:

1. **Equatorial:** corresponds to the region between latitudes 10° N and 10° S. The climate is characterized by a slightly varying high temperature and by monotonous heavy rains which sustain a permanent humidity. The annual mean value of N_s (refractivity at the surface of the earth = $(n-1) 10^6$ where n is the refractive index of the air) is about 360 N -units and the annual range of variation is 0 to 30 N -units.
2. **Continental sub-tropical:** corresponds to the regions between latitudes 10° and 20°. The climate is characterized by a dry winter and rainy summer. There are marked daily and annual variations of radio propagation conditions, with least attenuation in the rainy season. Where the land area is dry, radio ducts may be present for a considerable part of the year. The annual mean value of N_s is about 320 N -units and the range of variation, throughout the year, of monthly mean values of N_s is 60 to 100 N -units.
3. **Maritime sub-tropical:** also corresponds to the regions between latitudes 10° and 20° and is usually found on lowlands near to the sea. It is strongly influenced by the monsoon. The summer monsoon, which blows from sea to land, brings high humidity into the lower layers of the atmosphere. Although the attenuation of radio waves is relatively low at both the beginning and end of the monsoon season, during the middle of the monsoon the atmosphere is uniformly humid to great heights and the radio attenuation increases considerably despite a very high value of N_s . There is an annual mean N_s of about 370 N -units with a range of variation over the year of 30 to 60 N -units.
4. **Desert:** corresponds to two land areas which are roughly situated between latitudes 20° and 30°. Throughout the year there are semi-arid conditions and extreme diurnal and seasonal variations of temperature. This climate is very unfavourable for forward-scatter propagation, particularly in summer. There is an annual mean value of N_s of about 280 N -units and throughout the year monthly mean values may vary over a range of 20 to 80 N -units.
5. **Mediterranean:** corresponds to regions in both hemispheres on the fringe of desert zones, close to the sea, and lying between latitudes of 30° and 40°. The climate is characterized by a fairly high temperature which is reduced by the presence of the sea, and an almost complete absence of rain in the summer. Radio-wave propagation conditions vary considerably, particularly over the sea, where radio ducts exist for a large percentage of the time in summer.

6. Continental temperate: corresponds to regions between latitudes 30° and 60° . Such a climate in a large land mass shows extremes of temperature and pronounced diurnal and seasonal changes in propagation conditions may be expected to occur. The western parts of continents are influenced strongly by oceans, so that temperatures here vary more moderately and rain may fall at any time during the year. In areas progressively towards the east, temperature variations increase and winter rain decreases. Propagation conditions are most favourable in the summer and there is a fairly high annual variation in these conditions. The annual mean value of N_s is about 320 N -units and monthly mean values may vary by 20 to 40 N -units throughout the year.

7a. Maritime temperate, overland: also corresponds to regions between latitudes of about 30° to 60° where prevailing winds, unobstructed by mountains, carry moist maritime air inland. Typical of such regions are the United Kingdom, the West coast of North America and of Europe and the northwestern coastal areas of Africa. There is an annual mean value of N_s of about 320 N -units, with a rather small variation of monthly mean values over the year of 20 to 30 N -units. Although the islands of Japan lie within this range of latitudes, the climate is somewhat different and shows a greater annual range of monthly mean values of N_s , about 60 N -units. The prevailing winds in Japan have traversed a large land mass and the terrain is rugged. Climate 6 is therefore probably more appropriate to Japan than climate 7, but duct propagation may be important in coastal and adjacent overseas areas for as much as 5% of the time.

7b. Maritime temperate, overseas: corresponds to coastal and overseas areas in regions similar to those for climate 7a. The distinction made is that a radio propagation path having both horizons on the sea is considered to be an overseas path (even though the terminals may be inland); otherwise climate 7a is considered to apply. Radio ducts are quite common in occurrence for a small fraction of the time between the United Kingdom and the European continent and along the west coasts of the United States of America and Mexico.

8. Polar: corresponds approximately to the regions between latitudes 60° and the poles. This climate is characterized by relatively low temperatures and relatively little precipitation.

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SECTION 5F: ASPECTS RELATIVE TO SPACE TELECOMMUNICATION SYSTEMS
(INCLUDING SPACE RESEARCH)

Reports

REPORT 564-2 *

PROPAGATION DATA REQUIRED FOR SPACE TELECOMMUNICATION SYSTEMS

(Study Programme 5C/5)

(1974-1978-1982)

1. Introduction

In the design of Earth-space links for communication systems, several effects must be considered. Effects of the non-ionized atmosphere need to be considered at all frequencies, but become critical above about 1 GHz and for low elevation angles. These effects include:

- (a) absorption in atmospheric gases; absorption, scattering and depolarization by hydrometeors (water and ice droplets in precipitation, clouds, etc.); emission noise from absorbing media; all of which are especially important at frequencies above about 10 GHz;
- (b) loss of signal due to beam-divergence of the earth-station antenna, due to the normal refraction in the atmosphere;
- (c) a decrease in effective antenna gain, due to phase decorrelation across the antenna aperture, caused by irregularities in the refractive-index structure;
- (d) relatively slow fading due to beam-bending caused by large-scale changes in refractive index; more rapid fading (scintillation) and variations in angle of arrival, due to small-scale variations in refractive index;
- (e) possible limitations in bandwidth due to multiple scattering or multipath effects, especially in high-capacity digital systems;
- (f) attenuation by the local environment of the ground terminal (buildings, trees, etc.);
- (g) possible limitations in the accuracy of up-link power control, due to short-term variations of the ratio of attenuations at the up- and down-link frequencies.

The basic characteristics of these effects are discussed in Section 5C of this Volume. This Report deals with the propagation data required in system planning.

Effects of the Earth's ionosphere and of extra-terrestrial ionized media which may need to be considered for systems operation above 1 GHz are treated in Report 263 (Volume VI) and include:

- (h) rotation of the plane of polarization (Faraday rotation), particularly if frequency re-use and linear polarization are employed;
- (j) dispersion, which results in a differential time delay across the bandwidth of the transmitted signal;
- (k) excess time delay;
- (l) scintillation, which affects amplitude, phase and angle-of-arrival of the received signal.

Table VI of Report 263 provides a particularly useful summary of these effects.

This Report deals only with the effects of the troposphere on the wanted signal. Interference aspects are treated in separate Reports, namely:

- interference between earth stations and terrestrial stations in Report 569,
- interference from and to space stations in Report 885.

The effects of refraction on the protection of the geostationary orbit are considered in Report 393 (Volume IX).

2. Effects of normal refraction

The regular decrease of refractive index with height causes ray-bending and hence both a defocusing effect and a deviation in pointing angle, and these effects need to be considered at low angles of elevation (see Report 718).

* This Report is brought to the attention of Study Groups 1, 2, 4, 6, 7, 8, 10 and 11.

The magnitude of the defocusing of the antenna beam has been evaluated by Yokoi *et al.* [1970] and Crane [1971]. The loss is independent of frequency and is less than 0.4 dB at 3° elevation, even for very high values of refractivity at ground level. It is therefore unlikely to be important in system design by comparison with the attenuation due to other causes.

Elevation-angle errors due to refraction are discussed in Report 718. The total angular refraction (the increase in apparent elevation) is about 0.65°, 0.35°, and 0.25°, for elevation angles of 1°, 3° and 5°, respectively, for a tropical maritime atmosphere. For a polar continental climate the corresponding values are 0.44°, 0.25° and 0.17°. Other climates will have values between these two extremes. A method of estimating the range of apparent elevation angles using statistics of refractivity at ground level, N_s , has been developed [CCIR, 1974-78]. The day-to-day variation in apparent elevation is of the order of 0.1° (r.m.s.) at 1° elevation, but the variation decreases rapidly with increasing elevation angle. Shorter-term variations, due to changes in the refractivity-height variation, may be of the order of 0.02° (r.m.s.) at 1° elevation, again decreasing rapidly with elevation angle. In practice, it is difficult to distinguish between the effect of the short-term changes in the refractivity-height distribution and the effect of random irregularities superimposed on that distribution.

3. Decrease in antenna gain due to wave-front incoherence

This effect decreases with increasing elevation angle, increases with frequency, and is a function of antenna diameter (see Report 718). Measurements made in Japan with a 22 m antenna [Yokoi *et al.*, 1970] suggest that at 5° elevation the loss is about 0.2 to 0.4 dB at 6/4 GHz. Measurements with a 7 m antenna at 15.5 GHz and 31.6 GHz gave losses of 0.3 and 0.6 dB, respectively, at 5° elevation angle [Yamada and Yokoi, 1974]. It is likely that, in practice, the effect is only significant for large antennas, high frequencies and elevation angles below 5°.

4. Signal variations in the absence of precipitation, including scintillation and multipath effects

As is pointed out in Report 718, tropospheric effects in the absence of precipitation are unlikely to produce serious fading in space telecommunication systems operating at frequencies below about 10 GHz and at elevation angles above 10°. However, ionospheric scintillations may be important at frequencies below about 6 GHz.

The magnitude of tropospheric amplitude scintillations depends on the sizes of the antennas used, the frequency and the elevation, as shown in Report 881. At low angles of elevation, as well as at frequencies above about 10 GHz, they can occasionally be serious. Unfortunately, although several important experiments have been carried out recently on scintillation fading using satellite transmissions, only few data are available on the statistical characteristics of this type of fading. This is even more so for scintillations of the angle-of-arrival. The information given in this section must therefore be regarded as providing only a general guide, pending more comprehensive measurements over longer periods of time and in a range of climatic conditions.

4.1 Measurements at angles of elevation greater than 10°

Scintillations on satellite links with elevations greater than 10° are caused, in general, by mesoscale atmospheric irregularities, e.g. in the cumulus clouds. Measurements have been made in the United Kingdom, the Netherlands and the United States of America at elevation angles of 20° to 40° and frequencies of 19 to 30 GHz. Dual-frequency observations at 20/30 and at 19/28 GHz have shown that fluctuations at the two frequencies are generally well correlated in time. Frequency scaling seems to be possible using the information given in Report 881. Measurements with two different polarizations showed that scintillation is polarization-independent.

Statistical data, measured with OTS (11.6 and 11.8 GHz) at several sites in Europe, are also available [Haddon *et al.*, 1981; Thirlwell and Howell, 1981]. In 1979, peak-to-peak amplitudes of 1 dB were exceeded for about 0.2% of the time. Large variations between different years and different locations should however be expected.

There is broad agreement in the various measurements which indicates that scintillations at an elevation angle of 20° to 30° in a temperate climate are of the order of 1 dB (peak-to-peak) in clear sky in summer, 0.2 to 0.3 dB in winter and 2 to 4 dB (very occasionally 6 dB) in some types of cloud. Data on the rate of fading are rather inconclusive. The marked scintillations observed in some cloudy conditions often have a fluctuation frequency of 0.5 to 1 Hz, but higher-frequency components (up to at least 10 Hz) have been detected by some observers. Much slower fading, with a period of 1 to 3 min, has also been observed, and this is probably caused by relatively large-scale changes in refractive index.

4.2 *Measurements at low angles of elevation ($0^\circ \leq \theta \leq 10^\circ$)*

In addition to local fluctuations of refractive index (e.g. in clouds), the effects of tropospheric stratification become of importance at low elevation angles.

Data obtained at angles below 10° have been reported by several organizations in North West Europe and North America. A summary of results of the longer-term measurements in the frequency range 4 to 12 GHz is given in Table III. Worst-month data are shown together with annual data, where possible.

In the measurements made at Svalbard (78° N, see Table III), the scintillations were found to follow Rice distributions with average values of the power ratio of the random component to the steady component of -20 dB, -13 dB and -10 dB for the best month, worst month and worst day, respectively [Gutteberg, 1981a].

At 20 and 30 GHz, scintillation was observed under varying low elevation angles at several sites in the United Kingdom and United States during a brief period while ATS-6 was changing station [CNET, 1977]. In some of the measurements made in the United States, a pronounced broadening of the antenna beam was observed in the vertical plane, for elevation angles below 10° [Stutzman *et al.*, 1975]. Multipath propagation was thought to be the cause. However, this effect was not observed in the United Kingdom experiments, which used a much narrower antenna beam.

4.3 *"Duration" of scintillation periods*

The Canadian measurements of scintillation fading at low angles of elevation (see Table III) included observations of fade duration and rate-of-change. At a frequency of 6 GHz and an elevation angle of 1° , it was estimated that about 90% of the fades exceeding 20 dB would last less than about 11 sec, and of those exceeding 12 dB, 90% would last less than about 35 sec. The rate of change of signal level exceeded 1 dB/s for 1% of the time, and 4 dB/s for 0.1% of the time.

4.4 *Practical implications*

To reduce the fading margins required for high reliability in links operating at low angles of elevation, space diversity may be necessary because of multipath effects. Very few measurements have been made. With a vertical separation of 180 m good improvement was found [Strickland, 1980]. For horizontal spacing, the data are inconclusive. In one case, good performance was found with a separation of 300 m [McCormick and Maynard, 1971] whereas in another case, with a separation of 500 m, the improvement was poor [Strickland, 1980].

Also, because of problems associated with power control on the up link, low-angle fading may be important in the design of transponders for space stations intended for multiple access use by several earth stations.

4.5 *Long-term level variations*

In order to make accurate measurements of rain attenuation, it is necessary to establish a reference level. This reference level in many cases is obtained by observing the signal level in the absence of rain and is then loosely referred to as the "clear-sky" level. However, atmospheric, satellite and earth-station effects can combine to cause significant uncertainties in the clear-sky level established. This can lead to errors, particularly when comparing the rain attenuations measured simultaneously at two frequencies along the same radio path.

For some systems an accurate knowledge of variations in atmospheric attenuation exceeded for large percentages of time (when no rain is present) may be important. A study of sky noise level variations at 11.4 GHz carried out with the aid of passive radiometers at several locations in Europe [Brussaard, 1981] showed that seasonal variations in the monthly median level of total attenuation did not exceed 0.1 dB and that total attenuation exceeded for 20% of the worst month was 0.05 to 0.15 dB above the monthly median value, depending on location.

5. *Absorption due to atmospheric gases*

Absorption due to atmospheric gases is discussed in Report 719. Data are given therein for the absorption in the vertical direction, for frequencies up to 350 GHz. The values for any other elevation angle, greater than about 5° , may be calculated by multiplying the vertical-path data by the cosecant of the elevation angle. Report 719 also shows the strong influence of water vapour on the total absorption at frequencies displaced from the oxygen absorption lines at 60 and 119 GHz.

Maps showing the seasonal variation of absolute humidity at ground level have been prepared by [Bean and Dutton, 1966]. (See also Figures 9 and 10 of Report 563). These can be used to estimate the seasonal variation in clear-air attenuation. The extreme range for humidity variation is indicated, for example, for parts of the USA, by values of 0.1 g/m^3 and 26 g/m^3 which are exceeded for 99% of the time in February, and 1% of the time in August, respectively.

6. Attenuation due to precipitation and clouds

6.1 Prediction

6.1.1 General remarks

To predict attenuation due to precipitation and clouds along a slant-path, it is necessary to obtain information on their distribution in space and time, and, on their specific attenuations (dB/km).

In Report 721, different methods of calculating attenuation statistics from rainfall rate data are discussed. As to the rainfall data, statistical information on both the point rainfall rate and the horizontal and vertical structure of precipitations may be found in Report 563. Using the data of Report 721 to convert from rainfall rate (mm/h) to specific attenuation (dB/km), these data can be used to estimate the attenuation expected to be exceeded for various percentages of the time under the various climatic conditions, provided also that the length of the path through the rain is known.

As pointed out in Report 721, the use of an "effective path length" has severe limitations. Nevertheless, since none of the other methods discussed in Report 721 has been shown to yield satisfactory results for all rain climates, the concept of "effective path length" is used in the general prediction method of the following section. It should be noted, however, that this procedure is only a provisional one. *

Attenuation due to water cloud or fog can also be calculated from Report 721, if the liquid water content is known. Except for clouds of high water content, total attenuations due to cloud will not be great, and are likely in any case to be included in the measured statistics. The effects of ice cloud, dry hail and dry snow can be generally neglected for frequencies of interest.

If reliable long-term statistical attenuation data are available which were measured at a frequency (or at frequencies) different from that for which a prediction is needed, it may often be preferable to scale this information to the frequency in question rather than using the general prediction formula. Frequency scaling is discussed in § 6.1.4 of this Report.

For a discussion of site diversity effects and their prediction, reference should be made to § 6.3.

6.1.2 Method of prediction

From an examination of the methods discussed in Report 721, the following simple technique appears to yield reasonable agreements with available data.

To calculate the long-term statistics of the slant-path rain attenuation at a given location, the following parameters are required:

R_p : the point rainfall rate for the location at the required percentage times (mm/h)

h_0 : the height above mean sea level of the earth station (km)

θ : the elevation angle (degrees)

ϕ : the latitude of the earth station (degrees).

* Administrations are asked to study this question as a matter of urgency.

The proposed method consists of the following steps 1 to 7 for 0.01% of the time, and step 8 for other time percentages.

Step 1: The rain height, h_R^* , is obtained from (see Report 563):

$$h_R = 5.1 - 2.15 \log \left(\left(1 + 10^{\left(\frac{p-27}{25} \right)} \right) \right) \quad \text{km} \quad (1)$$

Step 2: The slant-path length, L_s , below the rain height is obtained from:

$$L_s = \frac{2(h_R - h_0)}{\left(\sin^2 \theta + 2 \frac{(h_R - h_0)^{\frac{1}{2}}}{R_e} \right) + \sin \theta} \quad \text{km for } \theta < 10^\circ \quad (2)$$

where R_e is the effective radius of the Earth (8500 km).

For $\theta \geq 10^\circ$, equation (2) may be simplified to:

$$L_s = \frac{(h_R - h_0)}{\sin \theta} \quad \text{km} \quad (3)$$

Step 3: The horizontal projection, L_G , of the slant-path length is found from (see Fig. 1):

$$L_G = L_s \cos \theta \quad \text{km} \quad (4)$$

Step 4: The reduction factor, r_p , for 0.01% of the time can be calculated from:

$$r_p = \frac{90}{90 + 4L_G} \quad (5)$$

Step 5: Obtain the rain intensity, R_p , exceeded for 0.01% of an average year, (with an integration time of 1 min). If this information cannot be obtained from local data sources, an estimate can be obtained from the maps of rain climates given in Report 563.

Step 6: Obtain the specific attenuation, γ_R , using the coefficients given in Table I of Report 721 and the rainfall rate, R_p , determined from step 5, by using:

$$\gamma_R = k(R_p)^\alpha \quad \text{dB/km} \quad (6)$$

Alternatively, Figs. 1 or 2 of Report 721 may be used.

Step 7: The attenuation exceeded for 0.01% of an average year may then be obtained from:

$$A_{0.01} = \gamma_R L_s r_p \quad \text{dB} \quad (7)$$

Step 8: The attenuation to be exceeded for other percentages of an average year, in the range 0.001% to 0.1%, may be estimated from the attenuation to be exceeded for 0.01% of an average year by using:

$$A_p = A_{0.01} \left(\frac{p}{0.01} \right)^{-a} \quad (8)$$

where a is given by [Fedi, 1981]:

$$\begin{array}{lll} a = 0.33 & \text{for} & 0.001 \leq p \leq 0.01 \\ a = 0.41 & \text{for} & 0.01 < p \leq 0.1 \end{array}$$

* This method is based on the use of the rain height h_R as shown in Fig. 17 of Report 563, this height being the height of the zero degree isotherm. However, it should be noted that for the estimation of attenuation in tropical climates a vertical path reduction factor will be required (see Report 563). Insufficient quantitative information exists at this time to allow the application of this prediction method to a completely representative range of climates and elevation angles. Administrations are therefore invited to submit data to add to those set out in Annex II of this Report in order to provide an adequate basis for the determination of this vertical path reduction factor or an equivalent adjustment.

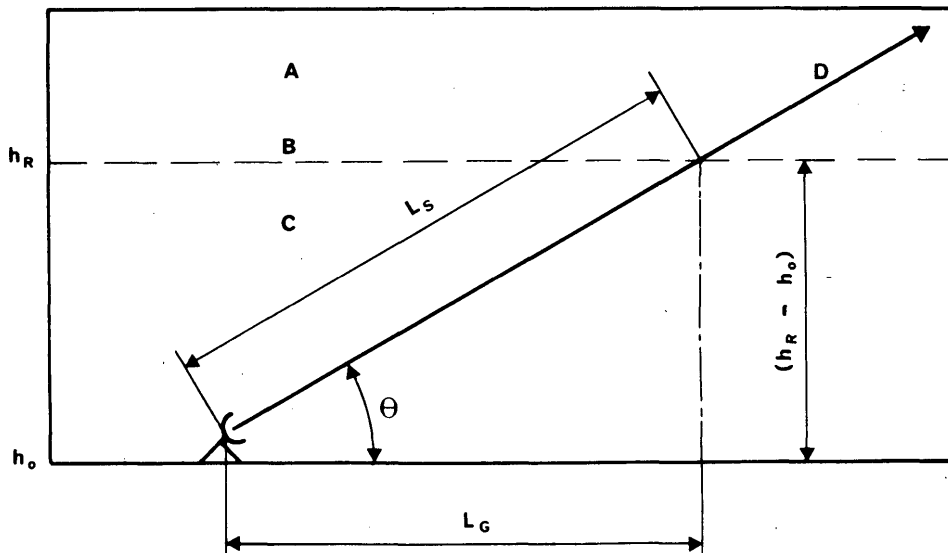


FIGURE 1 — Schematic presentation of an Earth-space path giving the parameters to be input into the attenuation prediction process (see § 6.1.2)

A: Frozen precipitation
 B: Rain height
 C: Liquid precipitation
 D: Earth-space path

The above procedure has been found to give reasonable agreement with available data, in particular in maritime climates. For continental climates and/or for time percentages greater than 0.1%, the procedure may be modified as follows:

- in step 1: obtain the rain height, h_R , for 0.001%, 0.01%, 0.1% and 1.0% of the time using Fig. 17 of Report 563;
- step 2 and step 3: remain unchanged;
- in step 4: obtain the reduction factor, r_p , for 0.001%, 0.01%, 0.1%, and 1.0% of the time from:

$$r_p = \frac{90}{90 + C_p L_G} \quad (9)$$

using the values of C_p given in Table I.

TABLE I

Percentage of a year	0.001	0.01	0.1	1.0
C_p	9	4	0.5	0

- in step 5: obtain the rain intensity, R_p , exceeded for 0.001%, 0.01%, 0.1% and 1.0% of the time of an average year;
- using steps 6 and 7 obtain the attenuation exceeded for the four time percentage values using equations (6) and (7);
- to calculate path attenuation A_p for an intermediate time percentage, p , between 0.001% and 1.0%, interpolation with the aid of the following approximate formula may be used:

$$\frac{A_p}{A_n} = \left(\frac{p}{p_n} \right)^{-a} \quad (10a)$$

where A_n is the attenuation calculated in step (e) for time percentage p_n , and where:

$$a = - \frac{\log (A_n/A_{n+1})}{\log (p_n/p_{n+1})} \quad (10b)$$

where A_n and A_{n+1} are the attenuations calculated for adjacent time percentages p_n and p_{n+1} respectively.

By applying the procedure for testing the prediction accuracy set out in Report 721, the above prediction method was found to be in agreement with available experimental attenuation data to within 20% when used with simultaneous rain rate measurements. When used with the rain climatic information from Report 563 as input, the errors to be expected are in general larger.

Note that this method provides an estimate of the long-term statistics of attenuation due to rain. When comparing measured statistics with the prediction, allowance should be given for the rather large year-to-year variability in rainfall rate statistics (see Report 563). The method may require revision as more detailed information, especially for non-temperate climates, becomes available. Administrations are invited to furnish additional information in the format of Annex I and to investigate possible improvements to the method.

6.1.3 Prediction for worst month

System planning often requires the attenuation value, exceeded for the time percentage p_w of the "worst month".

Using the following approximate relation (see Report 723), the corresponding annual time percentage, p , may be obtained:

$$p = 0.29 p_w^{1.15} \quad (\%) \quad (11)$$

The attenuation exceeded for this annual time percentage, p , calculated in step (e) or (f), may then be taken as the attenuation value exceeded for p_w per cent of the worst month.

6.1.4 Frequency scaling

Since data are not always available at the frequency of concern, it is often necessary to scale available information from one frequency to another.

Frequency scaling is examined in detail in Report 721, which summarizes the methods currently available. Sections 6.1.4.1 and 6.1.4.2 below outline suggested procedures for slant path.

6.1.4.1 Long-term statistics

If only attenuation data measured at one frequency are available, the following empirical formula may be applied in the frequency range 8 to 30 GHz [Battesti, 1981] (see Report 721):

$$\frac{A_1}{A_2} = \frac{g(f_1)}{g(f_2)} \quad (12)$$

where

$$g(f) = \frac{f^{1.72}}{1 + 3 \times 10^{-7} (f^{1.72})^2} \quad (13)$$

A_1 and A_2 are the equi-probable values of attenuation, in dB, at frequencies f_1 and f_2 (in GHz), respectively.

6.1.4.2 Short-term frequency scaling

Variations in the precipitation medium along the radio path can be very rapid. These, combined with temperature, humidity and cloud structure variations may cause variations in the instantaneous values of the ratio of attenuations at two frequencies. This can lead to inaccuracies in the near-instantaneous control of up-link power in satellite communications systems at frequencies above 10 GHz. Experimental results [Thirlwell and Howell, 1980; Otsu *et al.*, 1979] have shown that these short-term errors can be significant at elevation angles above 30°. The errors are expected to be higher for decreasing elevation angles. Other sources of error are the inaccuracies and equipment tolerances associated with the measurement of the down-link attenuation and the control of the up-link signal.

6.2 *Measurements*

6.2.1 *General*

The measurement of large attenuations which are exceeded for very small fractions of time requires the observation of rare events. For example, 0.01% of a year (a percentage used in system planning) is a total of about 50 min. Several events of short duration contribute to this total. One or more of the events may be extreme with a return period of many years. Hence, at these small time percentages, large year-to-year variability can be expected in the relevant statistics. Measurements over several years are therefore required to acquire meaningful data for prediction purposes.

Recently, valuable data have been obtained in several countries by direct measurements using satellite-transmitted beacon signals. Summaries of the results obtained so far are reviewed later in this section. However, these results do not yet extend over a sufficiently wide range of frequencies, elevation angles and climates. Consequently, it is necessary to supplement the satellite data with information obtained from other types of measurement. Some comments on various other types of measurement (e.g., radiometric and radar measurements) are given in Report 721. Whichever method is used, the interpretation of results must take into account the variability of the spatial (i.e. horizontal and vertical) structure of rain. At low elevations, the probability of the radio path intersecting more than one cell may not be neglected.

Some experiments have shown that, in certain climatic zones, snow and ice accumulations on the surfaces of antenna reflectors and feeds can produce prolonged periods with severe attenuation, which might dominate even the annual cumulative distribution of attenuation for the lower percentages of time.

6.2.2 *Results*

6.2.2.1 *Direct measurements using satellites*

Long-term observations of attenuation have been made at many places throughout the world using the beacon signals of various satellites. The results of these measurements have been summarized in the form of annual attenuation statistics. These are given in Tables IVa, IVb and IVc for the frequency bands 11 to 14, 18 to 22 and 28 to 35 GHz, respectively. When possible, values of attenuation exceeded are given for the percentages of time considered to be of most interest to system designers.

For the 11 to 14 GHz band, the US and Japanese stations tend to exhibit more severe attenuation than the European stations for given percentages, which is to be expected since rain conditions are more severe in the USA and Japan, particularly for thunderstorm occurrence periods, which account for most of the attenuation observed below about 0.05% of the time.

For the 18 to 22 GHz and the 28 to 35 GHz bands, respectively, a large data base of measurements is available for both the USA and Japan.

The measured attenuations are, as expected, more severe with increasing frequency, reaching very high levels at 30 GHz for 0.1% of the time and less. The variability of attenuation statistics between locations is due to the different rain climates, elevation angles and the year-to-year statistical variations.

The satellite beacon measurements available to date do not yield an adequate coverage of the different rain climatic zones. Further measurements are therefore urgently needed, especially for tropical and monsoon climates (see Annex I).

6.2.2.2 *Radiometric measurements*

Passive radiometry has been widely used to obtain data in various climates, at various frequencies and over a range of elevation angles. When an approximate correction for scatter was made (see Report 721) comparisons between results of radiometric and satellite measurements showed good agreement in a statistical sense, even at frequencies of about 30 GHz. In individual events, however, some discrepancies were observed.

Sun-tracking radiometers have also been used by several organizations; especially in the USA, the United Kingdom and Japan. The changing elevation angle, and the possibility of diurnal effects, make comparisons with the satellite technique difficult. In only a few experiments have sufficient data been obtained to enable valid statistics to be derived for different ranges of elevation angle. Nevertheless, much useful information is available at frequencies between about 9 and 40 GHz, with some limited data extending up to 71 GHz.

This section gives a summary of measured data relevant to system planning, obtained with both passive and sun-tracking radiometers. The results are again discussed in increasing order of frequency.

Figure 4 shows a summary of results obtained in the frequency band 9.4 to 19 GHz at various locations. As for satellite beacon measurements, there is generally a wide variability from year to year and hence, it is difficult to arrive at sound predictions on the effect of varying elevation angles. Attempts have been made to eliminate seasonal and year-to-year variability from measurements made in tropical areas of Australia, by extracting equi-probable values of point rainfall intensity and sky-noise temperature data. Only a weak elevation angle dependence was found between elevation angles of 30° and 90° [Flavin, 1978]. While there may have been some variation with elevation angle, the variability was substantially less than that represented by a cosecant law, particularly at high rain rates. Likewise, in N.W. Europe, no clear elevation dependence emerged from the European Space Agency's radiometer experiment [Brussaard, 1979]. In other climates, where the heavy rain is more uniform in horizontal extent (e.g. in monsoons) the elevation dependence may be approximated by a cosecant law for elevation angles greater than 10°. Figure 4 illustrates this marked influence of differences in rainfall climate. For example, the attenuations exceeded for 0.01% of the time in the 11 GHz band range from about 3 dB in British Columbia to about 20 dB in Malaysia.

The data in Fig. 4 generally refer to the excess attenuation above that for average clear sky conditions (the residual value being about 0.2 dB at 15 GHz for an elevation angle of 30°). They should only be used as a general guide, and the original papers should be studied for further details.

Figure 5 gives a summary of attenuation measurements made by radiometric techniques in the band 20 to 40 GHz. In this frequency range the effect of widespread rain becomes significant, and the dependence on elevation angle is more pronounced. The figure therefore gives some information on the effect of changing the angle of elevation. However, the results shown should be regarded as giving only a general guide. Nevertheless, the data, with those in Fig. 4 illustrate the marked increase in attenuation with increasing frequency, and also the large differences between the curves for different climates (e.g. the UK and Japan) at similar frequencies. Some locations (e.g. Hawaii) experience attenuations considerably in excess of any shown in Figs. 4 and 5.

The results from Japan at 35 GHz were obtained at two sites with a height difference of 3 km, (Mt. Fuji and Gotemba) and the data show that the mountain site gives a 7-fold reduction in the time percentage for which a given attenuation is exceeded [Otsu *et al.*, 1978]. Other results from Japan [Sato *et al.*, 1978] provide further information on the effect of changes in elevation angle.

From measurements in the Netherlands [Mawira *et al.*, 1981] there is evidence that the directly measured attenuation on a satellite path can be predicted by measuring the effective rain height using a zenith pointing radiometer and the horizontal structure of rain using a rain-gauge network.

6.2.2.3 Radar measurements

Attenuation statistics for various elevation angles and frequencies between 13 and 100 GHz have been generated from limited high resolution S-band radar data obtained at Wallops Island, Virginia [Goldhirsh, 1975].

Rain attenuation measurements have been carried out in Japan using a 14/5 GHz dual-frequency radar [Yamada *et al.*, 1981a]. The rain attenuations at 13.9 GHz for a 10° elevation angle for a 3-year period are 3.5, 10.8 and 20.3 dB and the rain rates 4, 19 and 51 mm/h respectively for 1%, 0.1% and 0.01% of the time.

6.2.3 Data on the worst month

For the definition of the "worst month" reference should be made to Report 723. Unfortunately, only few investigators have acquired attenuations statistics which are sufficiently comprehensive to enable worst month data to be derived. The most comprehensive data set available so far [Brussaard and Watson, 1978] is summarized in Table V and, together with some other data, in Report 723. These data indicate that the ratio of average yearly worst-month time percentage to average yearly time percentage, depends somewhat on the climate (see Fig. 4 of Report 723).

6.2.4 Duration of attenuation events

Fading durations have been obtained in experiments made in the United Kingdom at 11.6, 11.8, 19, 30, 37 and 71 GHz. These measurements, together with other more broadly based measurements, have been summarized in a review of the slant path work at Slough by Davies and Mackenzie [1981]. This review indicates, for example, that in the band 30 to 37 GHz, individual fades can exist for over 120 min.

Table VIa provides duration statistics for several locations in Europe [Brussaard, 1981] and Table VIb for two years of Sirio measurements in Italy [Matricciani, 1981a].

Measurements of the duration of fades exceeding 5 dB, using satellite beacon emissions have been carried out in Japan at 11.5 and 34.5 GHz [Tsukamoto *et al.*, 1979; Fujita *et al.*, 1980] and in Europe at 11.8 GHz. Results are summarized in Fig. 6. They indicate that the total time of 5 dB fades exceeding certain durations follows a log-normal distribution as a function of duration. The fade number versus fade duration was also found to be log-normally distributed.

Statistics of 13.9 GHz fade durations have been obtained from four years of dual-frequency radar data collected at an elevation angle of 10° in Japan [Yamada *et al.*, 1981a]. These data are summarized in Table VIc. At the 10° elevation angle of these measurements, relatively long durations were frequently observed even for fades in excess of 10 dB.

6.2.5 Rates of change of attenuation

With increasing frequency up-link power control and/or diversity operation may become mandatory. Criteria when to increase power or to re-route traffic will have to be derived from down-link signals. Fade slope can be one of these criteria, providing estimates of the time available for a given increase of attenuation.

Within the framework of the OTS propagation experiments, fade slope data at 11.8 GHz were analyzed at a fade level of 5 dB. Fade slopes were found to be log-normally distributed and the distribution was symmetric for the starting slopes and the ending slopes with a median value of 0.12 dB/s.

Similar results were obtained for various fade levels in an experiment conducted at Waltham, Massachusetts, using the CTS 11.7 GHz beacon [Nackoney, 1979]. The fade slope was found to be only slightly dependent on fade level.

Cumulative distributions for both of these experiments are shown in Fig. 7.

From the analysis of the European data it was concluded that fade slope and fade duration were related in a statistical sense [Dintelmann, 1981]. However, data are still sparse on this subject and hence these findings should be regarded only as a tentative guideline.

Observations made at a frequency of 11.6 GHz in Italy [Matricciani, 1981b] have shown that:

- the higher the attenuation, the higher the rate of change of attenuation;
- positive and negative rates of change have very similar distributions; and
- the distribution function is not affected by assuming different values of the separation between successive attenuations used to determine the rate of change. Results are summarized in Fig. 8.

6.2.6 Measurements at frequencies above 40 GHz

At frequencies above 40 GHz few experiments have been carried out which are sufficiently extensive to provide a basis for a quantitative evaluation of system performance. Nevertheless, some useful results of a preliminary nature have been obtained.

Davies [1975] has summarized data obtained from a 71 GHz beam-switching, sun-tracking radio-meter at Slough, United Kingdom. For all possible angles of elevation (0° to 62°), the excess attenuation, caused by cloud and rain (i.e. in addition to the clear-air value), which was exceeded for 3, 1 and 0.5% of the time in 2081 hours of observations over a 6-month period, was about 4.5, 9.5 and 12 dB respectively. Most of the large fades (above 15 dB) did not last longer than 8 to 10 minutes, but four of the fades exceeding 15 dB had durations in the range 40 to 140 minutes.

Some results of vertical-incidence measurements at 110 GHz at Slough, United Kingdom, have been described by Gibbins [1974]. Values of total attenuation (due to atmospheric gases, clouds and precipitation) were deduced from emission-noise data, with an estimated correction for scattering effects in rain. The attenuation so derived exceeded about 6, 10 and 13 dB for 5, 1 and 0.5% of the time, respectively.

As the frequency increases above 40 GHz, the effect of clouds becomes steadily more important (see Report 721). However, recent measurements, quoted in that Report, show that in some types of cloud (e.g. strato-cumulus) the additional attenuation produced at vertical incidence is no more than 0.5 to 1 dB, even at 150 GHz. On the other hand, clouds with a high liquid-water content, such as cumulo-nimbus, can cause an additional attenuation of about 4 to 5 dB at 100 GHz and up to 8 dB at 150 GHz.

6.3 *Site diversity*

Since the intense rain cells which cause a large attenuation on an Earth-space link often have horizontal dimensions of no more than a few kilometres, switching between two or more terminals on the Earth's surface (site diversity) can improve the system reliability considerably. To assess this improvement, the cumulative distribution of the joint probabilities of rain attenuation, as a function of site separation, are needed in addition to directly measured site diversity data. Site diversity may also be necessary to reduce the effect of scintillation fading (see § 4.2) and to reduce earth station coordination problems in regions where terrestrial and earth-space systems have to be located close to each other.

6.3.1 *Prediction of site diversity performance*

To assist in the development of general prediction procedures, it is helpful to generalize the results of several investigations of site diversity in a composite summary. This is attempted in Fig. 2, which is based on medium elevation angle data from mid-latitude locations in Japan, the USA and the UK [CCIR, 1978-82]. The curves illustrate how the probability of attenuation being exceeded simultaneously at two sites depends on their spacing. The curves also demonstrate that diversity improvement with site separation is more rapid for the lower percentages of time (see Fig. 9). This is consistent with meteorological data which show that the horizontal dimensions of rain cells causing large attenuations tend to decrease with the peak rainfall intensity in the cell.

This summary is based on limited data and should be used with caution, bearing in mind that (important at higher frequencies) the advantages of site diversity can be quite small if sites are so chosen that the rain in, for example, frontal systems tends to affect both sites simultaneously. Diversity improvement is also dependent on frequency, orientation of the baseline with respect to the satellite azimuth, and elevation angle; factors not evident in Fig. 2. Data demonstrating the elevation angle dependence are given in Fig. 10. Topographical effects can also be important. For example, Canadian experiments show that for two pairs of sites in the lee of an escarpment, the diversity performance is consistently poor.

6.3.2 *Measurements on site diversity*

Measurements of site diversity improvement for rain attenuation (ratio of single site to joint probabilities) have been performed at several locations, for frequencies of 11 to 40 GHz and elevation angles of 6° to 50°, using both radiometers and satellite beacons. The results of some of these experiments are summarized in Fig. 9. It appears from these data that, for the same site spacing and time percentage level, a greater diversity improvement was achieved in the USA than in Japan or Europe. For instance, at a site spacing of 30 km, a single-site probability of 0.1% was reduced to a joint probability ranging from 0.01% in Japan to 0.004% in the USA.

Other data, derived from radar observations in Canada and the USA, relevant to diversity operation are given in Report 563. A comprehensive review of diversity experiments and their results has been given in [Allnutt, 1978].

7. *Noise temperature*

The relationship between atmospheric absorption and the emission noise which sensitive receivers may detect is discussed in Report 720. As the absorption increases, so does the emission noise, until for a strongly-absorbing medium the emission noise approaches that for a perfect (black-body) radiator at the actual, kinetic temperature of the medium; usually in the range 260 K to 280 K. If the variation in atmospheric absorption is known for a particular location, frequency, and elevation angle, then the variation in emission noise can be estimated.

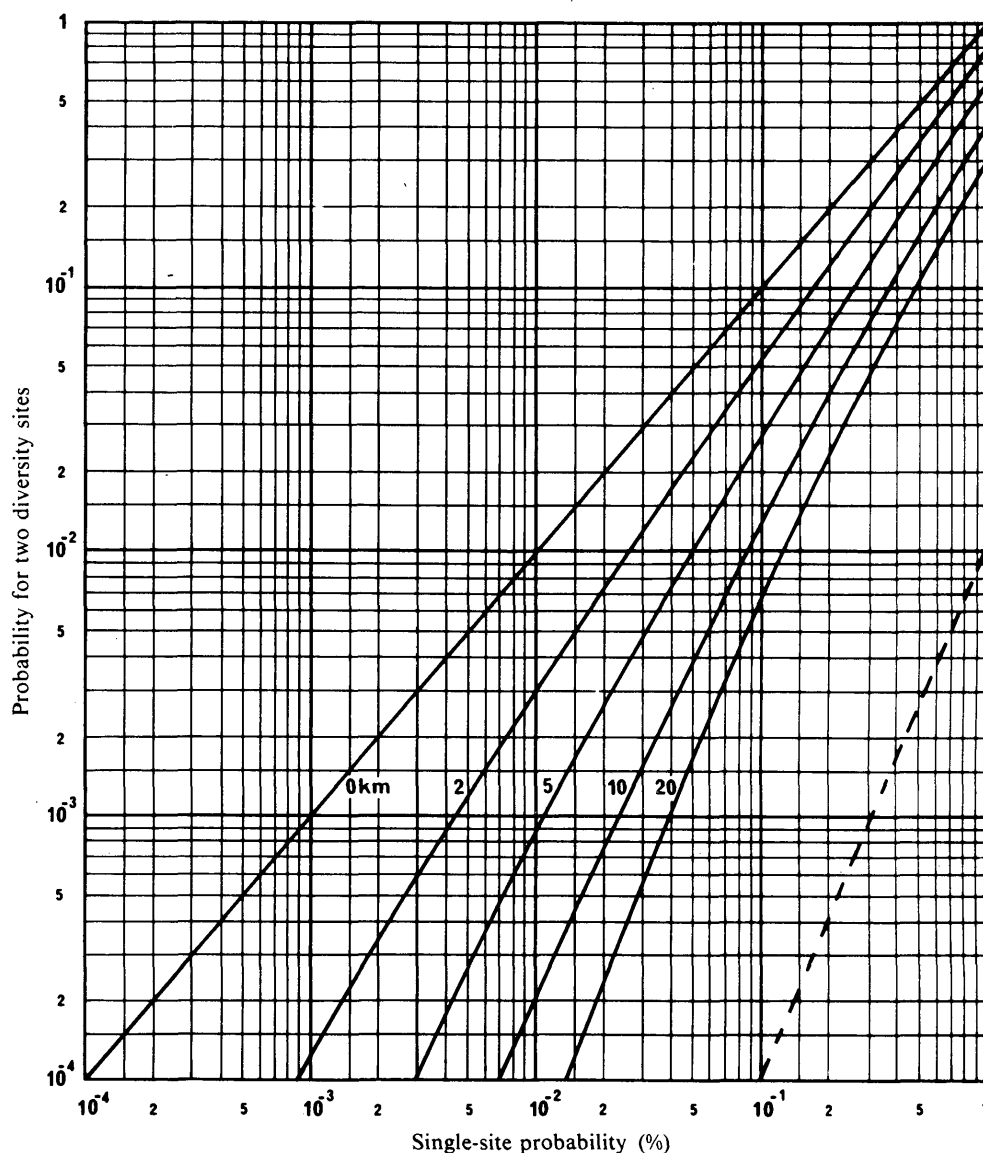


FIGURE 2 — Probability of attenuation being exceeded simultaneously at two diversity sites

Combination of data from Japan, the UK and the USA at frequencies of 11.6 to 35 GHz and elevation angles of 22° to 50°.

Parameter : spacing of the two diversity sites
 - - - - : limiting case of zero correlation between diversity sites

A few experiments have been carried out to obtain statistical data on emission noise directly. For example, the measurements of [Turner *et al.*, 1970] show that, in the United Kingdom, the sky-noise temperatures exceeded for 0.01% of the time at an elevation angle of 20° were 148 K and 223 K at frequencies of 12 and 17 GHz, respectively. At 5° elevation, the corresponding values were 260 K and 274 K, respectively. In Massachusetts, at 15 GHz, values of 10, 20, 55 and 100 K were exceeded for 10% of the time at elevation angles of 90°, 30°, 10° and 5°, respectively [Wulfsberg, 1964]. At higher frequencies, large values of emission noise prevail for appreciable percentages of time. For example, at 110 GHz in S. E. England vertical-incidence experiments show that noise temperatures of 160 K and 230 K were exceeded for 10% and 1% of the time, respectively. Long-term observations of sky noise exceeded for 50% to 1% of time at various locations in Europe have been reported [Brussaard, 1981].

If noise temperature information for rain and cloud is not available, it is permissible to estimate cloud brightness temperature from a relation such as equation (7) in Report 720, i.e.

$$T_b = T_m (1 - 10^{-A/10}) \quad \text{for } f < 60 \text{ GHz} \quad (14)$$

where T_m , the mean temperature of the medium, may be taken as 280 K for clouds, and the attenuation A (dB) may be obtained from § 6 of this Report or from Report 721.

Brightness temperature due to rain is much more difficult to estimate accurately. As an interim measure, pending better data on noise temperature of rain, a value of brightness temperature may be derived from equation (14) using $T_m = 260$ K and attenuation from § 6. The resultant brightness temperature may be considered an upper bound to the true brightness temperature.

For satellite telecommunication systems using the geostationary orbit, earth stations will find the Sun a significant noise source at all frequencies and the galactic background a possibly significant consideration at frequencies below about 2 GHz [Kraus, 1966].

For earth stations tracking orbiting satellites or spacecraft on deep-space missions the radio sources most likely to be of interest are Cygnus A and X, Cassiopeia A, and The Crab nebula.

To determine the system noise temperature of earth stations from the brightness temperatures discussed above the equations of Report 208 (Volume IV) may be used.

8. Cross-polarization effects

8.1 General

In order to increase capacity in space telecommunications systems, frequency re-use by means of orthogonal polarization is envisaged. This technique is restricted, however, by depolarization due to atmospheric propagation and to a lesser extent to the antennas used in these systems. A description of the polarization isolation characteristics of various antennas used in space telecommunications systems is given in Report 555 (Volume IV). Report 722 gives a more complete description of the various depolarization mechanisms, including refractive effects, that are important in both terrestrial and Earth-space links.

Faraday rotation of the plane of polarization by the Earth's ionosphere is discussed in Report 263 (Volume VI). As much as 1° of rotation may be encountered at 10 GHz (see Table VI of Report 263).

8.2 Prediction techniques for cross-polarization due to hydrometeors

Because of the importance of both rain and ice clouds in producing interference due to cross-polarization, both must be included in any prediction method. In predicting rain depolarization statistics from co-polarized rain attenuation statistics, an equation of the form:

$$XPD = U - V \log (CPA) \quad \text{dB} \quad (15)$$

can be used for both linear and circular polarizations (see Report 722). The following approximate forms for U and V appear to be in reasonable agreement with existing theory and available data:

$$U = \kappa^2 - 10 \log \frac{1}{2} \left[1 - \cos (4\tau) e^{-\kappa_m^2} \right] + 30 \log f - 40 \log (\cos \varepsilon) \quad (16)$$

for $8 \leq f \leq 35$ GHz, and $10^\circ \leq \varepsilon \leq 60^\circ$

$$V = 20 \text{ for } 8 < f \leq 15 \text{ GHz}; \quad V = 23 \text{ for } 15 < f \leq 35 \text{ GHz} \quad (17)$$

where

ε : angle of elevation;

τ : polarization tilt angle with respect to horizontal (for circular polarization $\tau = 45^\circ$);

κ, κ_m : effective parameters of the raindrop canting angle distribution in degrees.

The value of the parameter κ depends not only on meteorological factors discussed in Report 722, but also on elevation angle and the particular statistical relationship being fitted to the experimental data. In accounting for the effects of rain alone, a value of $\kappa = 0$ would appear to be conservative. Positive values of κ^2 have been observed, and are discussed in Report 722.

The second factor in equation (16) is the improvement of linear polarization with respect to circular polarization. A conservative value of $\kappa_m = 0.25^\circ$ is recommended at present. This gives a maximum improvement of 15 dB for $\tau = 0^\circ$ or $\tau = 90^\circ$. It should be noted, however, that higher improvements have been observed [Cox, 1981] as described in Report 722.

Equation (15) can be used to obtain *XPD* statistics for linear polarization using *CPA* statistics predicted with the method discussed in § 6.1.2. In the case of circular polarization the above value of τ should be noted.

In accounting for the effects of ice crystals, it has been proposed that a constant factor can be subtracted from the *XPD* for rain [Chu, 1980]. Although a value of 2 dB seems to be reasonable for North America, even for some maritime climates, a value of as much as 4 or 5 dB may be more appropriate for the maritime climate of north western Europe. Such an approach in allowing for the additional cross-polarization due to ice clouds must be used with extreme caution, particularly for low attenuations.

As noted in Report 722, a design approach based on joint probability cumulative distributions of *XPD* and *CPA* is preferable, particularly for Earth-space paths where the variability in *XPD* for a given *CPA* is large for the low attenuation margins normally employed. It should be noted, however, that the use of an equi-probability relation between *XPD* and *CPA* for outage calculations may give the same results as the use of joint probabilities if it is applied to the calculation of fading margins in systems using dual polarization [van Cappellen *et al.*, 1980]. Administrations are urged to give particular attention to this problem in future analyses.

For the frequency band 4 to 6 GHz where attenuation is low, *CPA* statistics are not as useful in predicting *XPD* statistics. For frequencies below about 8 GHz, it may be more useful to employ relationships between *XPD*, point rain rate, and effective path length [Oguchi, 1977; Kobayashi, 1977]. A simple prediction technique to obtain an overall cumulative distribution of *XPD*, has been suggested [Olsen and Nowland, 1978].

8.3 Frequency and polarization scaling for long-term statistics

Long-term *XPD* statistics obtained at one frequency and polarization tilt angle can be scaled to another frequency and polarization tilt angle using the semi-empirical formula

$$XPD_2 = XPD_1 - 20 \log \left[\frac{f_2 \sqrt{1 - \cos 4\tau_2 e^{-\kappa_m^2}}}{f_1 \sqrt{1 - \cos 4\tau_1 e^{-\kappa_m^2}}} \right] \quad \text{for } 4 \leq f_1, f_2 \leq 30 \text{ GHz} \quad (18)$$

where XPD_1 and XPD_2 are the *XPD* values not exceeded for the same percentage of time at frequencies f_1 and f_2 and polarization tilt angles τ_1 and τ_2 , respectively. A measured value for the parameter κ_m should be used if available; otherwise, the value given in § 8.2 should be employed.

Equation (18) is based on the same theoretical formulation as equation (15) [Olsen and Nowland, 1978; Chu, 1980; Cox, 1981]. It can be used to scale *XPD* data that include the effects of both rain and ice depolarization, since it has been observed that both phenomena have approximately the same frequency dependence at frequencies less than about 30 GHz (see Report 722). Equation (18) is provisional and must be used with particular caution for large differences between the respective frequencies and polarization tilt angles.

8.4 Measurements

8.4.1 Results relating to *XPD* distributions

The bulk of the results of the measurements seem to support the relation between *XPD* and *CPA* set forth in § 8.2. Frequency and polarization scaling as proposed in § 8.3 seems to be possible within the limits of the measuring accuracy. The spread of the individual measured values can be quite large and usually tends to increase at lower levels of attenuation. This may be attributed to the variable relative importance of ice depolarization as compared with rain depolarization. However, it should be borne in mind, too, that many measurements suffer from reduced accuracy at low levels of depolarization, because of imperfections of the antennas.

From a comparison of OTS measurements made at several sites with linear and circular polarization, it was tentatively concluded that the *XPD* due to ice varied with polarization tilt angle, τ , slightly less than suggested by equation (16).

In the CTS measurements carried out at five locations in Canada, degradations to an *XPD* as low as 17 dB, attributed to ice particles, were observed in the absence of significant attenuation [Schlesak and Strickland, 1980]. It appears that, within the USA, the effect of ice depolarization, in relation to rain depolarization, is greatest in the maritime regions and least in the continental regions [Cox, 1981].

Part of the statistical spread of the data may be ascribed to some variation in the *XPD/CPA* relationship between regions with different climate and geography [Cox, 1981]. But the information available at present does not allow a regional separation of the *XPD/CPA* relationship.

In polar areas, cross polarization due to sleet and snow on the path may be the most dominant effect. Based on measurements at Svalbard, Norway ($f = 11.8$ GHz, $\epsilon = 3.4^\circ$), the constants in an equi-probability equation of the form of equation (15) were found to be $U = 27$ and $V = 8$ [Gutteberg, 1981b].

A summary of experimental data is given in Table VII.

8.4.2 Results relevant to cross-polarization compensation

Studies assessing the feasibility of adaptive cross-polarization cancellation techniques have been carried out by several authors [Barton, 1976; O'Neill and Isaacs, 1980; McEwan *et al.*, 1981]. In the USA, a microprocessor-controlled 6/4 GHz adaptive polarization compensation network employing up/down-link correlation algorithms has been implemented and tested [Persinger *et al.*, 1981]. A 6/4 GHz compensation system has also been implemented in Japan [Yamada *et al.*, 1981b]. Preliminary results indicated the feasibility of maintaining acceptable isolation at both 6 and 4 GHz. These systems were sub-optimal because only differential phase shift was adaptively cancelled. Analytical investigations [Overstreet and Bostian, 1978; McEwan *et al.*, 1981] indicate that sub-optimal cancellation systems may be useful for some applications at higher frequencies as well.

Cross-polarization measurements carried out in the United Kingdom [Howell, 1977] and France [Fimbel and Ramat, 1977] have shown that in general the relative phase of the co- and cross-polar signals is fairly constant ($\approx \pm 20^\circ$); however, under certain conditions, abrupt changes ($\approx 180^\circ$) can occur. Several experimenters noted abrupt changes of the *XPD* (several dB within 0.1 to 0.3 s) which coincided with lightning strokes, suggesting changes in the alignment of the ice crystals [Howell, 1977; Watson *et al.*, 1979].

Measurements of the spectral characteristics of rain depolarization [Taur and Mass, 1976] have been made for widely spaced rain events of substantially different minimum *XPD* levels. The results show that the range of rain depolarization decreases at about 20 dB/decade from about 0.1 to 0.7 Hz to about 4 to 8 Hz.

Such data are useful in determining the response time of orthogonality restoring systems for the purpose of frequency re-use. Figure 11 shows the *XPD* durations at 34.5 and 11.5 GHz obtained from a one-year measurement programme using transmissions from the Engineering Test Satellite – Type II (ETS-II or Kiku-2) at an elevation angle of 47° [Fugono, 1979].

Measurements of durations of *XPD* degradation due to rain in Japan [Yamada *et al.*, 1977] have been shown to follow a log-normal distribution.

On Earth-space propagation paths with low elevation angles, rapid and irregular phase fluctuations between the co- and cross-polarized signals in the circularly-polarized waves were found in clear weather conditions [Furuta and Yamada, 1980]. These fluctuations were almost in phase with the amplitude scintillations of the received co-polar signal. The magnitude of the cross-polar phase fluctuations reached about 50° in the 4 GHz band at an elevation angle of 10° . The phenomenon may be due to the combination of the antenna cross-polarization characteristics and the focussing and de-focussing of the multiple radio waves caused by turbulence in the troposphere.

8.5 Practical implications

On the basis of the various measurements discussed above and the information on cross-polarization mechanisms provided in Report 722, some tentative conclusions can be drawn:

- The most significant causes of cross polarization on Earth-space paths are rain and ice-cloud depolarization, which have the same frequency dependence at frequencies below about 30 GHz. An exception to this is for linear polarization below about 6 GHz, where Faraday rotation is likely to be a more significant cause at some locations.
- Depolarization is usually strongest for fixed linear polarizations with a tilt angle of $\pm 45^\circ$, and for circular polarization. Depolarization is usually minimized for horizontal polarization and for “vertical” polarization. These maxima and minima occur for linear polarizations because the axes of symmetry of raindrops and ice crystals are oriented nearly vertically or horizontally [Cox, 1981].
- For a given *XPD*, the frequency of occurrence of ice depolarization relative to rain depolarization varies with climate and geography. However, rain dominates *XPD* statistics in regions that experience the severe rain attenuations associated with thunderstorms. Nevertheless, a high level of cross-polarization interference (not *XPD*) may occur more frequently in ice than in rain. This may be important in certain systems.
- Although there is a statistical variation in the relationship between *XPD* and *CPA* at any location, and there appears to be a climatic and geographic variation involved, the relationship between *XPD* and *CPA* is similar for all experimental locations and approximately follows the form given in § 8.2.
- In certain climatic zones it will be necessary to take measures to remove wet snow and ice accumulations from the surfaces of antenna reflectors and feeds. Otherwise prolonged periods with strong cross polarization could occur which might dominate even the yearly *XPD* statistics.

9. Propagation delays on Earth-space paths

9.1 General aspects

Several methods are available for estimating the average delay or range error in Earth-space propagation through the troposphere. However, for satellite ranging and for synchronization in digital satellite communications systems, the propagation delay variance is also required. At frequencies above 10 GHz, the ionospheric time delays are negligible compared to those for the troposphere. As noted in Reports 718 and 721, both the clear atmosphere and precipitation may contribute to propagation delay and its variations.

9.2 Delays through the precipitation-free atmosphere

The mean and variance of the propagation delay in the precipitation-free atmosphere can be derived from the regression relation between surface refractivity N_s and range error ΔR (or corresponding time delay error $\Delta\tau$) developed in the USA [Bean and Dutton, 1966]. Details of the procedures, particularly that for estimating the delay error variance, are given elsewhere [Nuspl *et al.*, 1975]. Most published statistics of N_s are given on a monthly basis, but estimates of the standard deviation $\sigma_{\Delta\tau}(T)$ for any time period T can be obtained by combining the one-month estimates with a semi-empirical frequency spectrum of the delay $\Delta\tau$.

Curves of $\sigma_{\Delta\tau}$ along a two-way Earth-space path are given in Fig. 3 as functions of “cut off frequency” $f_c = 1/T$ and for one-month standard deviations of 10, 20, and 30 N -units; f_c is the frequency below which the delay fluctuations are increasingly attenuated due to the finite observation period T . A typical path elevation angle of $\epsilon = 30^\circ$ has been assumed, along with an effective path length of 10 km and average wind speeds normal to the path of $U = 2, 5$, and 10 m/s. For elevation angles other than 30° , values obtained from the graph as well as the indicated wind speeds must be divided by the factor $2 \sin \epsilon$. The distribution of the delay fluctuations can be assumed to be Gaussian.

The curves in Fig. 3 must be used with caution since they are based on an average frequency spectrum and do not reflect the distribution of extreme variations that can occur. An approximate upper bound for short observation periods T is given by $\sigma_{\Delta\tau} \approx 0.25/\sin \epsilon$ (ns) for $\epsilon \geq 10^\circ$.

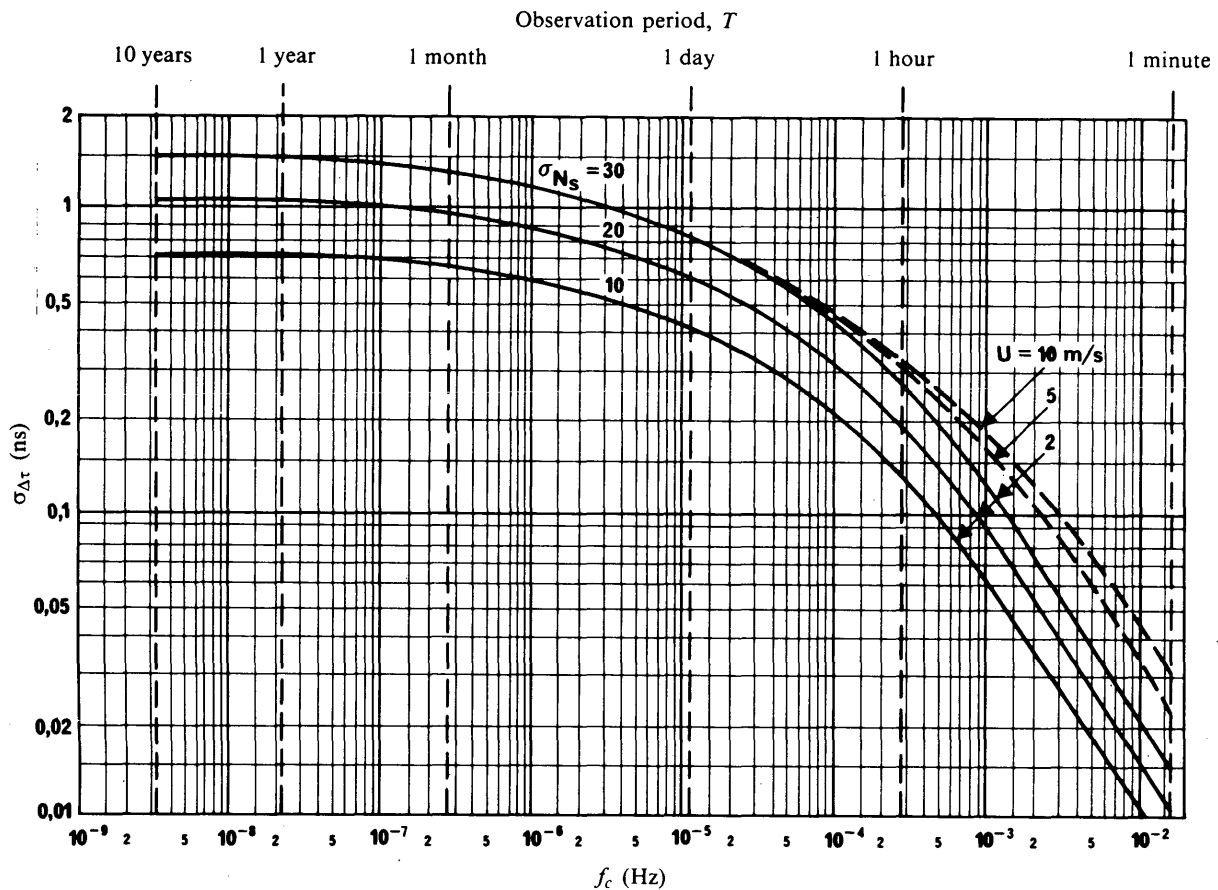


FIGURE 3 — Cumulative frequency dependence of $\sigma_{\Delta\tau}$ for a two-way Earth-space path at 30° elevation. Each curve corresponds to the specified values of σ_{N_s} for a one-month period

9.3 Delays through rain

In applications in which the fluctuations in propagation delay over several minutes or less must be taken into account, the effects of rain should also be considered. The change in delay due to a rain cell crossing the propagation path can be estimated using an approach similar to that used to calculate attenuation [Nuspl *et al.*, 1975] in the range up to about 15 GHz. For example, a TDMA satellite communications system having an attenuation margin of 6 dB at 14 GHz must be able to contend with a delay variation of 0.2 ns. Since this value is much smaller than the TDMA "guard times" presently in use or envisaged, the delay variations due to rain can be ignored.

10. Limitations on the bandwidth of space telecommunication systems

In the vicinity of the absorption lines due to atmospheric gases, anomalous dispersion produces small changes in the refractive index. However, these refractive index changes are small in any bands allocated to Earth-space communications, and will not restrict the bandwidth of systems.

Multiple scattering in rain can limit the bandwidth of incoherent transmission systems due to variation in time delays of the multiple-scattered signals; however, it has been suggested [Crane, 1971] that the attenuation itself under such circumstances will present a far more serious problem. A study of the problem of bandwidth limitations imposed by the frequency dependence of attenuation and phase shift due to rain on coherent transmission systems showed that such bandwidth limitations are in excess of 3.5 GHz for all situations likely to be encountered [Crane, 1967]. These are greater than any allocated for Earth-space communications below 40 GHz, and the rain attenuation will therefore be far more important than its frequency dependence.

However, further theoretical and experimental studies are required to establish the frequency dependence of the atmospheric transfer function (amplitude and phase) that takes account of the effects of non-spherical, canted raindrops. This transfer function taken together with the reliability, i.e. bit error ratio, can be used to determine bandwidth limitations both under good weather conditions and also in the presence of hydrometeors.

11. Impairments by sand and dust storms

Very little is known about the effects of sand and dust storms on radio signals on the slant path. Some information is contained in Report 721. More measurements are urgently needed.

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- [1978-82]: 5/321 (IWP 5/2).

ANNEX I

COLLECTION OF DATA

Further data are required for the prediction of radio noise and the attenuation and refraction of radio waves in relation to space telecommunication systems.

Administrations are therefore urged to undertake long-term radio measurements, particularly at frequencies above 10 GHz and, if possible, associated rainfall measurements. Radio measurements may include direct measurements, using, for example, the sun or a satellite beacon for signal sources and indirect measurements, for example, sky noise or radar-derived attenuation. The rainfall should preferably be integrated over 1-minute intervals. If possible, the sub-division of the total rainfall into the types of rain, i.e., convective or stratiform type should be indicated.

Administrations are further requested to forward their measured data to the Director of the CCIR who will, at a convenient time, publish all the collected data.

It will greatly increase the usefulness of the individual contributions if administrations will summarize their experimental data in the manner shown in the following Tables. Any Table IIa to IIc should contain data from concurrent measurements only; i.e. when data of one type of measurement are not available for a certain period of time, data of the other type(s) should be excluded from the statistics for that period.

Information is also required on:

- the improvement to be obtained by the use of site diversity techniques;
- the correlation between attenuation and noise;
- the correlation between cross-polarization discrimination and co-polar attenuation;
- the rate of change of attenuation on slant paths.

TABLE II

1. Country _____
2. Measuring station _____
 - Latitude _____
 - Longitude _____
 - Height above sea level _____
3. Radio signals
 - Source _____
 - Frequency (GHz) _____
 - Polarization _____
(for linear polarization: give tilt angle with respect to the horizontal)
 - Elevation angle _____
4. Receiving equipment
 - Type of antenna _____
 - Diameter (m) _____
 - Nature of feed _____
 - Beamwidth at 3 dB points (degrees) _____
 - Protection by radome? Yes ☐ No ☐
 - Figure of merit (dB(K⁻¹)) _____
5. Measurements
 - Total period from _____/_____/_____ to _____/_____/_____
(day/month/year) (day/month/year)
 - Total number of complete hours of measurement _____
 - Data sampling interval _____
 - Calibration interval _____
6. Was the attenuation due to water vapour and cloud separated from that due to precipitation? Yes ☐ No ☐
If yes, give details of the method of analysis under item 8.
7. Rainfall measurements
 - Number of rain gauges _____
 - Length of path covered by rain gauges (if more than 1 rain gauge) _____
 - Type of rain gauge _____
 - Integration time (s) _____
8. Additional remarks

TABLE IIa

		(X) Attenuation (dB) in excess of free-space attenuation, and (Y) Rainfall rate (mm/h) exceeded for following percentages of time						
Total period	X Y	50	20	10	1	0.1	0.01	0.001
Worst month	X							
	Y							

TABLE IIb

		(X) Noise (K) exceeded for following percentage of time, and (Y) Rainfall rate (mm/h) exceeded for following percentages of time						
Total period	X Y	50	20	10	1	0.1	0.01	0.001
Worst month	X							
	Y							

TABLE IIc

		(X) Cross-polarization discrimination (dB) not exceeded for following percentages of time (Y) Rainfall rate (mm/h) exceeded for following percentages of time (Z) Co-polar attenuation (dB) exceeded for following percentage of time						
Total period	X Y Z	50	20	10	1	0.1	0.01	0.001
Worst month	X							
	Y							
	Z							

TABLE II*d*

Fade duration (minutes)	Fraction of total fading time for given fade level					
	3 dB	6 dB	10 dB	15 dB	20 dB	25 dB
> 0.1						
> 0.3						
> 1						
> 3						
> 10						
> 30						
> 60						
Total fading time (minutes)						

ANNEX II

PROPAGATION DATA MEASURED ON SLANT PATHS

This Annex presents summaries of a considerable amount of data made available to Study Group 5.

Most of the prediction methods proposed in the body of the Report cannot fully reflect the effects of all the parameters producing and influencing the different propagation phenomena. This summary is therefore intended to give some idea as to the variability of the measured data, and to show where the data base available for deriving general conclusions is particularly sparse.

The data are presented in Tables and Figures in so far as possible in the same format as they were originally submitted to Study Group 5. For a discussion of the data, reference is made to the pertinent sections of the Report.

TABLE III - Statistical fading data predominantly due to scintillation and clear air low elevation - angle fading

Satellite and frequency	Location of measurements (latitude, longitude, height above mean sea level)	Antenna diameter	Elevation angle	Peak-to-peak amplitude exceeded for given percentages of					Period of measurement
				whole period			worst month		
				0.1%	0.3%	1%	0.1%	1%	
Anik-A, 4 et 6 GHz	Eureka, Canada	4.6 m	1°	-	-	-	20 dB	11 dB	(¹)
Intelsat-IV, 4 and 6 GHz	Goonhilly, UK		6.5°		3 dB		4 dB	3 dB	(2) 9 months
Intelsat-IV, 4 and 6 GHz combined	Goonhilly, UK Bahrain Yamaguchi, Japan	27.5 m	6.5° 9°				6 dB	5.2 dB	
7 GHz	Ottawa, Canada	9.1 m	1°	-	-	15 dB	-	-	(3) Summer period
			2-3°	-	-	8 dB	-	-	
			5°	5.5 dB	-	2.8 dB	-	-	
OTS, 11.8 GHz	Svalbard, Norway	3 m	3.2°	-	-	-	6.5 dB	3.4 dB	April-December 1979 - June-August 1980 (⁴)

(¹) [Nowland *et al.*, 1977].(²) [Harris, 1977].(³) [Webber and McCormick, 1980].(⁴) [Gutteberg, 1981a].

TABLE IVa - Annual attenuation statistics for the 11-14 GHz band

Location (latitude, longitude, height above mean sea level)	Frequency (GHz) polarization	Elevation angle	Time period	Attenuation (dB) (rain rate (mm/h) exceeded for given %)				References
				1 %	0.1 %	0.01 %	0.001 %	
Waltham, USA	11.7 circ.	24°	February 1977-January 1978 February 1978-January 1979	<1	2.5	10.5	(23)	[Nackoney, 1979]
Holmdel, USA	11.7 circ.	27°	June 1976-June 1977 June 1977-June 1978 June 1978-June 1979	<1 <1 <1	3 3 2.5	13.5 13.5 9.2	- - 29	[Arnold <i>et al.</i> , 1980a]
Greenbelt, USA	11.7 circ.	29°	July 1976-June 1977 July 1977-June 1978 July 1978-June 1979	<1 <1 <1	1.8 2.1 1.8	8.8 12 14	>30 26.4 29.2	[Ippolito, 1979]
Blacksburg, USA	11.7 circ.	33°	January 1978-December 1978 January 1977-December 1977	2 2	3.7 4	6.8 13	13 24	[Bostian <i>et al.</i> , 1979]
Austin, USA	11.7 circ.	49°	February 1978-January 1979	<1	3	13	23	[Vogel, 1979]
Munich, Germany	11.6 lin.	29°	January 1978-December 1978 (91.2% coverage)	3	6.8	-	-	[Dosch, 1979]
Fucino, Italy (41°50'N, 13°36'E, 650 m)	11.6 circ.	33°	January 1978-December 1980	<1	1.7	4.8	12	[Attisani <i>et al.</i> , 1980]
Lario, Italy (46°10'N, 9°25'E, 210 m)	11.6 circ.	32°	January 1978-December 1980	<1	2.7	8	16	[Attisani <i>et al.</i> , 1980]
Spino d'Adda, Italy (45°25'N, 85 m)	11.6 circ.	32°	October 1978-September 1980	<1	2.7	6.8	12	[Attisani <i>et al.</i> , 1980]
Gometz-la-Ville, France (48.7°N, 2.1°E, 170 m)	11.6 cir.	32°	November 1977-November 1978	1.3	3.7 (7)	6.3 (18)	8.5 (38)	[Ramat, 1981]
	11.8 circ.	33.6°	January 1979-November 1979	<1	2.5 (9)	5 (22)	10.5 (52)	
Nederhorst Den Berg, Netherlands	11.6	27.5°	August 1975-October 1975 April 1976-June 1977 (8100 hours)	0.8	1.5	3.2	6	[Neessen and Reinders, 1979]
Kjeller, Norway	11.6 lin.	22°	May 1980-September 1980	0.8 (3)	2.1 (15)	6.9 (40)	12.6 (75)	[Gutteberg, 1981b]
Bergen, Norway	11.6 lin.	21°	May 1979-September 1979	1.7	3.4	6.4	10.1	[Gutteberg, 1981b]
Trondheim, Norway	11.6 lin.	18°	May 1979-July 1979	0.9	2.0	4.1		[Gutteberg, 1981b]

TABLE IVa - (continued)

Location (latitude longitude, height above mean sea level)	Frequency (GHz) polarization	Elevation angle	Time period	Attenuation (dB) (rain rate (mm/h) exceeded for given %)				References
				1 %	0.1 %	0.01 %	0.001 %	
Eik, Norway	11.6 lin.	23°	April 1980-June 1980	1.0	2.0	4.2		[Gutteberg, 1981b]
Leeheim, Germany (Federal Republic of) (49.9°N, 8.4°E, 86 m)	11.6 lin.	32.9°	January 1979-December 1980	<1	1.1	5.7	13.8	[Dintelmann, 1982]
Slough, UK	11.8 circ.	30.3°	July 1978-August 1980	-	<3	4.3	16	[Davies <i>et al.</i> , 1981]
Slough, UK	11.6 circ.	29.5°	September 1977-August 1980	-	<3	3	9	
Martlesham, UK	11.8 lin.	29.9°	July 1978-June 1980	-	<3	3.7	7.2	[Thirlwell and Howell, 1981]
Martlesham, UK	11.8 circ.	29.9°	July 1978-June 1980	-	<3	5.6	10.4	
Kashima, Japan (35.6°N, 140.4°E, 40 m)	11.7	37°	August 1978-July 1980	<1 (4)	2 (14)	7 (37)		[Fukuchi <i>et al.</i> , 1981a]
	11.5	47°	May 1977-April 1978	<1 (5)	2.5 (18)	6.2		[Fugono, 1979]
Wakkanai, Japan (45.2°N, 141.4°E, 60 m)	12.1	29°	1 year	<1 (2.5)	1.7 (9.9)	2.9 (20.3)	8.0 (52.1)	[Ishizuka <i>et al.</i> , 1981]
Yamagawa, Japan (31.1°N, 130.3°E, 80 m)	12.1	47°	July 1979-June 1980	1 (7)	3 (39)	8 (>50)		
Kasennuma, Japan (31.5°N, 141.3°E, 10 m)	12.1	34°	1 year	0.8 (3.6)	2.4 (12.9)	5.9 (33.7)	10.6 (71.6)	[Otsu <i>et al.</i> , 1979]
Osaka, Japan (34.4°N, 135.3°E, 40 m)	12.1	41°	1 year	1.7 (5.1)	5.6 (26.0)	15.1 (57.3)	- (85.5)	
Owase, Japan (34.0°N, 136.1°E, 10 m)	12.1	42°	1 year	1.6 (13.3)	11.5 (61.0)	>20		
Matsue, Japan (35.3°N, 133.0°E, 20 m)	12.1	42°	1 year	1.3 (4.7)	4.3 (21.8)	13.3 (54.0)	(87.5)	
Ogasawara, Japan (27.0°N, 142.1°E, 50 m)	12.1	43°	1 year	1.0 (3.6)	3.1 (22.6)	7.9 (67.7)	11.0 (118.7)	

TABLE IVa - (continued)

Location (latitude, longitude, height above mean sea level)	Frequency (GHz) Polarization	Elevation angle	Time period	Attenuation (dB) (rain rate (mm/h) exceeded for given %)				References
				1%	0.1%	0.01%	0.001%	
Ashizuyi, Japan (32.5°N, 135.9°E, 100 m)	12.1	45°	1 year	1.9 (7.3)	5.0 (31.0)	10.2 (71.1)	13.6 (107.7)	[Otsu <i>et al.</i> , 1979]
Izuhara, Japan (34.2°N, 129.2°E, 430 m)	12.1	45°	1 year	0.7 (6.2)	2.1 (22.0)	4.9 (47.3)	8.6 (76.3)	
Minamidaito, Japan (25.5°N, 131.0°E, 190 m)	12.1	52°	1 year	1.4 (3.1)	6.0 (22.9)	16.7 (75.7)	>20 (113.2)	
Yonaguni, Japan (24.3°N, 122.4°E, 200 m)	12.1	58°	1 year	2.7 (5.6)	8.1 (37.8)	14.3 (82.8)	16.7 (117.1)	

TABLE IVb - Annual attenuation statistics for the 18-22 GHz band

Location (latitude, longitude, height above mean sea level)	Frequency (GHz) polarization	Elevation angle	Time period	Attenuation (dB) (rain rate (mm/h) exceeded for given %)				References
				1%	0.1%	0.01%	0.001%	
Holmdel, USA	19 lin.	18.5°	June 1976-June 1977	2.3	12	>40	-	[Lin <i>et al.</i> , 1980]
Grant Park, USA	19 lin.	27.3°	July 1976-June 1977	-	9.5	>30	-	
Palmetto, USA	19 lin.	29.9°	June 1976-July 1977	-	10	>28	-	
Waltham, USA	19 lin.	35.3°	January 1978-December 1978 ⁽¹⁾	<2	3.5	29	-	[Tang, 1979]
Holmdel, USA	19 lin.	38.6°	May 1977-May 1978	1	6.5	22	>44	[Lin <i>et al.</i> , 1980]
Grant Park, USA	19 lin.	41.8°	August 1977-August 1978	-	9	>30	-	
Blacksburg, USA	19 lin.	45°	January 1978-December 1978 January 1979-December 1979 ⁽²⁾	1.7 2	4.9 5	11.3 13.5	24.5 25	[Bostian <i>et al.</i> , 1979]
Palmetto, USA	19 lin.	49.5°	August 1977-August 1978	-	9	>30	-	[Lin <i>et al.</i> , 1980]
Austin, USA	19 lin.	52°	October 1978-October 1979	1	7.2	23	-	[Kaul <i>et al.</i> , 1980]
Tampa, USA	19 lin.	54.5°	January 1978-December 1978 January 1979-December 1979	- <1	21 >30	- -	- -	[Tang, 1979]
Kashima, Japan (35.6°N, 140.4°E, 40 m)	19.5	48°	April 1978-March 1980	2 (4)	6 (14)	17 (35)		[Fukuchi <i>et al.</i> , 1981a]
Yokosuka, Japan (35.1°N, 139.4°E, 105 m)	19.5	48°	April 1978-March 1980	3 (5)	7 (16)	27 (57)		[Sato <i>et al.</i> , 1981]
Yokohama, Japan (35.2°N, 139.4°E, 20 m)	19.5	48°	April 1978-March 1980	4 (5)	8 (17)	16 (49)		
Wakkanai, Japan (45.2°N, 141.4°E, 60 m)	19.5	37°	1 year	<1 (2.5)	2.9 (10)	8.4 (28.4)	14.3	[Ishizuka <i>et al.</i> , 1981]
Yamagawa, Japan (31.1°N, 130.3°E, 80 m)	19.5	53°	1 year	2 (7)	10 (34)	17 (50)		
Sendai, Japan (38.2°N, 140.5°E, 65 m)	19.5	45°	April 1979-March 1980	3 (4)	6 (12)	18 (38)		[Sato <i>et al.</i> , 1981]

⁽¹⁾ September excluded.⁽²⁾ February excluded.

TABLE IVc - Annual attenuation statistics for the 28-35 GHz band

Location	Frequency (GHz) polarization	Elevation angle	Time period	Attenuation (dB) (rain rate (mm/h) exceeded for given %)				References
				1%	0.1%	0.01%	0.001%	
Grant Park, USA	28.6 lin.	27.3°	July 1976-June 1977	-	17	-	-	[Lin <i>et al.</i> , 1980]
Palmetto, USA	28.6 lin.	29.9°	June 1976-July 1977	-	20	-	-	
Waltham, USA	28.6 lin.	35.3°	January 1978-December 1978 ⁽¹⁾	<2	7.5	>30	-	[Tang, 1979]
Holmdel, USA	28.6 lin.	38.6°	May 1977-May 1978	3.5	14.5	44	-	[Lin <i>et al.</i> , 1980]
Wallops Island, USA	28.6 lin.	41.6°	April 1977-March 1978	2.3	12.5	-	-	[Goldhirsh, 1979]
Grant Park, USA	28.6 lin.	41.8°	August 1977-August 1978	-	20	-	-	[Lin <i>et al.</i> , 1980]
Blacksburg, USA	28.6 lin.	45°	January 1978-December 1978 January 1979-December 1979 ⁽²⁾	5 4	11.8 8.5	24 25	- -	[Bostian <i>et al.</i> , 1979]
Palmetto, USA	28.6 lin.	49.5°	August 1977-August 1978	-	18	-	-	[Lin <i>et al.</i> , 1980]
Austin, USA	28.6 lin.	52°	October 1978-October 1979	1.5	17	-	-	[Kaul <i>et al.</i> , 1980]
Kashima, Japan	34.5	47°	May 1977-April 1978	5 (5)	19.5 (18)	-	-	[Fugono, 1979]

⁽¹⁾ September excluded.

⁽²⁾ February excluded.

Note. -Results obtained during the European ATS-6 campaign are also of interest to system planning. However, as these data are scanty due to limited allocation of satellite time to these experiments, and due to the fact that this period (August 1975 - August 1976) was exceptionally dry, these data must be regarded with due caution, and are not given in the Table. These European ATS-6 results are summarized in ESA SP-131 (October 1977).

TABLE V – Worst month attenuation data: W. Europe
Radiometric observations at 11.4 GHz, $\theta = 20^\circ$ - 45°

Time % of worst month (%)	90% of cases (dB)	50% of cases (dB)	10% of cases (dB)
20	0.3	0.4	0.6
5	0.4	0.6	0.9
1	0.9	1.1	1.4
0.3	1.2	1.8	2.4
0.1	1.5	3.3	6.0
0.03	3.1	7.3	11.0

TABLE VIa – Fade duration statistics for 5 dB fades
Radiometric observations at 11.4 GHz

Fade duration	Fraction of total fading time at a given location							
	1	2	3	4	5	6	7	8
>1 min	1.0	0.93	0.95	0.97	0.98	0.93	0.89	0.97
>3 min	1.0	0.78	0.85	0.76	0.96	0.76	0.42	0.90
>10 min	0.74	0.39	0.49	0.25	0.69	0.48	-	0.61
>30 min	-	-	-	-	0.36	-	-	0.07
No. of events	4	51	31	51	28	43	44	110
No. of years	2	4	4	6	2	2	3	6

Locations

1. Leuk, Switzerland	1975-1976, elevation 35°
2. Fucino, Italy	1973-1976, elevation 42°
3. Leeheim, Germany (Federal Republic of)	1973-1976, elevation 33°
4. Stockholm, Sweden	1973-1979, elevation 21°
5. Milano, Italy	1973-1974, elevation 37°
6. Milo, Italy (Sicily)	1979-1980, elevation 46°
7. Porto, Portugal	1974-1980, elevation 40°
8. Graz, Austria	1974-1980, elevation 37°

TABLE VIb - *Fade duration at 11.6 GHz*
(SIRIO experiment, Italy)

Fade duration (seconds)	Fraction of total fading time for given fade level		
	3 dB	10 dB	15 dB
> 10	97%	95%	90%
> 50	90%	85%	74%
>100	87%	78%	65%
>300	72%	48%	0%

TABLE VIc - *Annual duration statistics of attenuation*

Fade duration (minutes)	Fraction of total fading time for given fade level					
	3 dB	6 dB	10 dB	15 dB	20 dB	25 dB
>0.3	100%	100%	100%	100%	100%	100%
>1	72.6	84.7	39.8	≈90	≈90	≈90
>3	56.6	66.5	75.9	70.7	67.1	67.6
>10	36.1	46.2	54.3	32.2	41.1	56.8
>30	17.3	31.8	28.1	10.0	27.4	-
>60	13.3	14.8	3.5	-	-	-
Total fading time (minutes/year)	6833	2628	946	239	73	37

Frequency: 13.9 GHz

Elevation angle: 10°

Period: June 1975-May 1980 (except for June 1977-May 1978)

Location: Ibaraki, Japan

TABLE VII – Annual XPD statistics based on measurements

Location (latitude, longitude, height above mean sea level)	Frequency (GHz)	Elevation angle	Polarization C,L (°)	Time period	XPD/CPA (Rain rate) Corresponding to given %			Nominal clear-sky XPD	References
					0.001%	0.01%	0.1%		
Blacksburg, USA	11.7	33°	C	1/78-12/78 1/79-7/79	14/13 16/-	20/6.8 21/-	22/3.7 24.5/-	≥30 ≥30	[Bostian, 1980]
Austin, USA	11.7	49°	C	6/76-6/79 (three years)	15/-	20.5/-	28/-	≥40	[Vogel, 1979]
Holmdel, USA	19 19	39° 39°	L (21°) L (69°)	5/77-5/78 5/77-5/78	>10/>44 >10/>44	16/22 18/22	24/6.5 25/6.5	>35 >35	[Arnold <i>et al.</i> , 1980b]
Holmdel, USA	28.6	39°	L (69°)	5/77-5/78	-	12/44	22/14.5	>35	[Arnold <i>et al.</i> , 1980b]
Blacksburg, USA	28.6	45°	L (60°)	1/78-12/78 1/79-6/79	9.5/- 7/-	13/24 12.5/-	15/11.8 18/-		[Bostian, 1980]
Yamaguchi, Japan (36.5°N, 140.5°E, 57 m)	4.1	9°	C	8/75-7/77	5/- (110)	11/- (67)	16/- (24)		[Kurihara <i>et al.</i> , 1979]
Ibaraki, Japan (34.1°N, 131.4°E, 111 m)	4.1	35°	C	4/76-3/77	27/- (88)	32/- (46)	36/- (19)		[Kurihara <i>et al.</i> , 1979]
	6.3	35°	C	4/76-3/77	25/- (88)	28/- (46)	33/- (19)		
Kashima, Japan (35.6°N, 140.4°E, 40 m)	11.5	47°	C	5/77-4/78	-	24/5.3 (45)	29/2.5 (18)	20	[Fukuchi <i>et al.</i> , 1981a]
	19.5	48°	C	8/79-7/80	-	20/- (31)	26/- (13)		[Fukuchi <i>et al.</i> , 1981b]
Yokohama, Japan (35.2°N, 139.4°E, 20 m)	19.5	48°	C	4/79-3/80	-	17/16 (49)	21/8 (17)		[Sato <i>et al.</i> , 1981]
Kashima, Japan (35.6°N, 140.4°E, 40 m)	34.5	47°	C	5/77-4/78	-	17/- (45)	22/19.5 (18)	17	[Fujita <i>et al.</i> , 1980]
Leeheim, Germany (Federal Republic of) (86 m)	11.6	32.9°	C	1/79-12/80	14/14.3 ()	20/5.7 ()	28/1.1 ()		[Dintelmann, 1982]
Albertslund, Denmark (33 m)	11.8	26.5°	C	1/79-12/79	17/4.9 (66)	23/2.1 (17)	>28/0.8 (7)	35	[Larsen, 1980]
	14.5	26.5°	C	1/79-12/79	13/7.8 (66)	18/3.8 (17)	26/1.4 (7)	35	

TABLE VII - (continued)

Location (latitude, longitude, height above mean sea level)	Frequency (GHz)	Elevation angle	Polarization C,L (τ°)	Time period	XPD/CPA (Rain rate) Corresponding to given %			Nominal clear-sky XPD	References
					0.001 %	0.01 %	0.1 %		
Svalbard, Norway (7 m)	11.8	3.4°	C	4/79-8/79 mainly sleet and snow		20/7	22/5	35	[Gutteberg, 1981b]
Martlesham, UK	11.6	29.9°	L (8°)	7/78-7/80	28/-	30/-	-		[Thirlwell and Howell, 1981]
	11.8	29.9°	C	7/78-7/80	19/-	22/-	-		
Martlesham, UK	14.5	29.9°	C	7/78-7/80 some events missing, for comparison	17/-	20/-	-		[Thirlwell and Howell, 1981]
	11.8	29.9°	C		18.7/-	24/-	-		
Gometz-la-Ville, France (170 m)	11.6	32°	C	11/77-11/78	17/8.5 (38)	22/6.3 (18)	27/3.7 (7)		[Ramat, 1981]
	11.8	33.6°	C	1/79-11/79	16/10.5 (52)	22/5 (22)	28/2.5 (9)		

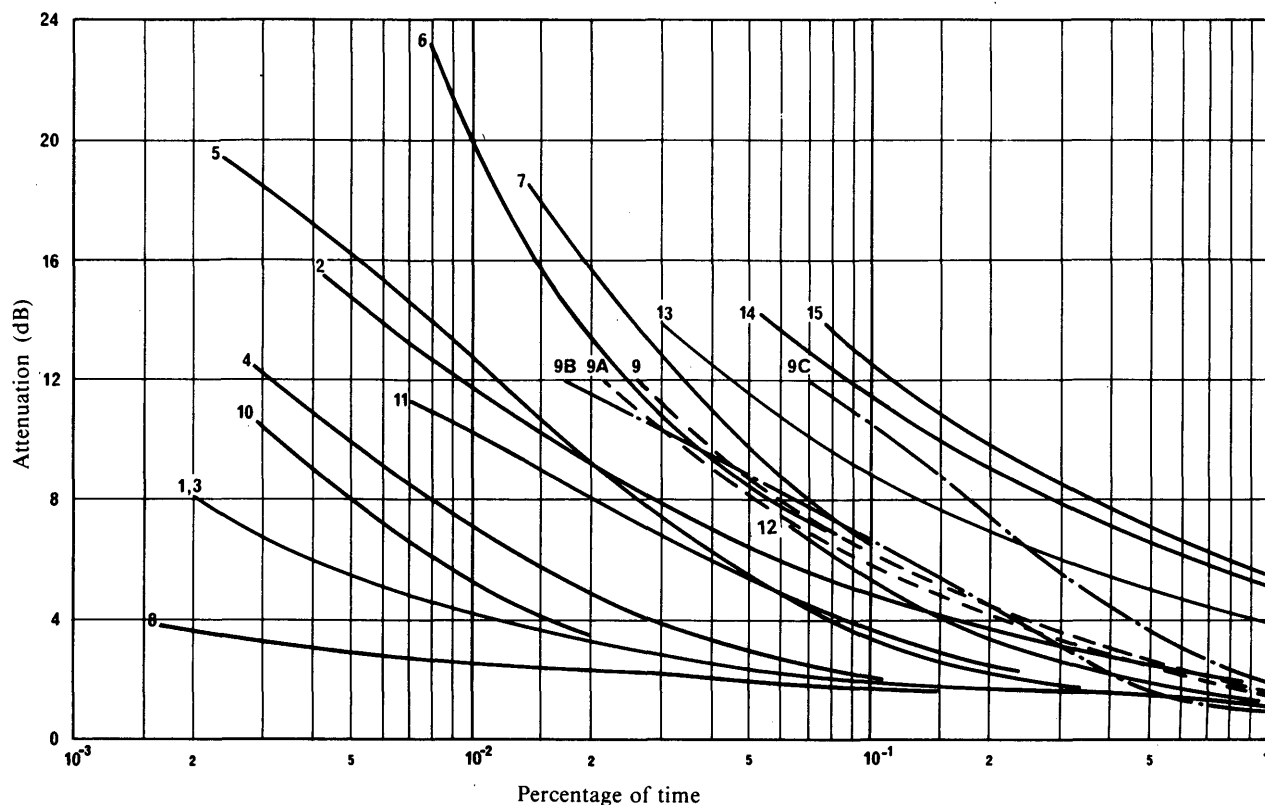


FIGURE 4 — Radiometric measurements of attenuation on Earth-space paths

$f = 9.4$ to 19 GHz

1 Slough, UK	12 GHz $\theta = 30^\circ$	[Allnutt, 1976]
2 Slough, UK	19 GHz $\theta = 10^\circ$ to 50°	[Davies, 1973 and 1975]
3 Toyokawa, Japan	9.4 GHz $\theta = 45^\circ$	[Kinase and Kimpara, 1969]
4 Setagaya, Japan	11.8 GHz $\theta = 45^\circ$	[Kinase and Kimpara, 1973]
5 Mitaka, Japan	17 GHz $\theta = 45^\circ$	[Makino, 1971]
6 Klang, Malaysia	11.8 GHz $\theta = 45^\circ$	
7 New Jersey, USA	16 GHz $\theta = 30^\circ$	
8 Lake Cowichan, Canada	13 GHz $\theta = 33^\circ$	
9 Innisfail, Australia	11 GHz $\theta = 30^\circ$ (December 74 – October 76)	[Jenkinson, 1975 and 1977]
9A Innisfail, Australia	11 GHz $\theta = 45^\circ$ (November 76 – April 79)	[Jenkinson, 1975 and 1977]
9B Darwin, Australia	11 GHz $\theta = 60^\circ$ (wet season only)	[Flavin, 1978]
9C Darwin, Australia	14 GHz $\theta = 60^\circ$ (November 77 – April 79)	[Flavin, 1978 and 1980]
10 Leeheim, Fed. Rep. of Germany	11 GHz $\theta = 27^\circ$	[Dintelmann and Rucker, 1977]
11 Maryland, USA	11.6 GHz $\theta = 45^\circ$	
12 West Virginia, USA	11.6 GHz $\theta = 18^\circ$	[Rogers and Hyde, 1979]
13 Marugame, Japan	11.9 GHz $\theta = 6^\circ$	
14 Hamada, Japan	11.9 GHz $\theta = 8.4^\circ$	
15 Yamaguchi, Japan	11.9 GHz $\theta = 9.2^\circ$	[Yasukawa and Yamada, 1981]

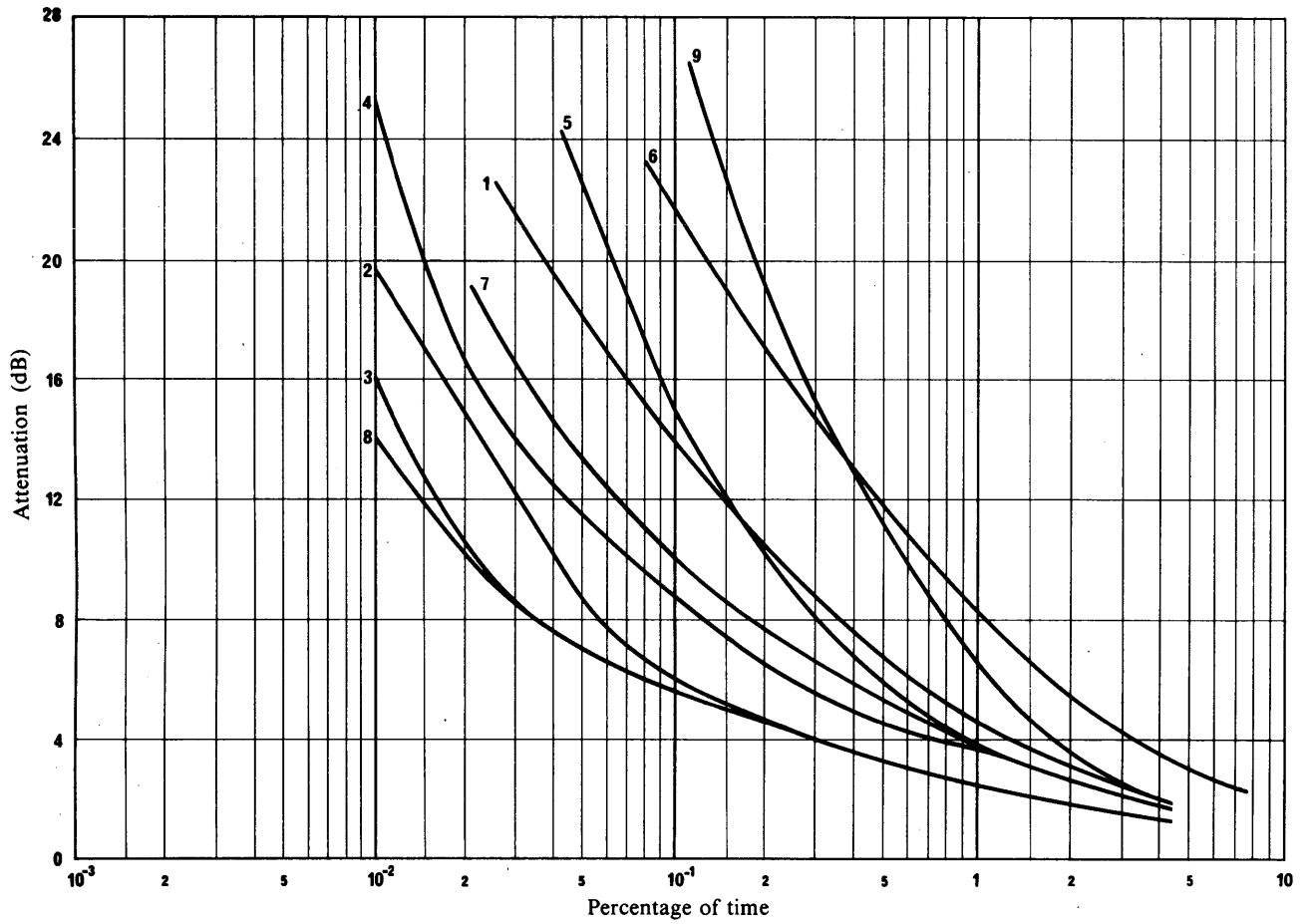


FIGURE 5 — Radiometric measurements of attenuation on Earth-space paths
 $f = 20$ to 37 GHz

1	Slough, UK	37	GHz $\theta = 5^\circ$ to 15°
2	Slough, UK	37	GHz $\theta = 45^\circ$ to 55°
3	Martlesham, UK	20	GHz $\theta = 23^\circ$
4	Martlesham, UK	30	GHz $\theta = 23^\circ$
	Langley, UK	30	GHz $\theta = 22^\circ$
	Winkfield, UK	30	GHz $\theta = 23^\circ$
5	Tokyo, Japan	23	GHz $\theta = 45^\circ$
6	Gotemba, Japan	35	GHz $\theta = 45^\circ$
7	Mt. Fuji, Japan	35	GHz $\theta = 45^\circ$ (site altitude 3.8 km)
8	Paris, France	20	GHz $\theta = 23^\circ$ to 39°
9	New Jersey, USA	30	GHz $\theta = 5^\circ$ to 70° (average of data)

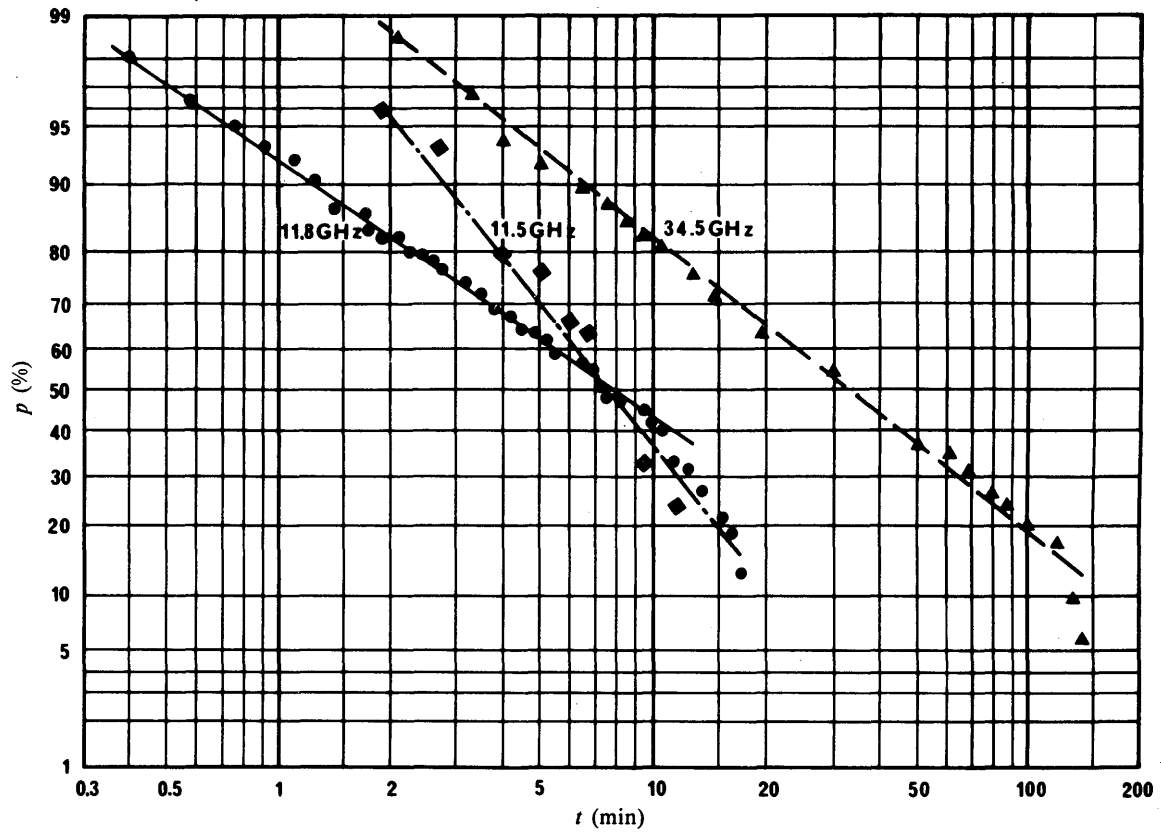


FIGURE 6 - Cumulative distribution of duration of co-polar attenuation exceeding 5 dB

t : duration of CPA events ≥ 5 dB

p : conditional probability (percentage of total 5 dB fading time)

▲■: ETS-II, measured in Japan, May 1977 - April 1978

●: OTS, measured in W. Europe, July 1978 - December 1980 (7 stations)

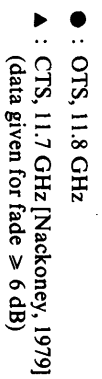


FIGURE 7 – Cumulative distribution of fade slopes for fades exceeding 5 dB

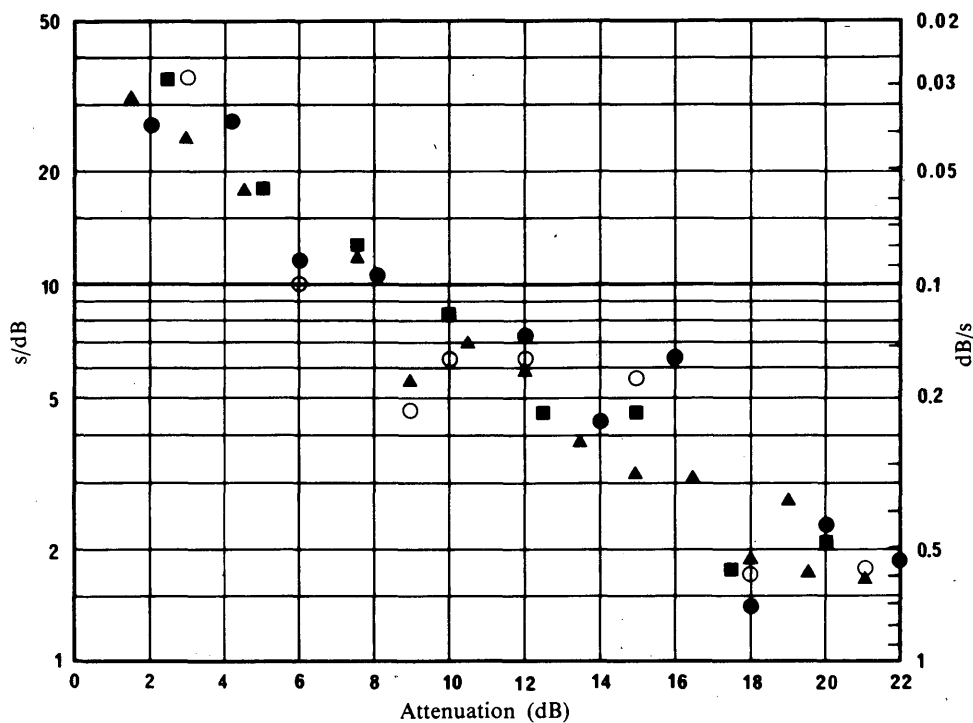


FIGURE 8 — Mean values of positive rates in dB/s (right scale) and in s/dB (left scale) versus attenuation for the indicated values of the incremental threshold ΔS [CCIR, 1978–82a]

- ▲ $\Delta S = 1.5 \text{ dB}$
- 2
- 2.5
- 3

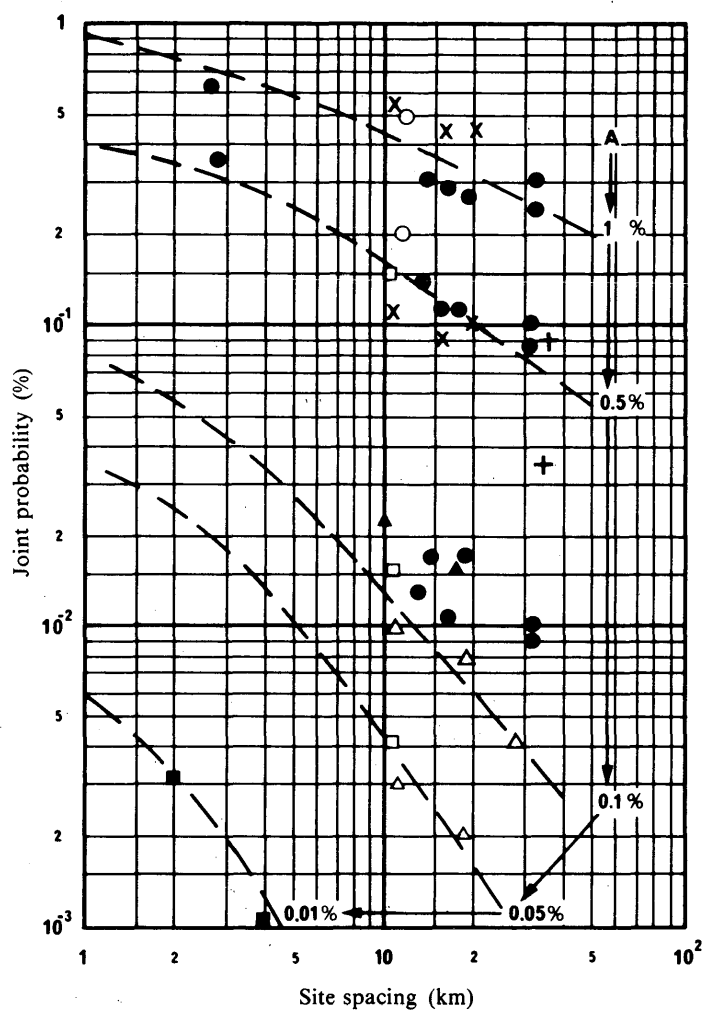


FIGURE 9 — Probability of attenuation being exceeded simultaneously at 2 diversity sites as a function of spacing

- Japan (17–35 GHz) [Funakawa and Otsu, 1974 ; Morita and Higuti, 1978 ; Hosoya *et al.*, 1980]
 - Slough (30 GHz) [Davies, 1976]
 - ▲ Slough (37 GHz) [Davies, 1976]
 - △ New Jersey (16 GHz) [Wilson and Mammel, 1973]
 - Slough (11.6) [Allnutt, 1976 and 1977]
 - Austin, Texas (30 GHz)
 - x Florida, USA (19 GHz) [CCIR, 1978–82b]
 - + West Virginia, USA (11.6 GHz) [Rogers and Hyde, 1979]
- (Note. — The data points refer to 1.0 and 0.5%)
- A Corresponding single-site percentage (in %)
- — — Predicted values from Fig. 2 of this Report

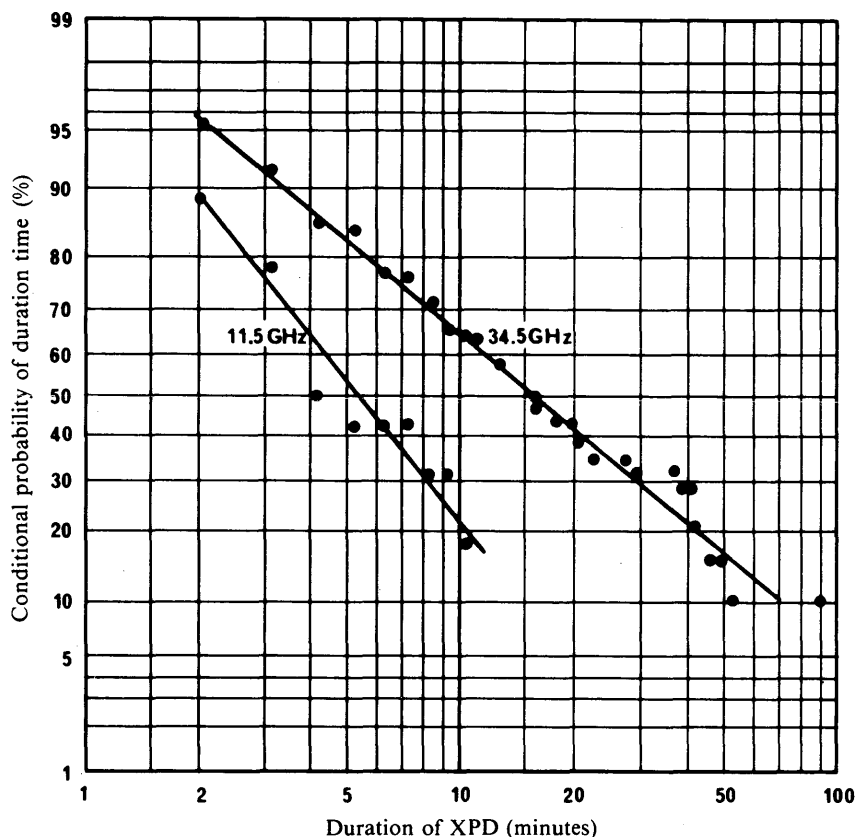


FIGURE 11 — Conditional probability of duration time for which cross-polarization discrimination is not exceeded for 25 dB

(Elevation angle of 47° (ETS—II), May 1977—April 1978)

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CCIR Documents

[1978-82]: a. 5/337 (Italy); b. 5/261 (United States of America).

REPORT 565-2 *

PROPAGATION DATA FOR BROADCASTING FROM SATELLITES **

(Study Programme 7B/5)

(1974-1978-1982)

1. Introduction

Broadcasting by satellites leads to problems that are not entirely comparable with those occurring in the fixed-satellite service. Attenuation data are needed in the form of statistical averages and/or contour maps of attenuation and depolarization for large areas. Specific problems may arise at the margin of the service area and, in the case of coordination, between satellite broadcasting systems, on the one hand, and terrestrial or space fixed services on the other. This Report gathers related data in order to facilitate planning of satellite broadcasting systems. Some data for satellite broadcasting system planning are also included in Report 564. Note that feeder links are considered to be part of fixed-satellite services and, as such, it is appropriate to treat feeder links using the methods and data of Report 564.

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

** For a full discussion of the worst month, see Report 723.

2. Attenuation

Attenuation of broadcasting signals can arise due to absorption by the gases in the atmosphere and to the effects of rain and other hydrometeors.

2.1 Attenuation in the gaseous atmosphere

Figure 1 gives the theoretical one-way attenuation at the zenith (elevation angle $\theta = 90^\circ$) through the atmosphere for a moderately humid atmosphere (7.5 g/m^3 of water vapour) over the frequency range from 1 to 30 GHz. Below 1 GHz, attenuation due to the gaseous atmosphere may be considered statistically negligible in the satellite broadcasting service. For the range of water vapour concentration 1 to 20 g/m^3 , scaling of attenuation as a linear function of water vapour content is a useful approximation. Similarly, for the range of elevation angles $5^\circ < \theta \leq 90^\circ$, cosecant θ scaling may be used in conjunction with the curve in Fig. 1 (for $\theta = 90^\circ$). More precise methods are spelled out in Report 719.

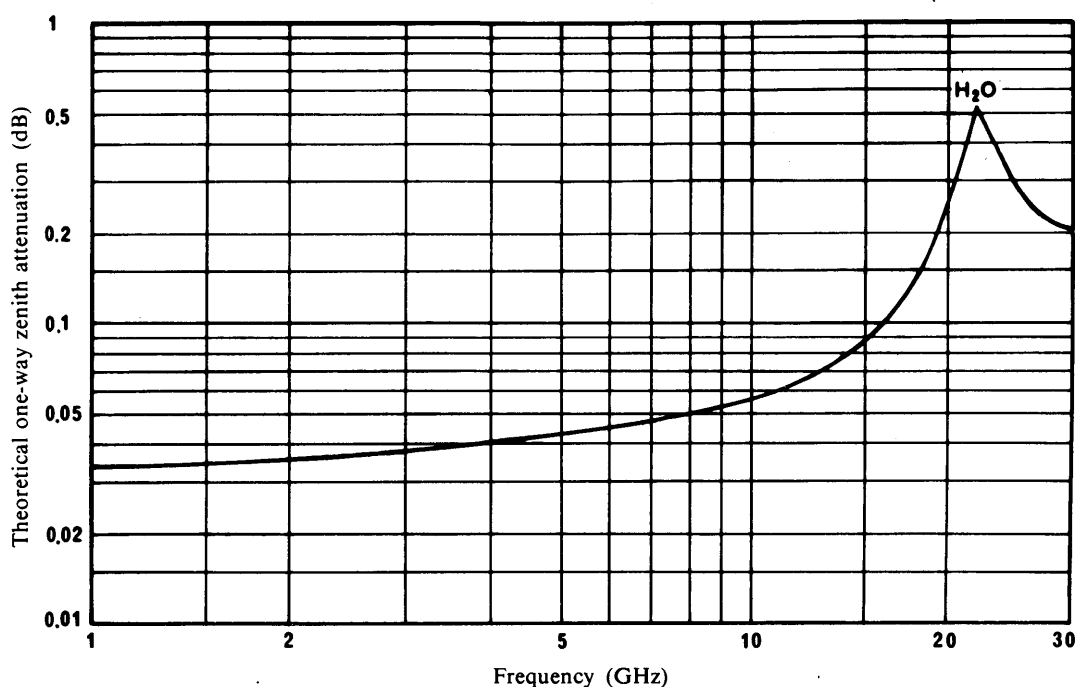


FIGURE 1 – Theoretical vertical one-way attenuation due to a moderately humid atmosphere (7.5 g/m^3 at the surface)

2.2 Attenuation due to rain

Attenuation due to rain is statistically not significant for broadcasting frequencies below 3 GHz. For frequencies above 10 GHz, attenuation due to rain is often the dominant impairment. Report 563 contains information on rainfall around the world and may be used where local rainfall and rain-rate data is not available. Report 564 is referred to for further information on modelling and measured data.

2.2.1 Rain attenuation modelling

The following technique for prediction of rain-induced attenuation is suggested for percentage of time range from 1% to 0.01%. It derives from the work of Fedi [1981] as defined in Report 564, where in the text and in Fig. 1 the variables and parameters of this method are defined.

The proposed method consists of the following steps:

2.2.1.1 The vertical extent of the rain, rain height, h_R (see the footnote to § 6.1.2 of Report 564) is obtained from:

$$h_R = 5.1 - 2.15 \log \left(1 + 10^{\left(\frac{\varphi - 27}{25} \right)} \right) \quad \text{km} \quad (1)$$

where:

φ : latitude in degrees of the earth station.

2.2.1.2 The slant-path length, L_s , below the rain height is obtained from:

$$L_s = \frac{(h_R - h_0)}{\sin \theta} \quad \text{km; } \theta \geq 5^\circ \quad (2)$$

where:

h_0 : altitude (km) of earth station,

θ : elevation angle (degrees) of slant path.

2.2.1.3 The horizontal projection, L_G , of the slant-path length is found from (see Fig. 1 of Report 564):

$$L_G = L_s \cos \theta \quad \text{km} \quad (3)$$

2.2.1.4 The reduction factor, r_p , for 0.01% of the time can be calculated from:

$$r_p = \frac{90}{90 + 4 L_G} \quad (4)$$

2.2.1.5 Obtain the surface point rain intensity at the earth station exceeded for 0.01% of an average year, $R_{0.01}$ (with an integration time of 1 min). If this information cannot be obtained from local data sources, an estimate can be obtained from the maps of rain climates given in Report 563.

2.2.1.6 Obtain the specific attenuation, γ_R , using the coefficients given in Table I of Report 721 and the surface point rainfall rate, $R_{0.01}$, determined from step 2.2.1.5 by using:

$$\gamma_R = k(R_{0.01})^\alpha \quad \text{dB/km} \quad (5)$$

2.2.1.7 The attenuation exceeded for 0.01% of an average year may then be obtained from:

$$A_p = \gamma_R L_s r_p \quad \text{dB} \quad (6)$$

2.2.1.8 The attenuation exceeded for other percentages of an average year, in the range 0.01% to 1.0%, may be estimated from the attenuation exceeded for 0.01% of an average year by using:

for the range 0.01 to 0.1%:

$$A_p = 0.15 A_{0.01} p^{-0.41} \quad (7)$$

for the range 0.1 to 1.0%:

$$A_p = 0.13 A_{0.01} p^{-0.5} \quad (8)$$

It is believed that the deviation between experimental and predicted values in this method is of the order of 20% (see Report 721) (of the dB value). For greater precision between 0.1% and 1.0% of the time, the extension of the above method discussed in Report 564 is suggested. Equations (12) and (13) of Report 564 may be used for frequency scaling.

2.2.2 Measured data

The European Space Agency has been carrying out a series of radiometric measurements at nine different locations in Europe since 1972.

As a result of three years of measurements it became clear that, for angles of elevations between 20° and 45° , year-to-year variations in attenuation distributions are much larger than any systematic elevation dependence, and that in worst month attenuation values, no elevation dependence could be found.

Table I lists the results of a total of 31 attenuation distributions for the worst attenuation months of calendar years [Brussaard, 1977]. The values given are valid for the European part of Region 1. Although for the time being one does not have 10 years of measurements — which would be advisable for meteorological reasons — one may consider that the 50% values represent a mean year and that the 90% values represent the worst year over a 10-year period.

In Region 3, sun-tracking radiometric measurements have been carried out in Tokyo and Klang/Malaysia [Kinase and Kimpara, 1973].

TABLE I – Worst month attenuation observed at 11.5 GHz in Europe

Number of worst attenuation months out of 31 months	Attenuation not exceeded during	
	99% of the worst month in a calendar year	99.9% of the worst month in a calendar year
28 (90%)	1.6 dB	6.4 dB
16 (50%)	1.1 dB	3.2 dB
3 (10%)	0.8 dB	1.6 dB

TABLE II – Worst month attenuation observed at 11.8 GHz in Tokyo and Klang

Location of measurement	Period	Attenuation not exceeded during	
		99% of the worst month in an average year	99.9% of the worst month in an average year
Tokyo	1967-1973	0.9 dB	4.2 dB
Klang	Oct. 1970 Nov. 1972	1.7 dB	8.7 dB

Table II lists the results where measurements were corrected to an elevation angle of 45° by using the cosecant law.

Attenuation measurements have been carried out at 12 GHz in Japan since August 1978, using signals from the medium-scale broadcasting satellite for experimental purpose (BSE) in geostationary orbit at 110° East longitude [Otsu *et al.*, 1979].

Attenuation statistics were obtained at various locations for angles of elevation from about 30° to 60°. The measurements showed that the attenuation had a greater dependence on rainfall climate than on the angle of elevation.

TABLE III – Worst month attenuations observed with BSE at 12 GHz in Japan

	Attenuation (dB) not exceeded during	
	99% of the worst month in a calendar year	99.9% of the worst month in a calendar year
Worst attenuation	6.6	19.0
Moderate attenuation	2.4	6.9
Least attenuation	1.0	2.0

Table III lists the results of attenuation measurements for 12 to 14 months at 12 locations distributed all over Japan.

Measurements with the BSE when analyzed to obtain the statistics of duration of fades due to rain indicate that the distribution is approximately log normal. The results of the analysis are summarized in Table IV.

TABLE IV - Fade duration observed with BSE at 12 GHz in Japan

	Fade duration exceeded (minutes) at fade depth of 2 dB to 6 dB		
	90% of locations	50% of locations	10% of locations
50% of fades	2.6	3.6	4.9
10% of fades	11.0	16.5	25.0
Mean	4.9	7.3	11.0

Based on the rates of rainfall data for a number of years and a large number of stations in India, All India Radio has computed the attenuation caused by rainfall at 12 GHz for slant paths at an angle of elevation of 45° in the worst month for different percentages of locations [CCIR, 1978-82a]. The results compare favourably with the measurements made by the National Physical Laboratory, India, using sun-tracking radiometer, and are summarized in Table V.

TABLE V - Attenuation (measured and calculated) due to rain at 12 GHz for slant paths of 45° angle of elevation in the worst month for different percentages of time and locations in tropical areas

Parameters	Rain attenuation (dB) not exceeded for the indicated percentage of time					
	1%		0.1%		0.01%	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
50% of locations	1.6	2.02	8.5	8.02	15.7	12.2
90% of locations	4.3	4.81	11.6	9.99	> 18	> 13.4

The dependence on time of day, i.e. diurnal dependence, of the occurrence of deep fades is a significant consideration in the design of broadcasting-satellite systems. Attenuation measurements using the OTS signals at 11.6 GHz and 11.8 GHz were made in Brittany and near Paris. Analysis of these data showed a tendency towards increased fading in mid-morning and early evening [CCIR, 1978-82b]. Further results from these measurements can be found in Report 564. Measurements by the European Space Agency have also shown a slight tendency for deep fades to occur in the early evening. It should be noted, however, that measurements over a period of years are required at most European sites for the generation of reliable diurnal statistics.

3. Depolarization

Hydrometeors (principally ice particles and rain) may cause statistically significant depolarization to signals at frequencies above about 2 GHz. This subject is treated in detail in Reports 722 and 564. Summary information is given below.

The state of ice particle depolarization modelling and measurement is not adequate to provide definitive information at this time. However, depending upon climate, ice crystal depolarization may be the dominant depolarization mechanism for percentages of time greater than about 0.1%. Administrations are encouraged to provide additional information on this subject.

In predicting rain depolarization statistics from rain attenuation statistics, an equation of the form

$$XPD = U - V \log (CPA) \quad \text{dB} \quad (9)$$

can be used for both linear and circular polarizations (see Report 722). The following approximate forms for U and V appear to be in reasonable agreement with existing theory and available data.

$$U = \kappa^2 - 10 \log \frac{1}{2} \left[1 - \cos (4\tau) e^{-\kappa_m^2} \right] + 30 \log f - 40 \log (\cos \varepsilon) \quad (10)$$

$$\text{for } 8 \leq f \leq 35 \text{ GHz, and } 10^\circ \leq \varepsilon \leq 60^\circ$$

$$V = 20 \text{ for } 8 < f \leq 15 \text{ GHz; } \quad V = 23 \text{ for } 15 < f \leq 35 \text{ GHz} \quad (11)$$

where:

ε : angle of elevation,

τ : polarization tilt angle with respect to horizontal (for circular polarization $\tau = 45^\circ$),

κ, κ_m : effective parameters of the raindrop canting angle distribution in degrees.

The value of the parameter κ depends not only on meteorological factors discussed in Report 722, but also on elevation angle and the particular statistical relationship being fitted to the experimental data. In accounting for the effects of rain alone, a value of $\kappa = 0$ would appear to be conservative. Positive values of κ^2 have been observed, and are discussed in Report 722.

The second factor in equation (10) is the improvement of linear polarization with respect to circular polarization. A conservative value of $\kappa_m = 0.25^\circ$ is recommended at present. This gives a maximum improvement of 15 dB for $\tau = 0^\circ$ or $\tau = 90^\circ$.

Equation (18) of Report 564 may be used for frequency scaling.

4. Broadcasting from satellites at frequencies below 10 GHz

A simulation experiment was conducted in Paris in 1979 [Guilbeau, 1979] on FM sound broadcasting at 839 MHz, using a circularly-polarized transmitter on top of the Eiffel Tower. Field-strength measurements and subjective observations of car radio reception were conducted over an area in which the elevation angle and field strength were comparable to geostationary-satellite transmissions.

The field-strength fluctuations for an urban area (in the streets) were of the order of 15 dB. The same fluctuations were observed in measurements of field strength of the horizontally-polarized 100 MHz FM transmitters (also at the top of the Eiffel Tower). These fluctuations seem to be practically the same for reception using either horizontally or vertically polarized antennas. The sound quality appears to be unimpaired by the observed field-strength fluctuations under multipath conditions, even in narrow and unfavourably oriented streets.

In suburban and rural areas reflection from the ground may be a factor in determining the preferred polarization (Report 229) or [Hall, 1979] as the ground-reflected vertically-polarized wave experiences a deep null at the pseudo-Brewster's angle but the horizontally-polarized wave does not. Thus the horizontally-polarized ground-reflected wave will always be stronger than the vertically-reflected one for the smooth earth case and the sum of the direct and ground-reflected waves results in deeper null as well as higher peaks for the horizontally-polarized case relative to the vertically-polarized one.

5. Ionospheric effects

Ionospheric effects may be important, particularly at frequencies below about 3 GHz. For convenience these are calculated at frequencies of 500 MHz, 1 GHz, 3 GHz and 10 GHz and appear in Table VI for the maximum values given in the summary of Report 263.

6. Attenuation by buildings

Measurements have been made in the USA of the ATS-6 satellite signals received within private homes [Wells and Tryon, 1976]. Although the signal attenuation by timber-framed buildings showed little variation with weather or terrestrial elevation angle (3° to 56°), they did show a systematic variation with: frequency, polarization, construction materials, insulation, and position within the structure. See Table VII. A few limited measurements demonstrated that some insulating materials (aluminium-backed) and construction materials (such as in mobile homes) could contribute up to 20 dB. Further measurements are required to properly assess these and other residential building configurations.

TABLE VI - Estimated maximum* ionospheric effects for elevation angles of about 30° one-way traversal
(derived from Table VII, Report 263)

Effect	Frequency dependence	0.5 GHz	1 GHz	3 GHz	10 GHz	30 GHz ⁽¹⁾
Faraday rotation	$1/f^2$	1.2 rotation	108°	12°	1.1°	0.12°
Propagation delay	$1/f^2$	1 μ s	0.25 μ s	0.028 μ s	0.0025 μ s	0.28 μ s
Refraction	$1/f^2$	$\leq 2.4'$	$\leq 0.6'$	$\leq 4.2''$	$\leq 0.36''$	$\leq 0.04''$
Variation in the direction of arrival	$1/f^2$	48 sec. of arc	12 sec. of arc	1.32 sec. of arc	0.12 sec. of arc	0.013 sec. of arc
Absorption (auroral and/polar cap)	$\sim 1/f^2$	0.2 dB	0.05 dB	6×10^{-3} dB	5×10^{-4} dB	6×10^{-5} dB
Absorption (mid latitude)	$1/f^2$	< 0.04 dB	< 0.01 dB	< 0.001 dB	$< 10^{-4}$ dB	$< 1 \times 10^{-5}$ dB
Dispersion	$1/f^3$	0.0032 ps/Hz	0.0004 ps/Hz	1.5×10^{-5} ps/Hz	4×10^{-7} ps/Hz	1.5×10^{-8} ps/Hz

*This estimate is based on a total electron content (TEC) of 10^{18} electrons/m², which is a high value of TEC encountered at low latitudes in daytime with high solar activity (see Report 725).

⁽¹⁾ This column is included to show that ionospheric effects above 10 GHz are negligible.

TABLE VII - UHF signal attenuation (dB) through timber framed buildings

Building condition		Frequency (MHz) and polarization			
Exterior	Insulation (non-metallic type)	860 H	860 V	1550 V	2569 V
Wood siding	Ceiling only	4.7	2.9	5.0	5.8
	Ceiling and wall	6.3	4.5	6.6	7.4
Brick veneer	Ceiling only	5.9	4.1	6.2	7.0
	Ceiling and wall	7.5	5.7	7.8	8.6

The table is for rooms located nearby to the exterior wall; for interior rooms, a 0.6 dB should be added.

7. Additional information

For low elevation angles (less than 20°) higher attenuation values than those given in Table I can be encountered. Report 564 provides information for estimating the slant path attenuation for all areas of the world and for different elevation angles.

The frequency dependence of rain attenuation is treated in Report 721.

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REPORT 884 *

**PROPAGATION DATA FOR MARITIME AND
LAND MOBILE-SATELLITE SYSTEMS ABOVE 100 MHz**

(Study Programme 7C/5)

(1978-1982)

1. Introduction

Telecommunications over Earth-space links for maritime and land mobile-satellite systems lead to propagation problems that are substantially different from those arising in the use of satellites by the other services. For instance, the effects of reflections and scattering by the sea surface on received signals are quite severe, in particular where antennas with wide beamwidths are routinely installed. Furthermore, mobile-satellite systems may operate on a world-wide basis, including locations with low elevation angles.

This Report presents data and models specifically needed to characterize the sea-space path impairments. The propagation impairments addressed include:

- variations of the clear atmosphere including gaseous absorption, tropospheric refraction, scattering and scintillation occurring at low arrival angles over the sea and land surfaces;
- multipath effects including multipath due to secondary paths arising from the reflection of radio waves from the sea surface and from the reflection of radio waves from the urban, suburban and rural surfaces;
- effects of local environment (other antennas, buildings, towers and vehicles, ship structure, masts, stacks and cranes);
- ionospheric effects such as Faraday rotation and ionospheric scintillation in the gigahertz bands (see Report 263 (Volume VI)).

This Report covers the frequency range from 100 MHz through 10 GHz. Various frequency bands are allocated to satellite-to-mobile services throughout this frequency range but particularly the 121, 222, 420, 800, 1550 to 1650 and 7000 to 8000 MHz frequency bands. It should be noted that the physical environment affects propagation substantially differently over the range of frequencies considered by this Report. In particular, the treatment of multipath reflections by sea is different for the various frequency bands. More data are needed to improve the modelling and characterization of propagation impairments for sea-space links.

Cross references to other Reports in Sections 5C and 5F shall be used (as needed) as background information.

2. Propagation

2.1 Free-space attenuation

Free-space conditions apply beyond the ionosphere and the power loss is then solely due to the divergence of the radiation. The power loss of a link is a function of frequency, distance and the characteristics of the antennas at each end of the transmission link (see Recommendation 525).

* This Report is brought to the attention of Study Groups 4, 6 and 8.

2.2 *Tropospheric attenuation*

The upper end of the usable radio-frequency spectrum will be determined by the absorption caused by precipitation, clouds and gases in the atmosphere, so an upper frequency between 10 GHz and 20 GHz is required to provide high reliability under the worst conditions. Below about 3 GHz, except at extremely low elevation angles, tropospheric attenuation may be neglected.

Report 719 discusses calculation of gaseous absorption, not including rain. It should be noted that the gaseous absorption may be obtained by linear interpolation from the water vapour content from 0 to approximately 20 g/m³ and interpolation proportional to the cosecant of the elevation angle from 10° to 90°.

For frequencies less than 2 GHz, attenuation due to rain is less than 0.25 dB for statistically significant percentages of time and may be neglected. For higher frequencies refer to Report 564 for applicable attenuation prediction methods.

2.3 *Tropospheric ducting*

When meteorological conditions are such that a layer exists in the atmosphere in which the refraction index increases rapidly with height, radiation, originating in the layer at low angles of elevation, may be trapped and guided around the curved surface of the Earth. Under these conditions, abnormally good point-to-point ground communications are obtained at VHF, UHF and at microwave frequencies. This ducting also gives rise to severe interference from remotely sited co-channel stations.

A communication-satellite system may be severely affected under conditions of strong ducting, when transmissions from satellites at low angles of elevation may suffer complete refraction and never reach a receiver on the ground. However, in practice, it is believed that the angles of elevation of an operational aeronautical or maritime satellite system would be sufficiently large for this effect not to occur frequently.

2.4 *Ionospheric effects*

2.4.1 *General characteristics*

Ionosphere effects may be important, particularly at frequencies below 1 GHz. For convenience these are calculated for frequencies of 0.1, 0.25, 0.5, 1.0, 3.0 and 10.0 GHz and appear in Table I for the maximum values given in the summary of Report 263 [ICAO ASTRA PANEL IV, 1971; Lawrence *et al.*, 1964; Schachne, 1970].

2.4.2 *Ionospheric attenuation*

The lower limit of the usable radio-frequency spectrum will be determined by ionospheric reflection and absorption which, in general, increase with decreasing frequency. For equatorial and temperate regions a lower frequency limit of about 70 MHz will assure penetration of the ionosphere without significant attenuation for better than 95% of the time.

In addition to the diurnal and seasonal variations which occur in the ionosphere there are sporadic variations. These sporadic variations have the greatest effect in the auroral zones and must be allowed for in planning a service for a region which overlaps these zones.

Report 263 should be consulted for more comprehensive information on ionospheric attenuation.

2.4.3 *Scintillation*

Scintillations occur when radio waves pass through the ionosphere and significant irregularities of electron density are present. The consequent variations of the refractive index give rise to variations of amplitude and phase. These fluctuations decrease as frequency is increased and depend upon path geometry, location, season, solar activity and local time. This dependence is discussed in a number of texts, particularly Report 263.

In equatorial and mid-latitude regions there is a marked diurnal variation, with increases in scintillation amplitude of several times the normal daylight values occurring during the hours around midnight, local time. Such diurnal variations are not evident in polar cap regions. However, the diurnal variation is evident at lower polar latitudes particularly during "quiet" periods.

TABLE I – Estimated maximum* ionospheric effects for elevation angles of about 30° one-way trasversal
(derived from Table VI, Report 263)

Effect	Frequency dependence	0.1 GHz	0.25 GHz	0.5 GHz	1 GHz	3 GHz	10 GHz
Faraday rotation	$1/f^2$	30 rotations	4.8 rotations	1.2 rotations	108°	12°	1.1°
Propagation delay	$1/f^2$	25 μ s	4 μ s	1 μ s	0.25 μ s	0.028 μ s	0.0025 μ s
Refraction	$1/f^2$	$\leq 1^\circ$	$\leq 0.16^\circ$	$\leq 2.4'$	$\leq 0.6'$	$\leq 4.2''$	$\leq 0.36''$
Variation in the direction of arrival	$1/f^2$	20 min of arc	3.2 min of arc	48 sec of arc	12 sec of arc	1.32 sec of arc	0.12 sec of arc
Absorption (auroral/and polar cap)	$\sim 1/f^2$	5 dB	0.8 dB	0.2 dB	0.05 dB	6×10^{-3} dB	5×10^{-4} dB
Absorption (mid-latitude)	$1/f^2$	<1 dB	<0.16 dB	<0.04 dB	<0.01 dB	<0.001 dB	< 10^{-4} dB
Dispersion	$1/f^3$	0.4 ps/Hz	0.026 ps/Hz	0.0032 ps/Hz	0.0004 ps/Hz	1.5×10^{-5} ps/Hz	4×10^{-7} ps/Hz

*This estimate is based on a total electron content (TEC) of 10^{18} electrons/m³, which is a high value of TEC encountered at low latitudes in daytime with high solar activity (see Report 725).

The maximum scintillation depth of fading in equatorial regions will be greater than in either mid-latitude or high-latitude regions. Only a limited amount of data exists for equatorial regions but simultaneous measurements at 136 and 1550 MHz [Golden, 1970; Golden and Sessions, 1972] suggest that the law of frequency dependence lies between inverse frequency and inverse square root frequency. However, extrapolation of the limited equatorial VHF data which exists, leads to depths of fading which are considerably less than those observed at 2.2 GHz [Christiansen, 1971] and at 4 and 6 GHz [Craft, 1971]. More data on depth of fading and its distribution are required for high-latitude regions and particularly for equatorial regions before guidance similar to that in Table II can be given.

TABLE II - *Distribution of mid-latitude fade depths due to ionospheric scintillation (dB)*

Percentage of time (%)	Frequency (MHz)			
	100	200	500	1000
1.0	5.9	1.5	0.2	0.1
0.5	9.3	2.3	0.4	0.1
0.2	16.6	4.2	0.7	0.2
0.1	25.0	6.2	1.0	0.3

Ionospheric scintillation is discussed in detail in Report 263 and this text should be consulted to assure that the most up-to-date information is utilized.

2.4.4 *Faraday rotation*

Faraday rotation of the plane of polarization of a wave transmitted through the ionosphere is a consequence of the interaction of the Earth's magnetic field and the motion of the electrons in the ionosphere when excited by the transmitted wave. There are two distinct propagation velocities for the components of the polarized wave, one normal to and the other along the direction of the magnetic field component.

A linearly polarized wave, in passing through the ionosphere, undergoes a progressive rotation in the plane of polarization. The magnitude of the polarization rotation is dependent upon the total electron content over the propagation path and changes as the electron content changes diurnally and with solar activity. Maximum rotation occurs during the day (Report 725 and 263). The total polarization rotation is proportional to the strength of the Earth's magnetic field, resolved along the direction of propagation. These propagation characteristics have the effect of causing fading between linearly polarized antennas. The total rotation experienced by the linearly polarized wave is inversely proportional to the square of the frequency [Lawrence *et al.*, 1964] for quasi-longitudinal propagation.

The maximum change in polarization angle at 100 MHz can be of the order of 30 rotations but the effect of latitude and lower solar activity may reduce this by a factor of 2 or 3 [Garriott *et al.*, 1970] (Report 263).

The avoidance of fading between linearly polarized antennas due to Faraday rotation, particularly at the lower frequencies, would require polarization tracking at the receive end of the link, a technique generally considered impractical for links between satellite and mobile stations. Therefore a circularly polarized antenna must be used on at least one end of the satellite-to-mobile link. A link between a linearly polarized and a circularly polarized antenna would produce a constant 3 dB loss compared to an ideal link with matched polarizations (e.g. circular-to-circular). Perfect circular polarization is usually not achievable in practical antenna designs so that on actual links some signal fluctuation will be observed due to Faraday rotation, the amplitude of which will be dependent upon the axial ratio (degree of polarization ellipticity) of the antennas.

Also to be taken into account when computing the effect of multipath from reflection at the Earth's surface is the fact that the axial ratio of an incident elliptically polarized wave may be increased or decreased upon reflection (particularly at small angles) since Faraday rotation varies the orientation of the principal polarization axis of the incident wave. This results from the difference in reflection coefficient to be expected between vertical and horizontal components in most multipath situations.

The effects of Faraday rotation on wideband signals can be of significance to system performance. When observed on a linearly polarized antenna the differential rotation effects cannot be fully corrected at VHF by reorientation of the antenna axis. On circularly polarized antennas, the effect is to introduce differential phase shifts of signal components across the band. Thus the effects of Faraday rotation for signal components separated in frequency may be expected to be subject to frequency and phase selective distortion. The total Faraday rotation observed with signals at 136 MHz indicates that this effect will not impose a serious limitation on the RF bandwidth of a narrow-band VHF satellite system.

As the magnitude of Faraday rotation is the integral of the product of local electron density and the projection of the Earth's magnetic field vector on the direction of propagation, Faraday rotation is accentuated near the Earth where the magnetic field is most intense, and its variability may be related to the variability of the total electron content N_T . This is further discussed in Report 725.

2.5 *Multipath*

Signals propagating on paths between ships and satellites may have alternate paths from reflections. The reflecting surface will usually be sea-water. The combination of both the direct and reflected signals may cause serious variation of the levels of received signal. Frequency dependence of this phenomenon is closely associated with the nature of the reflecting surface (ocean waves), as well as various other factors that are involved in the reflection, such as whether they are specular or diffuse.

2.5.1 *Reflection from Earth surfaces*

2.5.1.1 *General model for sea reflections*

The electromagnetic field above the surface of the sea may be considered as being the resultant of three vectors arising from the direct wave, the coherently reflected wave, the phase and amplitude of which are determined by the geometry and the roughness of the sea and finally, a non-coherent reflected (scattered) wave, with uniformly distributed random phase and a Rayleigh distribution of amplitude [Beard *et al.*, 1956]. These analytic expressions apply primarily to the VHF frequency bands.

An expression has been derived [Beckmann and Spizzichino, 1963] for the magnitude of the coherently reflected wave as a function of the surface roughness factor, s , which is defined by:

$$s = \frac{h}{\lambda} \sin \psi \quad (1)$$

where:

h : is the r.m.s. sea wave height,

ψ : is the elevation angle of the satellite at the point of reflection (i.e. the grazing angle), and

λ : is the radio wavelength:

Assuming that the first Fresnel zone contains a large number of scatterers, the magnitude of the coherently reflected wave is obtained by modifying the smooth-sea reflection coefficient, p , by a factor k , where:

$$k = \exp(-8\pi^2 s^2) \quad (2)$$

It may be readily determined that for sea state 5 and satellites at angles of elevation above 20°, coherent reflection at 120 MHz should be of negligible proportions. At 1600 MHz coherent reflection should be negligible for satellites at angles of elevation above 6° at sea state 3.

2.5.1.2 *Magnitude of signal fluctuations over sea*

The peak-to-peak magnitude of the fading may be obtained from the foregoing data provided that the radiation pattern of the antenna is known. If the gain of the antenna in the direction of the satellite is greater than the gain in the direction of the incoming reflected wave then the smooth-sea reflection

coefficient is modified accordingly. Knowledge of the surface roughness factor then enables the peak-to-peak fading magnitude to be obtained. Also of importance to the system engineer is the absolute depth of a fade below the signal which would be received in the absence of coherent multipath reflections; such depths of fading may be obtained from use of the equations of § 2.5.1.

2.5.1.3 Reflection coefficients of a smooth sea

Figure 1 shows the theoretical reflection coefficients for vertically and horizontally polarized waves incident on flat smooth sea.

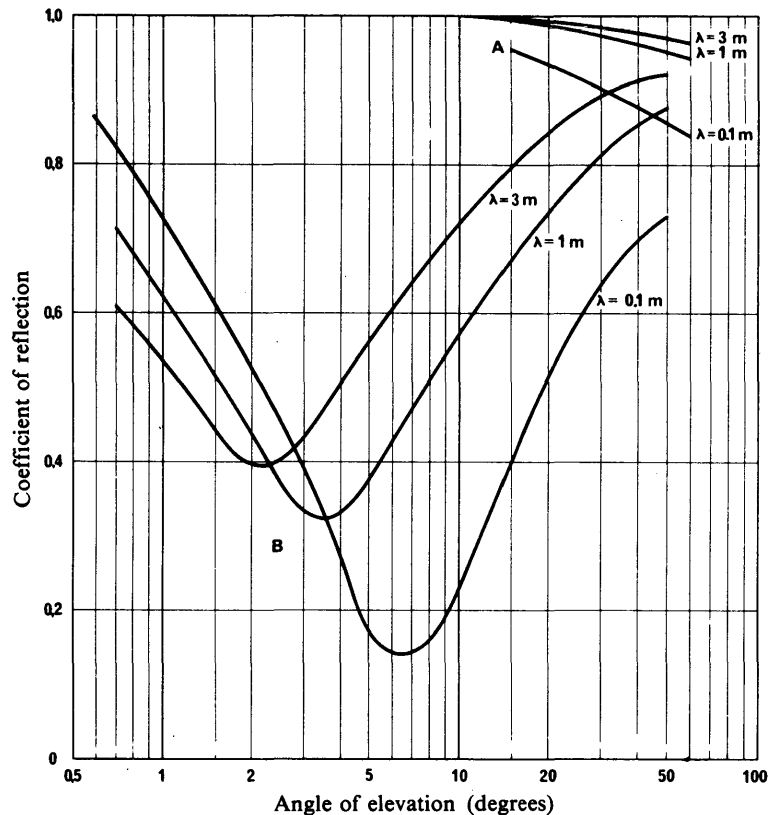


FIGURE 1 — Coefficient of reflexion of smooth plane sea as a function of the angle of elevation

Curves A : horizontal polarization
B : vertical polarization

2.5.1.4 Reflection coefficients of ice caps

The reflection coefficients shown in Fig. 2 are based on the electrical properties of a *névé*, i.e. a surface consisting of snow which gradually changes with depth to compact snow and finally to ice. Such a surface is found in Greenland and the Antarctic ice cap. Measurements of dielectric properties of *névé* have been made in Antarctica [Yoshino, 1967] and are valid up to temperatures around -15°C and approximately correct up to a few degrees below freezing point. At around 0°C the polycrystalline ice begins to thaw and the dielectric constant changes rapidly from 4 to 78. Hence rapid changes in reflection coefficient are to be expected where the surface temperature approaches 0°C . The Brewster angle is about 40° for a *névé* and since a geostationary satellite is always viewed from lower angles of elevation over such surfaces, reflected circularly polarized waves have a large component of the original sense of polarization.

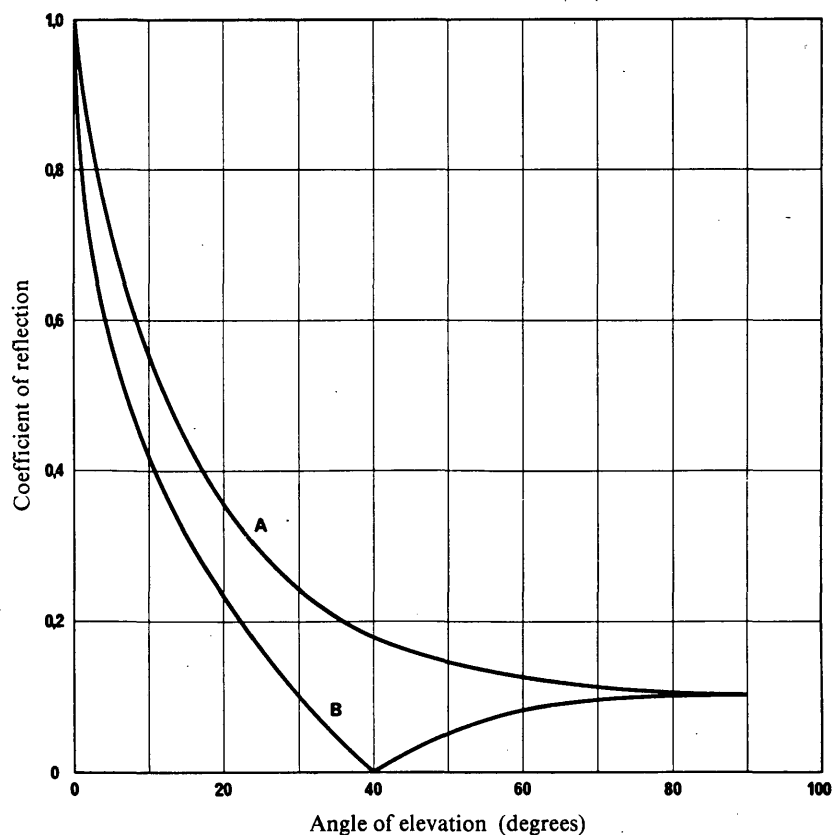


FIGURE 2 — Coefficient of reflexion of an ice cap (névé) as a function of the angle of elevation

Curves A : horizontal polarization
B : vertical polarization

2.5.1.5 Reflection coefficients of land

The reflection coefficients shown in Fig. 3 are based on the electrical properties of "average" ground and assume a perfectly plane surface. For angles of elevation above 10° , the reflection coefficients are lower than the corresponding coefficients over a sea surface, much lower in the case of vertical polarization. Below 10° values are, in general, higher than the corresponding values for smooth sea. It is probable, however, that coherent reflection coefficients are considerably lower than shown in Fig. 3 because of the non-smooth nature of most land surfaces. Reflections from land surfaces have characteristics which vary considerably as a function of the location of the reflection area.

2.5.2 Theoretical model of diffuse reflections on seas

The purpose of a theoretical model is to meet the need for data on fading due to the multipath effect for various parameter values [Beckmann and Spizzichino, 1963]. For this study, only diffuse reflection is taken into account. Further studies are required in order to investigate the effects of specular reflection, particularly at low elevation angles and under smooth sea conditions. Account has not been taken of antenna polarization discrimination. No account has been taken of fluctuations due to the atmosphere; their effect is decisive when the effects due to the sea are negligible, in other words at high elevation angles.

The model used assumes that reflection is produced under the effect of the various sea facets (shiny points) within a "glistening surface". The area of this surface increases with the agitation of the sea, since a given state of the sea corresponds to a given maximum value of the slope of the facets, a value related to the dimensions of the surface. The reflected signal resulting from it is assumed to be in accordance with the Rayleigh distribution. This analysis applies particularly to the 800 and 1550-1650 MHz frequency bands.

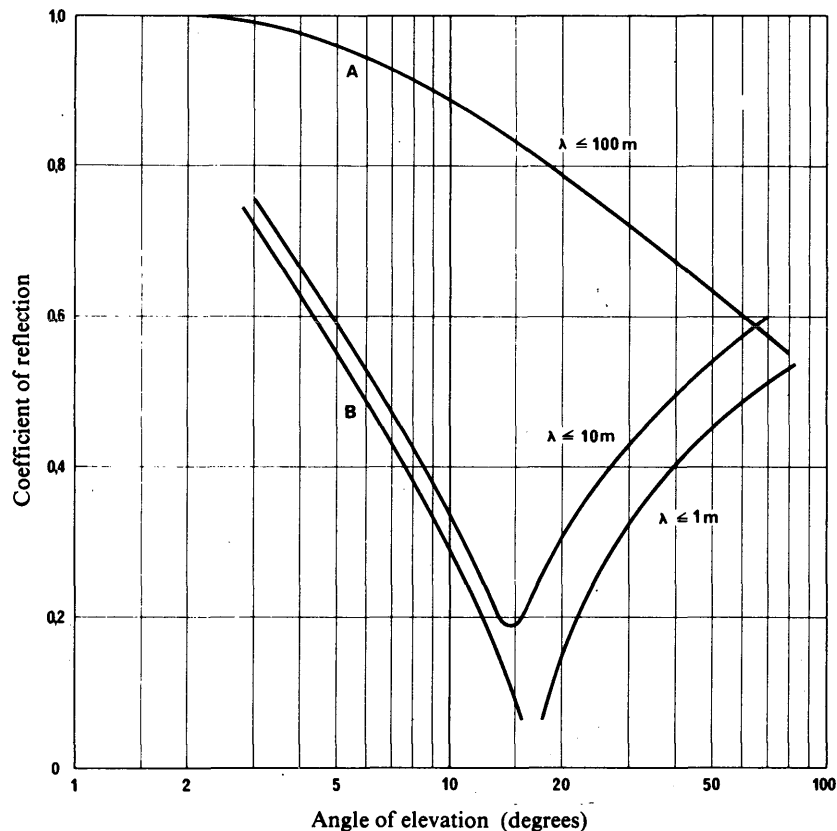


FIGURE 3 — Coefficient of reflexion for plane average ground as a function of the angle of elevation

Curves A : horizontal polarization
B : vertical polarization

In this model the fading value, A , for p percentage of the time, is obtained by the formula:

$$1 - \frac{p}{100} = \frac{\rho^2}{2 e^{1/\rho^2}} \int_0^{\frac{2 \times 10}{\rho^2}} \frac{t}{e^{\rho^2 t^2/4}} I_0(t) dt \quad (3)$$

where $I_0(t)$ designates the modified Bessel function of order zero, and ρ^2 is the equivalent reflection coefficient of the glistening surface. It is inversely proportional to a factor β_0^2 , which is a measure of the sea surface roughness.

The results of the theoretical fading calculations are presented in Figs. 4, 5 and 6. The vertically polarized single frequency carrier fade depth is shown as a function of sea state with elevation angle as the parameter, for antenna gains of 23, 15, 10 and 5 dB and 99% of the time that the fade depth is not exceeded. It has been shown that the fading depth increases with decreasing wave height until the seas become very calm, when the fading depth abruptly and rapidly drops, due to the fact that the antenna lobe does not meet the sea. These data and these figures do not apply to the VHF and lower UHF frequencies.

That is, the figures appear to show a maximum fade depth for slight and moderate sea states. As the predicted multipath fading is quite severe, further consideration of values of fading predicted for 95% of the time for lower elevation angles may be required.

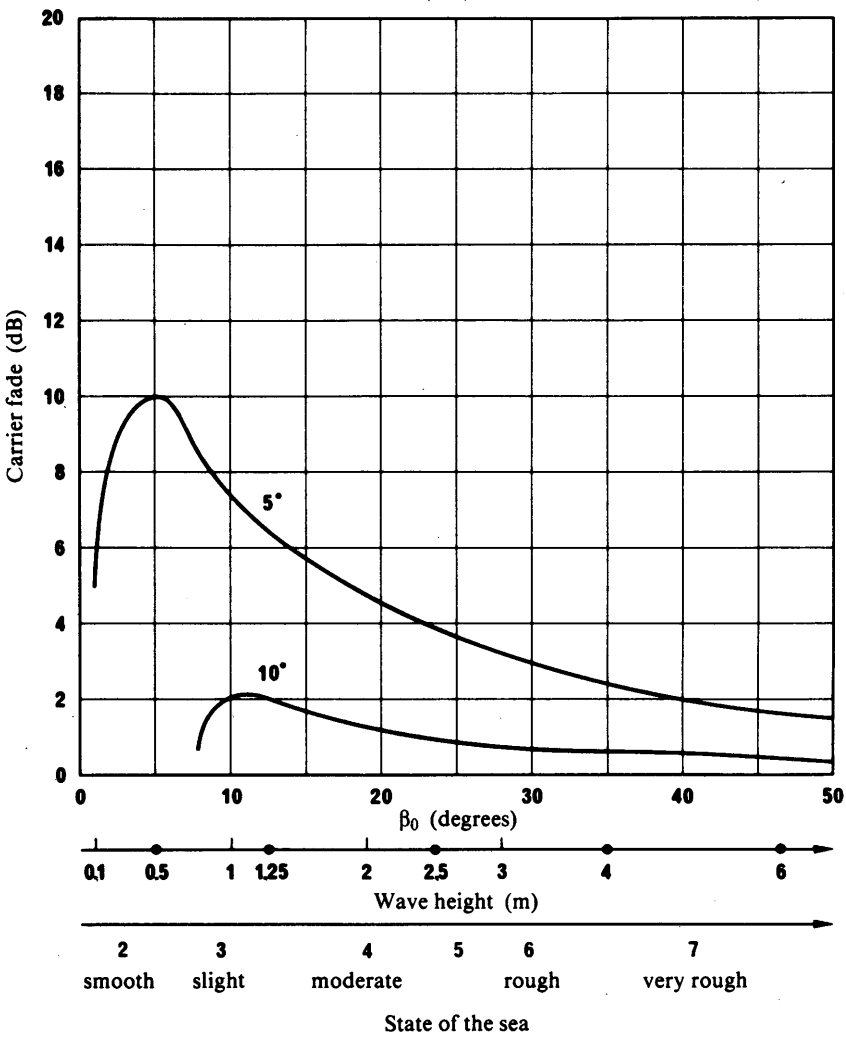


FIGURE 4 — Carrier multipath fade (dB) for the sea state specified for 99% of the time (dB)

Curve parameter is elevation angle
 $G=23$ dB

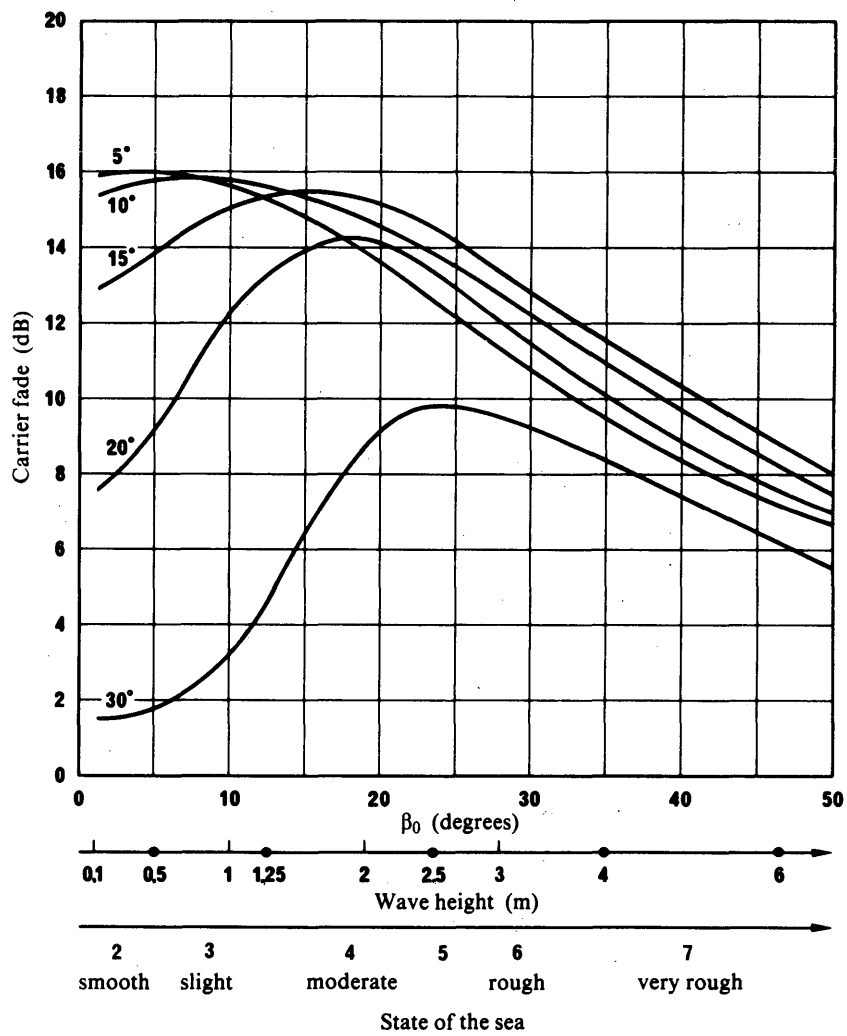


FIGURE 5 — Carrier multipath fade (dB) for the sea state specified for 99% of the time (dB)

Curve parameter is elevation angle

$G = 10$ dB

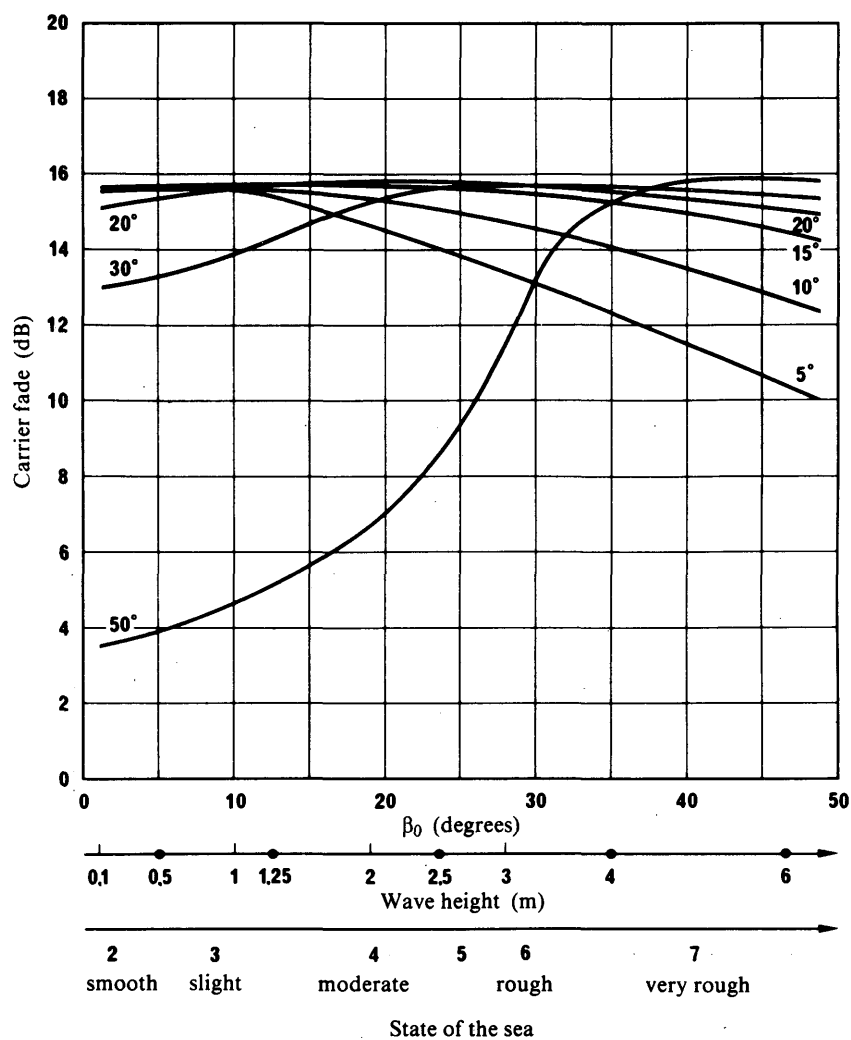


FIGURE 6 — Carrier multipath fade (dB) for the sea state specified for 99% of the time (dB)

Curve parameter is elevation angle

$G = 5$ dB

2.5.3 Additional data required

It should be noted that current modelling does not account for the effects of the platform tilt upon signal polarization and phase as well as the effects of the terrain and structures.

On ships, the effects of sea direction has not been considered, and very little data is available. Administrations are encouraged to submit improvements and augmentation to the theory and measured data base of this Report.

3. Use of circular polarization

Due to the reversal in sense of circularly polarized radiation on reflection from a surface at angles of elevation greater than the Brewster angle, circularly polarized satellite and shipboard antennas may be used to reduce multipath fading. Calculations have been made [Levatich, 1966] of the depth of fading over a smooth sea

for a number of configurations of aircraft and satellite antennas. The general conclusion is that, provided an aircraft antenna can maintain good circularity over the hemisphere of interest, coherent fading will be reduced to small proportions for angles of elevation of the satellite above about 10° . Incoherent fluctuations will also probably be reduced significantly by the use of circular polarization.

Over ice, circular polarization gives no help in reducing the depth of fading for a geostationary satellite. Vertically polarized emissions would appear to be the least subject to fading under these conditions.

4. Measured data

4.1 Satellite to maritime mobile systems

During the past few years, experiments have been conducted in the USA to determine the extent of degradation of satellite-to-ship and ship-to-satellite signals in the band 1535 to 1660 MHz shipboard receive/transmit frequencies at low elevation angles.

The experiment was performed in October, 1978 aboard the S.S. MOBILE AERO, on a route from Norfolk (Virginia) to Texas City (Texas) with elevation angles changing from 17° to 0° [Fang *et al.*, 1982]. The peak-to-peak signal fluctuations were 5 dB at 2.4° and 2 dB at 5.7° elevation angles respectively [Tseng, 1979].

In Japan, shipboard measurements were conducted on 100 and 9000 ton ships using two low-gain receive antennas (short back-fire) [Yoshikawa *et al.*, 1980]. The antennas had gains of 12 dB and 16 dB with beamwidths of 44° and 24° , respectively. Each set of antennas was fixed in the direction of the Marisat satellite beacon with the ship holding a constant course, while pitch and roll were less than $\pm 2^\circ$.

Shipboard measurements in the Federal Republic of Germany were conducted at low elevation angles [ESA, 1977]. The signal amplitude variations were measured for signals received from the ATS-6 satellite in geostationary orbit with an antenna of 25 dB gain.

Satellite data and maritime mobile experimental parameters and principal results are shown in Tables III and IV.

TABLE III - Data on maritime mobile systems

Satellite	Launch date	Orbit location	Frequency (GHz)		Transponder data
			Ship	Shore	
Marisat F-1	February, 1976	345°E	1.5/1.6	4/6	[Morgan, 1980]
Marisat F-2	1976	176.5°E	1.5/1.6	4/6	[Morgan, 1980]
Marisat F-3	1976	73°	1.5/1.6	4/6	[Morgan, 1980]
ATS-6	June, 1974	140°W	1.6	-	Beacon

4.2 Satellite to land mobile-satellite systems

In the Eastern USA, measurements were made for elevation angles from 11° to 22° [Anderson *et al.*, 1981] for ATS-6 received signals from vehicles and earth stations near 1650 MHz and retransmitted on 1550 MHz. It was concluded that a 5 dB propagation margin would provide satisfactory service if the vehicle had line-of-sight transmission to the satellite, suburban and rural areas.

A second series of satellites to mobile propagation measurements were carried out in the Middle West and Western United States using the ATS-6. The measurements were directed towards determining excess path loss at 860 MHz and 1550 MHz. The ATS-6 satellite was observed at elevation angles varying from 19° (Chicago) to 43° (San Francisco). Excess path loss was determined [Hess, 1980] as a function of local environment, vehicle heading, frequency, satellite elevation angle, and street side. In these measurements the excess path loss difference between 860 MHz links and 1550 MHz links was generally small, on the order of 1 dB. Figure 7 illustrates the trade-off between percentage of locations served and percentage of time that service is available for the Denver location.

Tables V and VI summarize the satellite data and the land mobile experimental parameters and principal results.

TABLE IV - Satellite to maritime mobile experimental parameters and principal results

Satellite	Ship location	Antenna height above sea (m)	Elevation angle (degrees)		Sea state	Atmospheric conditions	Antenna		Fade		References
			Ship	Shore			Gain (dB)	Beamwidth (degrees)	% time	Depth (dB)	
Marisat F-1	Norfolk, Virginia to Texas City, Texas	25	5.7	16	0-4	Clear and calm to moderate rain in squalls	-	-	1% 5% 20%	4.5 3.5 1.0	[Lipke <i>et al.</i> , 1977]
			2.4	16	0-4		-	-	1% 5% 20%	18 9 5	
Marisat F-3	Japan	5.20	7	-	2	Clear	12	44	99%	8.1	[Yoshikawa <i>et al.</i> , 1980]
Marisat F-2	Japan	5.20	10	-	2	Clear	12	44	99%	4.8	
Marisat F-3	Japan	5.20	7	-	2	Clear	16	26	99%	5.9	
Marisat F-2	Japan	5.20	10	-	2	Clear	16	26	99%	3.0	[ESA, 1977]
ATS-6	Germany (Federal Republic of)	-	8	-	0-4	Clear	25	-	95% 1%	+1 -1	
ATS-6	Germany (Federal Republic of)	-	2	-	0-4	Clear	25	-	95% 1%	+2 -4.5	

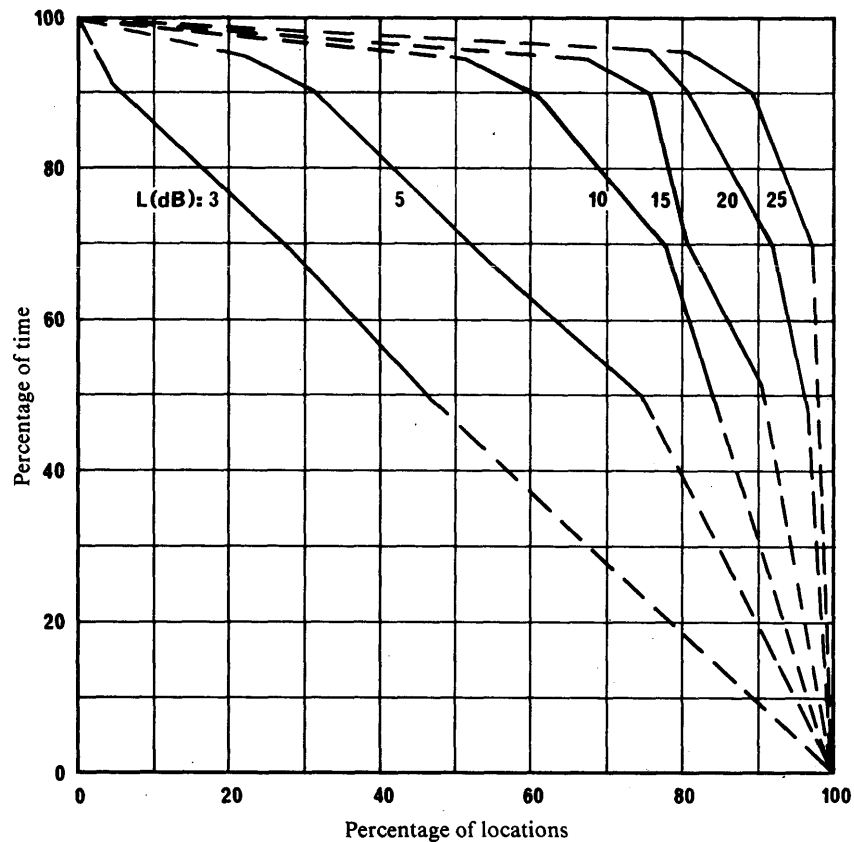


FIGURE 7 — Measured propagation loss (L) relative to free space required to achieve indicated degrees of service in terms of location and time

(Transmission from a geostationary satellite at 860 MHz and reception with a quarter-wave grounded vertical monopole on a vehicle passing through urban Denver, Colorado [Hess, 1980])

TABLE V — Satellite to land mobile data

Satellite	Launch date	Orbit location	Frequency (GHz)		Transponder data
			Mobile	Terminal	
ATS-6	June 1974	140°W	0.860 reception 1.550 reception 1.650 transmission	4/6	-

TABLE VI - Land mobile to satellite experimental parameters and principal results

Satellite	Mobile location	Antenna height above ground (m)	Elevation angle (degrees)		Atmospheric conditions	Terrain conditions	Antenna			Fade	C/N	References
			Mobile	Terminal			Gain (dB)	Beamwidth (degrees)				
								V	H			
ATS-6	Chicago, Denver, San Francisco USA	3	19 to 43	-	-	Urban, suburban, plains, mountains	-1	90	360	0 to ∞	33	[Hess, 1980]
ATS-6	New Jersey to Nebraska, USA	3	9 to 23	-	Clear	Rural	7.3	4 to 19 11 to 28	360	1 to 2 dB	-	[Anderson <i>et al.</i> , 1981]

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CCIR Texts

The following texts, to be found in Volume VIII, are referenced specifically:
 Reports 504, 505, 598, 760, 762, 763, 920, 921 and 925.

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SECTION 5G: PROPAGATION FACTORS IN INTERFERENCE: SPACE AND TERRESTRIAL SYSTEMS

Recommendation and Reports

RECOMMENDATION 452-3 *

**PROPAGATION DATA REQUIRED FOR THE EVALUATION OF INTERFERENCE
WITHIN AND BETWEEN THE SPACE AND TERRESTRIAL SERVICES
AND FOR THE CALCULATION OF COORDINATION DISTANCES**

(1970-1974-1978-1982)

The CCIR,

CONSIDERING

- (a) the terms of Resolution No. 60 of the World Administrative Radio Conference, Geneva, 1979;
- (b) that the coordination area is that area, around an earth station, so defined that any interference between the earth station in question and terrestrial stations outside this area may be considered as negligible;
- (c) that the determination of the coordination area should be based on the best propagation data available and that methods of predicting attenuation along an interference path should be compatible with those of determining the relevant coordination area,

UNANIMOUSLY RECOMMENDS

1. that, for the evaluation of interference to point-to-point services between stations on the surface of the Earth at frequencies higher than about 500 MHz, administrations make use of the propagation prediction method set out in Report 569;
2. that, in the case of the prediction of the propagation of interference signals affecting point-to-point services operating at frequencies below about 500 MHz, the data of Recommendation 370 is to be used as follows:
 - to derive information relative to 1% of the time with respect to point-to-point services, the appropriate Recommendation 370 curves for 1% of the time are to be used, and the conversion factor relative to 1% of locations is to be applied as obtained from Fig. 5 of that Recommendation;
 - the curves in question are to be found in Figs. 4a, 4b and 4c of Recommendation 370 which correspond to land, cool seas and warm seas respectively and therefore are equivalent to zones A, B and C respectively as defined in Report 724;
 - due to insufficient data being available at the present time, it is not yet possible to propose a method for the prediction of the propagation of interference signals for less than 1% of the time;
3. that, for the evaluation of interference to point-to-area services between 30 MHz and 1 GHz, administrations make use of the propagation prediction methods set out in Recommendations 370, 528 and 529 as appropriate;
4. that, for the determination of the coordination area with respect to frequencies between 1 and 40 GHz, administrations use the propagation calculation methods set out in Report 724 for domestic (i.e. non-international) planning;
5. that for the evaluation of interference between space stations and those on the surface of the Earth, administrations use the propagation calculation methods set out in Report 885.

* This Recommendation is brought to the attention of Study Groups 1, 2, 4, 7, 8, 9, 10 and 11.

REPORT 569-2 *

**THE EVALUATION OF PROPAGATION FACTORS IN INTERFERENCE
PROBLEMS BETWEEN STATIONS ON THE SURFACE OF THE EARTH AT
FREQUENCIES ABOVE ABOUT 0.5 GHz**

(Question 5/5)

(1974-1978-1982)

1. Introduction

Congestion of the radio-frequency spectrum has necessitated the sharing of frequencies between a number of services, involving both entirely terrestrial systems and also terrestrial/space systems. The possibilities of interference arise therefore between terrestrial systems themselves and also between terrestrial and space systems. Hence, in systems planning the engineer needs to know both how to establish a reliable signal in the absence of interference, and also how to evaluate interference which may arise due to frequency sharing with other systems. It is this second question, relating to the incidence of interference, that this present Report treats, and it goes on to offer methods for the quantitative assessment of this question for frequencies greater than about 0.5 GHz.

In order to estimate mutual interference between different radio systems it is necessary to know the statistical distribution of the difference in decibels of the level of the interfering signal and the level of the wanted signal. For most radio systems, except trans-horizon radio-relay links, the wanted signal level may be considered to be approximately constant, although multi-path fading of the wanted signal can cause complications.

Therefore it is essential for the engineer to have statistics describing the occurrence of the interference, the variability of which is due to the existence of several different propagation mechanisms, each of which is itself subject to variations arising from the nature of the tropospheric propagation medium. Changes in the medium are a function of climate, and it is necessary to take into consideration both the effects due to the propagation characteristics in clear air and phenomena which may arise due to the presence of hydrometeors in the propagation path.

The methods described in this Report are essentially for the evaluation of signal strengths over point-to-point paths. ** In most cases radio-relay stations employ exposed sites. Nevertheless, it should also prove feasible to apply the propagation data contained in this Report to specific interference problems associated with the planning of other services, among these the broadcasting and mobile services. To do this, allowances will have to be made for the additional losses due to terrain irregularities, vegetation and man-made structures in the vicinity of the stations of such services. Information on these additional losses is contained in Report 239.

In systems planning it is generally required to estimate the level of interference not to be exceeded for both the small time percentages ($\leq 1\%$ of the time), and for about 20% of the time. Where appropriate data are not contained in other CCIR Reports, propagation data are given for estimating the level of interference not exceeded for these percentages of time. Unless stated otherwise, all percentages of time quoted in this Report refer to percentages of an average year.

In evaluating levels of interference, which are relevant to the time percentages below about 50%, the propagation mechanisms mainly to be considered are:

- line-of-sight;
- diffraction over isolated obstacles;
- diffraction over irregular terrain;
- tropospheric forward scatter.

At the time percentages below about 10%, additional mechanisms require consideration for the evaluation of the stronger interference levels. These are:

- superrefraction and ducting;
- scatter from hydrometeors (mainly rain);
- reflections from aircraft.

* This Report is brought to the attention of Study Groups 1, 2, 4, 7, 8, 9, 10 and 11.

** In the special case of the prediction of interference by rain scatter between two terrestrial stations, reference should also be made to Report 882 as indicated in § 5.4 of this Report.

Methods for predicting the transmission loss for each of the propagation mechanisms are based on input data regarding: path geometry, general or specific earth surface characteristics, general or specific climatic conditions and certain station characteristics. However, the mechanisms are not equally sensitive to these input data nor do they show the same variation in time. It is therefore necessary to determine the transmission loss for each mechanism, and so to identify those producing the higher field strengths in the given circumstances. Usually one mechanism will predominate to such a degree that the others may be ignored.

In all cases other than those of tropospheric forward scatter and scattering by rain, the propagation data in this Report are given in terms of loss in decibels with respect to free-space transmission. The propagation characteristics associated with rain scatter, on the other hand, are dependent on antenna radiation patterns, and here it is convenient to present the data in terms of transmission loss, i.e. the ratio in dB between the power delivered to the transmitter antenna and the power delivered to the input of the radio receiver at the other end of the path.

While it is not yet possible to provide completely rigorous evaluations of interference which will be experienced under all specific conditions, the methods presented in this Report will, in general, enable initial systems planning to be carried out in such a way as to avoid serious interference problems. In addition the methods also help to identify conditions where serious interference is highly probable, and which therefore merit more rigorous calculations on the basis of detailed topographical and climatological data.

It is necessary to determine the level of interfering fields in the evaluation of coordination distances. Report 724 gives a simplified method of calculation to establish whether there is a necessity for more rigorous coordination procedures to be followed, in which case this present Report enables more detailed calculations to be made.

2. Propagation mechanisms and path characteristics

Before the attenuation can be calculated, the relevant propagation mechanism must be known. However, as the initial data consist mainly of the geographical characteristics of paths, classification of propagation mechanisms and path characteristics is necessary.

2.1 *Propagation mechanisms*

All propagation mechanisms may be classified in two groups: surface mechanisms (line-of-sight and ground-wave propagation) and volume mechanisms.

2.1.1 *Surface mechanisms*

In this group, the presence of the Earth's surface plays a role in reflection and diffraction, while the atmosphere above this surface has an overall effect in terms of refraction.

For practical reasons, distinction is often made between line-of-sight paths (that is, those cases in which diffraction may be neglected) and trans-horizon paths. Nevertheless it should be noted that a fairly long interference path may be at some times line-of-sight and at other times trans-horizon, depending on the vertical gradient of the refractive index of the atmosphere at any instant.

Figures 1a and 1b illustrate, for frequencies of 4 and 12 GHz respectively, the attenuation due to diffraction over a smooth Earth as a function of refractive index gradient (Report 715). Typical antenna heights of 100 and 15 m have been assumed.

It can be seen from Figs. 1a and 1b that, for example, for a path of 150 km length, when the vertical gradient of refractive index is positive or less negative than $-140 N$ units/km, the path is a diffraction path with high attenuation, and then, when the gradient is between -140 and -157 , the attenuation decreases and the path becomes a line-of-sight path. Beyond $-157 N$ units/km, a tropospheric duct with low attenuation appears (see Report 718).

Ducting likely to cause significant interference levels over trans-horizon paths can occur at both the surface and at elevated positions of up to a few hundred metres above the surface (see Report 718). The procedures in this Report relating to ducting take account of both these modes of duct propagation.

In all these surface mechanisms, propagation takes place more or less on the great circle path.

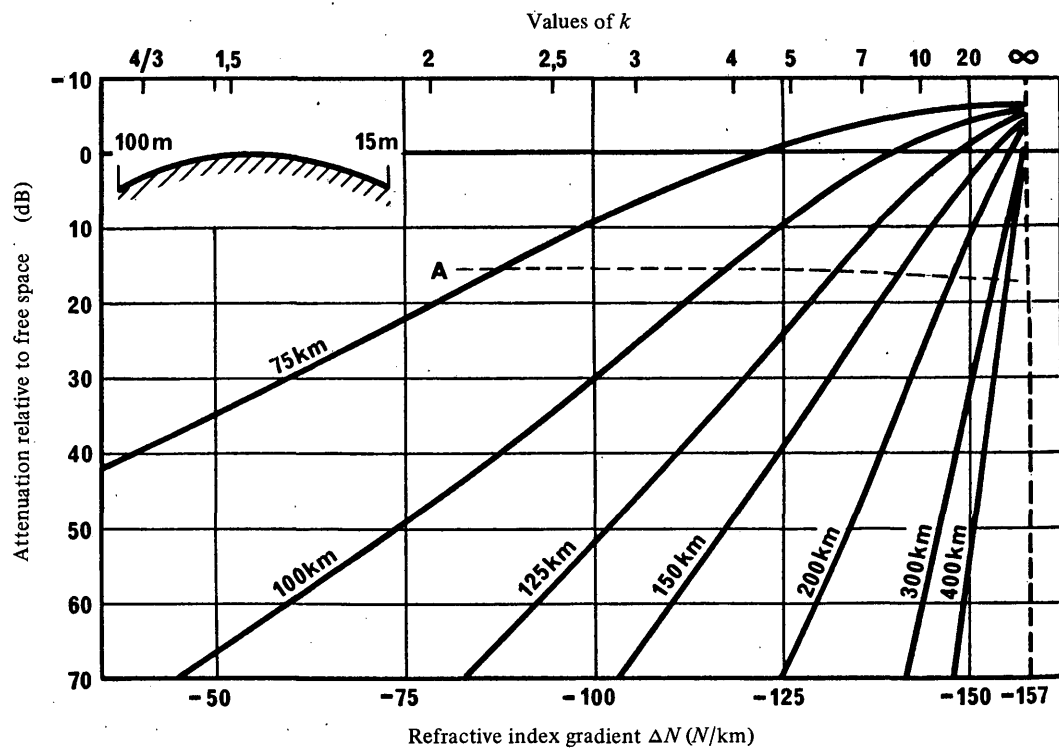


FIGURE 1a – Attenuation due to spherical diffraction: 4 GHz, as a function of refractive index gradient ΔN

A: limit of visibility

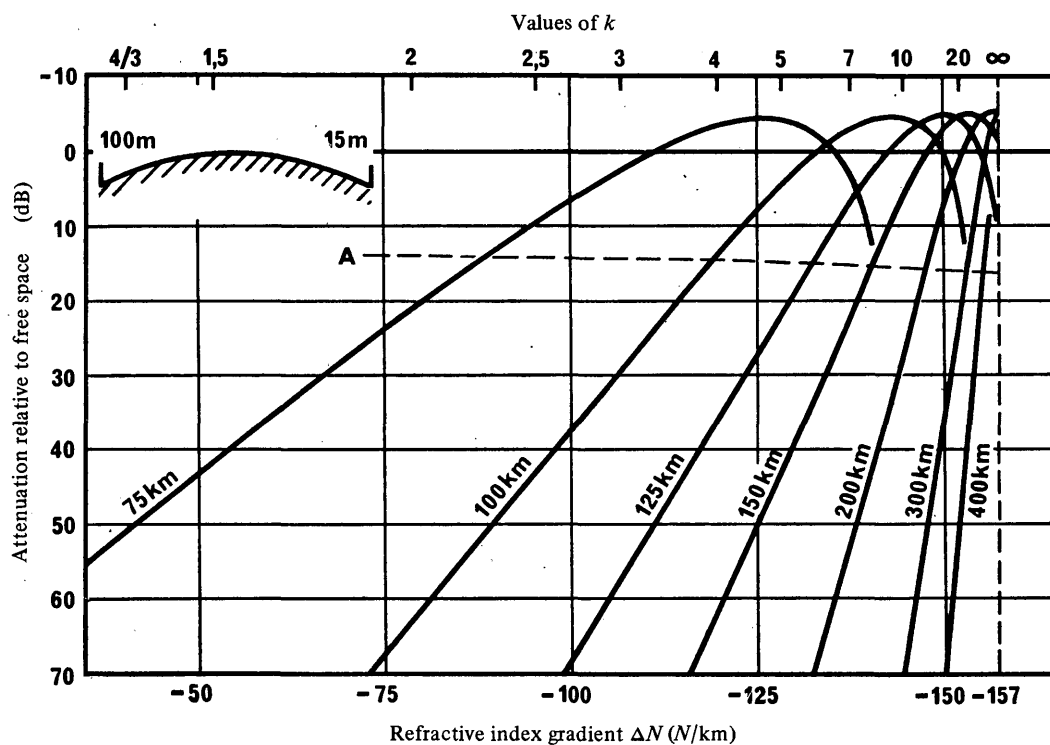


FIGURE 1b – Attenuation due to spherical diffraction: 12 GHz, as a function of refractive index gradient ΔN

A: limit of visibility

2.1.2 *Volume mechanisms*

Volume mechanisms are due to scatter in the fine structure of the troposphere.

The surface of the Earth plays no role, except in limiting the geometry of the path. The two principal mechanisms of this group are tropospheric scatter from fluctuations in refractive index due to the gaseous composition of the atmosphere, on the one hand, and scatter caused by solid or liquid particles in the atmosphere, in particular rain drops, on the other.

Tropospheric scatter is continuously present, giving rise to propagation along great circle paths. There is always relatively high attenuation in the true scatter mode, when no form of super-refraction exists. Scatter from hydrometeors must clearly be intermittent, but it is the only mechanism giving rise to significant propagation off the great circle path.

2.2 *Path characteristics*

For estimating interference, two classes of path need be considered. All propagation mechanisms other than scatter from particles, produce the highest field strength in the plane of the great circle path between the transmitter and receiver; it suffices therefore to investigate great circle paths in these cases. Scatter from particles, on the other hand, is not confined to the great circle plane but is highly dependent on the radiation characteristics and relative geometry of the antennas at both the transmitting and the receiving stations; terrain features are of little concern except to limit the radiation characteristics of the antennas.

2.2.1 *Paths in the great circle plane*

In order to estimate attenuation along a great circle path it is necessary to determine the effective path profile.

The largest seasonal value of ΔN , the decrease in N over the first kilometre (see Report 563), for the location of the path under investigation should be determined from Figs. 5-8 of Report 563. The effective earth radius " ka " is then calculated:

$$ka \approx (-\Delta N \cdot 10^{-6} + 1/a)^{-1} \quad \text{km} \quad (1)$$

where $a = 6400$ km is the true Earth radius. For a long path, the *mean* of the smallest seasonal values of ΔN should be used where ΔN is normally a positive quantity.

Using this effective Earth radius and using profile data for the terrain along the path, the class of path may be determined by simple geometry. It is useful to distinguish between the following classes of path;

- (a) line-of-sight, including line-of-sight with grazing conditions;
- (b) trans-horizon, with up to three major isolated obstacles, but not obstructed by the curve of the Earth; this is a knife-edge diffraction path;
- (c) trans-horizon, with up to three major isolated obstacles and such that the curve of the Earth also obstructs the path; this may be termed an extended knife-edge diffraction path;
- (d) trans-horizon, with more than three major obstacles or very irregular terrain;
- (e) trans-horizon, with no major obstacles (including oversea paths). This is a smooth-earth path.

From statistical data on ΔN values the effective path profile for the percentage of time of interest may be determined.

To aid the engineer attempting to predict path attenuation for the assessment of interference, the following Table I identifies the sections of this Report which are relevant to the various path types.

2.2.2 *Paths off the great circle plane*

In this Report, scatter due to rain is considered to be isotropic. Hence, the path of minimum transmission loss will depend on the rain density distribution in the troposphere and on the relative orientation and polarization of antennas.

2.2.3 *Reflections from aircraft*

In addition to the propagation mechanisms above, interference caused by reflections from aircraft may have to be considered for paths, where the intersection of the main beams coincides with a flight path. The resulting signals are characterized by short individual durations and high relative intensities. This effect is treated in § 6 of this Report.

TABLE I - Sections pertinent to different types of path

Type of path	Percentage range of the relevant interference criterion	
	10 - 50%	< 10%
(a)	§ 3.1	(§ 3.1)
(b)	§ 3.2.1	(§ 3.2.1) §§ 3.2.3; 5; 6
(c)	§§ 3.2.1; 3.2.2; 3.2.4; 4	§§ 3.2.3; 4; 5; 6
(d)	§ 4	§§ 4; 5; 6
(e)	§§ 3.2.2; 4	§§ 3.2.3; 4; 5; 6

3. Prediction of transmission loss due to surface propagation mechanisms

3.1 Line-of-sight paths

When calculations indicate that, with the effective Earth radius obtained from § 2 for long-term reference conditions, the propagation path under investigation yields a geometric line-of-sight condition with no obstacle obscuring the first Fresnel zone, it may first be assumed that the basic transmission loss is equal to the free-space loss. The values obtained should then be increased by gaseous absorption, which may be estimated from the curves given in Report 719, assuming the following values for water vapour concentration in various regions of the world:

Over land, latitude $\geq 23^\circ$	: 1 g/m ³
Over sea, latitude $\geq 23^\circ$	} : 2 g/m ³
Over land, latitude $< 23^\circ$	
Over sea, latitude $< 23^\circ$	: 5 g/m ³

The result is the long-term reference value of basic transmission loss. The basic transmission loss exceeded for all but $q\%$ of the time is then:

$$L_{bf} + A_g - G_q \quad (2)$$

where:

- L_{bf} : free space loss,
- A_g : gaseous absorption loss,
- G_q : statistical sum of instantaneous focusing effects and multipath interference between rays arriving over different paths in the atmosphere. Values of G_q are given in Table II.

TABLE II - G_q in dB: not exceeded for more than $q\%$ of the time

q	0.001	0.01	0.1	1
G_q	8.5	7.0	6.0	4.5

The values given in Table II apply to paths of 50 km and more; for shorter distances they may be proportionally reduced.

To estimate the basic transmission loss exceeded for all but 20% of the time, the free-space loss is increased by 1.5 dB, except when the path geometry shows grazing or near-grazing conditions of terrain along the path (i.e. within $2/3$ of the first Fresnel zone). Then, diffraction may produce attenuation below free-space values. However, to assess such attenuation, the appropriate values of surface refractivity gradient must be available; the calculation method is described in Report 715.

3.2 *Trans-horizon paths*

General methods for estimating path attenuation due to Earth diffraction are discussed in Report 715. The following prediction method complements this information.

Diffraction round the curve of the Earth causes high attenuation in normal refraction conditions. In the absence of superrefraction conditions, however, diffraction round the curve of the Earth may become significant.

When considerable superrefraction occurs in the atmosphere (for example, refractive index gradient more negative than -120 N/km) the effective attenuation rapidly diminishes, and as from -157 N/km ducting conditions are encountered. These two propagation mechanisms, diffraction and ducting, although differing in principle, have nevertheless several characteristics in common:

- in both cases, propagation is determined by the nature of the terrain (configuration, vegetation) and by the characteristics of the lower layers of the atmosphere (up to a maximum of a few hundred metres).
- in both cases the received signal level is an almost exponential function of the distance. In effect, in the case of diffraction, this same exponential function is a good approximation to the more complicated functions that should strictly be used and in the case of ducting this exponential function is due to the attenuation resulting from the imperfections of the guiding mechanism, as in any transmission line.

Summarizing, there is a continuity between these two phenomena: the relevant laws have similar forms and the nature of the Earth's surface is generally important.

The possibility of long-distance wave propagation at UHF and SHF due to snow on mountain tops is discussed in Report 236.

3.2.1 *Knife-edge diffraction*

This mechanism applies to paths consisting of a limited number (usually not more than 3 or 4, depending on the profiles) of major, isolated obstacles, with no terrain intervening in the line of propagation between the crests of adjacent obstacles, or between an end of the path and the adjacent obstacle. Variations in the signal level with respect to time will mainly be due to variations in k -factor affecting the diffraction angles, and such angle variations do not normally have a large effect on signal level. Therefore the signal tends to be stable.

The knife-edge attenuation relative to free space may be determined as indicated in Report 715 to obtain the long-term reference value. When more than one obstacle is present, the attenuation for each obstacle must be determined individually for the path section bounded by either the visible terminal and the next obstacle, or by the two adjacent obstacles (3-obstacle case). Corrections for the total path length may be made for gaseous absorption as in § 3.1.

3.2.2 *Spherical diffraction*

This mechanism applies to paths without a major diffraction edge, and in such cases the signal levels with respect to distance are in general considerably lower than those over a knife-edge diffraction path. Nevertheless, because of their stability, signals propagated by this mechanism over favourable paths may well be significant in the absence of ducting, i.e., for time percentages exceeding say 20%.

For a smooth Earth the diffraction loss will be dependent on the effective radius of the Earth which is given by expression (1) of § 2.2.1 (see Figs. 1a and 1b). For the determination of signal levels due to spherical diffraction, reference should be made to Report 715. As in the case of knife-edge diffraction, corrections for gaseous absorption may be appropriate (see § 3.1).

3.2.3 Superrefraction and ducting

This mechanism usually applies to small percentages of time and is evaluated in this Report for $\leq 1\%$ of the time.

The prediction method is based on the calculation of the propagation of energy in a tropospheric duct. The method is also valid for the cases of high superrefraction without ducting, and of reflections from thin layers, because of the similarity of the mathematical functions involved.

For this calculation, the Earth is considered to be divided into four geographic zones:

- Zone A1: coastal areas, i.e. land with an altitude less than 100 m above sea level, but not extending more than 50 km inland from zones B or C (see below).
- Zone A2: all other land.
- Zone B: seas, oceans and other substantial bodies of water (as a criterion, one which can encompass a circle of diameter of 100 km) at latitudes greater than 23.5° N or S, but excepting the Black Sea and the Mediterranean.
- Zone C: seas, oceans and other substantial bodies of water (as a criterion, one which can encompass a circle of diameter of 100 km) at latitudes less than 23.5° N or S, and including the Black Sea and the Mediterranean.

3.2.3.1 Prediction method for paths contained entirely within one zone

The attenuation A , in excess of the free-space loss which results for small percentages of time due to superrefraction and ducting, is expressed in the form:

$$A = L_b - L_{bf} = -10 \log d + \gamma_g \cdot d + A_c + \gamma_d \cdot d + A_s \quad \text{dB} \quad (3)$$

where:

L_b : basic transmission loss (dB);

L_{bf} : free-space loss for a path of the same length (dB);

d : path length (km);

γ_g : specific attenuation (dB/km) due to gases (see Report 719). For the values of the water vapour concentration to be applied, see § 3.1;

A_c : coupling loss (dB), dependent on the zone containing the path and the percentage of time (Table III);

γ_d : specific attenuation (dB/km), depending on the zone containing the path, the frequency and the percentage of time (Figs. 2a, 2b, 2c and 2d);

A_s : diffraction loss (dB) when a positive horizon elevation angle applies to either or both terminals (§ 3.2.3.2).

The values of coefficients A_c and γ_d quoted in Table III and Figs. 2a, 2b, 2c and 2d are mainly based on experimental data relating to a large number of circuits within Europe, the North Sea and the Baltic Sea, as well as the Mediterranean. These data include measurements made below and around 1 GHz, and also initial results from experiments at frequencies up to 12 GHz [Neessen and de Haas, 1981; Hewitt and Adams, 1980; CCIR, 1978-82a].

TABLE III – Values of coupling loss, A_c (dB)

Zone ⁽¹⁾	Percentage of the time			
	0.001%	0.01%	0.1%	1%
A2	9	10	11	14
A1, B, C	6	7	8	11

⁽¹⁾ If the two stations involved belong to different zones the average of the pertinent A_c values should be used.

These measurements have all shown a large yearly variation in basic transmission loss, and the values given should therefore be used with reasonable caution, especially for frequencies above 10 GHz.

The data provided refer to typical path geometries and some adjustment to predicted levels may be required for situations where the path geometry is atypical. Measurements made at 1.8 GHz in Japan [Tsuzuki *et al.*, 1980] with negative horizon elevation angles show evidence of lower basic transmission loss.

Measurements made at 11.4 GHz in the UK [Hewitt and Adams, 1980] show that, for land, sea and coastal paths, the percentage of time appertaining to a defined transmission loss will be the sum of a relatively small number of events whose durations extend from a few minutes to many hours.

The curves for γ_d applicable to land paths are based on data for regions where the highest monthly mean value of ΔN is below 70 N units/km. For regions where the highest monthly mean value of ΔN is significantly greater than this, the values of γ_d given in Fig. 2b should be multiplied by 0.6, 0.7, 0.8 and 0.8 for time percentages of 1%, 0.1%, 0.01% and 0.001% respectively.

The terrain roughness ΔH^* is the difference in the heights exceeded by 10% and by 90% of the terrain over the whole length of a substantially horizontal great-circle interference path. If the path is not substantially horizontal, ducting – and hence ΔH – may be disregarded, but in cases where ducting is not applicable, diffraction and tropospheric scatter should not be overlooked. For an over-water path ΔH is zero. For $\Delta H > 50$ m, the values of γ_d given in Fig. 2b should be increased by $(\Delta H - 50) \times 10^{-3}$ dB/km.

In the evaluation of interference likely to be experienced by a terrestrial radio-relay station, some caution is required in applying the ducting mode calculations. It has been shown [Doble, 1981] that, because of the similarity of the atmospheric processes involved, there may be some correlation between the incidences of multipath fading of the wanted signal and ducting or superrefractive enhancements of the interfering signal.

3.2.3.2 Additional diffraction loss A_s

To estimate the amount of energy coupled into this propagation mode when either or both terminals see a positive horizon elevation angle, the attenuation is increased by an additional loss which may be determined as a single knife-edge attenuation with the assumption that the diffraction angle θ equals the horizon elevation angle in a standard atmosphere θ . To estimate this additional attenuation the following expression may be used:

$$A_s \simeq 20 \log [1 + 6.3\theta (fd_h)^{1/2}] + 0.46 \theta (fC_r)^{1/3} \quad \text{dB} \quad (4)$$

where:

θ : horizon elevation angle (degrees), $\theta \geq 0$,

f : frequency (GHz),

d_h : horizon distance (km),

C_r : obstacle radius of curvature (m).

For values of $\theta < 0$, $A_s = 0$.

3.2.3.3 Prediction method for paths extending from one zone into another zone (mixed paths)

For mixed paths, the term $\gamma_d \cdot d$ in equation (3), is to be replaced by:

$$\gamma_{A1} \cdot d_{A1} + \gamma_{A2} \cdot d_{A2} + \gamma_B \cdot d_B + \gamma_C \cdot d_C$$

where:

γ_{A1} , γ_{A2} , γ_B and γ_C are the sums of the specific attenuations due to ducting for zones A1, A2, B and C respectively;

d_{A1} , d_{A2} , d_B and d_C are the lengths of the sections of the path contained in zones A1, A2, B and C respectively, such that $d_{A1} + d_{A2} + d_B + d_C = d$.

* The definition of ΔH in the context of interference propagation is different from that in other applications such as the planning of broadcasting and mobile services: see Recommendation 370 (Recommends 1.4) and Report 239 for examples.

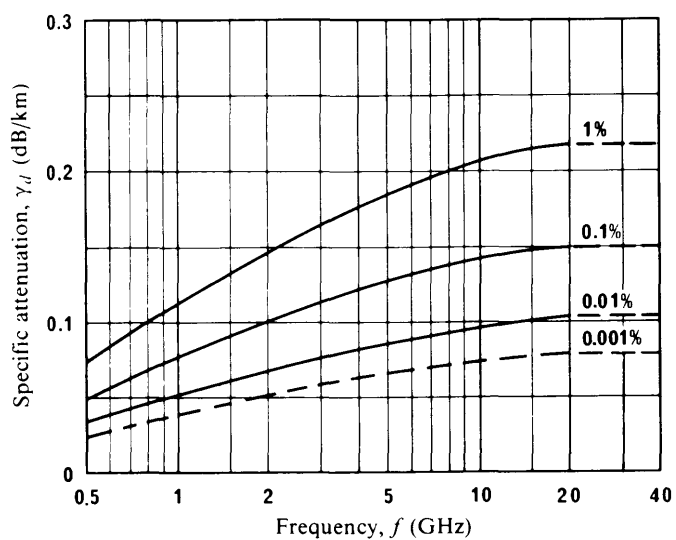


FIGURE 2a — Specific attenuation (Zone A1)

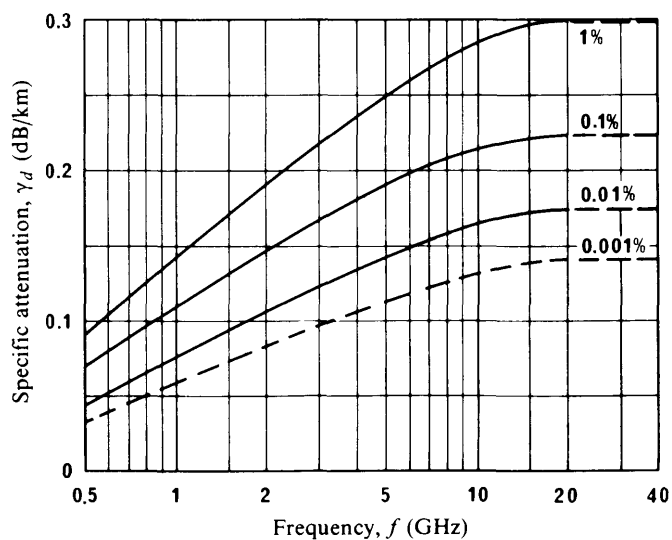
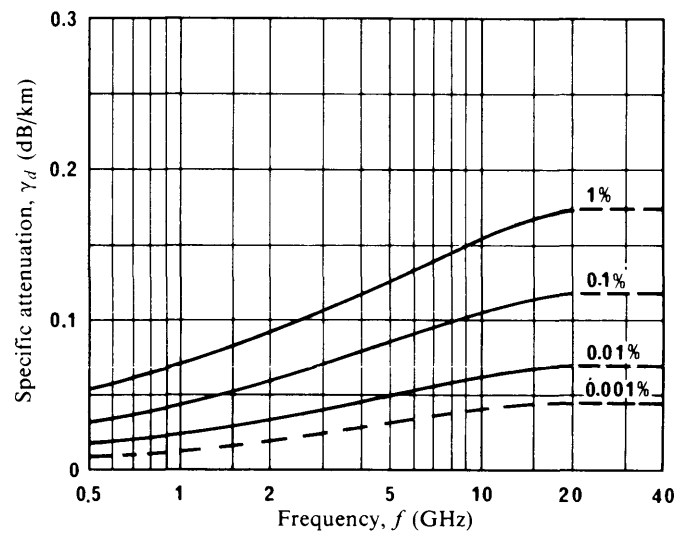
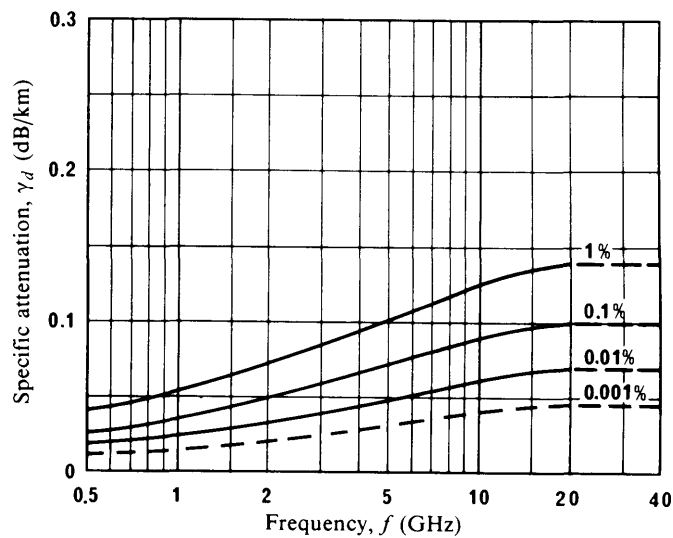


FIGURE 2b — Specific attenuation (Zone A2)

$$\Delta H \leq 50 \text{ m}$$

Note. — The dashed curves are provisional.

FIGURE 2c — *Specific attenuation (Zone B)*FIGURE 2d — *Specific attenuation (Zone C)*

Note. — Current data do not indicate clearly a difference between Zones B and C at time percentages of 0.01 or less. The dashed curves are provisional.

3.2.4 Combination of several mechanisms

For some paths a combination of several of the above mechanisms may be assumed. The most important case is that of a path with diffraction edges which are not visible from each other or from one end.

The attenuation relative to free space is estimated as discussed in the previous section, ignoring the presence of the isolated obstacle(s), with (a) the appropriate additional knife-edge attenuation values obtained from the procedure discussed in § 3.2.1, and (b) the additional attenuation due to that portion of the path not visible from the top of the obstacle; the latter data may be obtained by reference to § 3.2.2.

4. Tropospheric forward scatter

In the context of this Report the tropospheric forward scatter mode is taken to be the mode of propagation which results predominantly from inhomogeneous scattering by random fluctuations of the refractive index of the atmosphere. It results in transmission of signals beyond the horizon at a strength greater than would occur simply through the phenomenon of diffraction round the curved surface of the Earth. On overseas paths and for small percentages of the time the field strength of such signals is much lower than that resulting from forms of superrefraction, (including ducting). The latter are therefore responsible for interference in a clear atmosphere, as discussed in § 3.

However, under two conditions the tropospheric scatter propagation mode may be the predominant propagation mechanism and hence, the predominant cause of interference:

- (a) for percentages of the time between about 1 and 50% on overland and overseas paths;
- (b) for small percentages of the time ($\leq 1\%$) on predominantly overland paths when either of the terminal stations is credited with very high site shielding (> 30 dB) in the procedures of § 3. In this case, the prediction method of § 3 yields field strengths which may be lower than those to be expected from "pure" tropospheric forward scatter propagation.

For these cases, the basic transmission loss due to tropospheric forward scatter may be estimated using the methods of Report 238, but using, instead of the term $Y(q)$ in equation (7a) or (7b), the term $-Y(q)$, where $100 - q$ is the percentage of the time of interest ($100 - q \leq 50\%$). This suggested procedure is based on the assumption that the familiar log normal cumulative distribution of "pure" tropospheric forward scatter field strength as observed for percentages of the time greater than 50% can, without change in the standard deviation, be extrapolated to the small percentages of the time. There is some limited experimental support for this assumption [Larsen, 1973].

For paths crossing more than one propagation climate, it is suggested that the climate in Report 238 which yields the lower value of transmission loss be used for the entire path.

The antenna gain degradation for small percentages of time (see item (b)) should be calculated from formula (13) of Report 238, assuming $\theta_h = 0$ and $\theta_v = 1.7^\circ$. For propagation mechanisms other than scattering such as ducting (see § 3.2) there may be no gain degradation.

The methods of Report 238 for calculating loss due to tropospheric scatter propagation have not been validated for frequencies above 4 GHz. Some preliminary studies suggest that the formula for the median transmission loss may still hold approximately at frequencies up to about 12 GHz. However, theoretical calculations suggest that at frequencies between about 2 and 6 GHz, the frequency dependence of the transmission loss will change from $30 \log f$ to about $20 \log f$. It is therefore suggested that, for interference calculations at frequencies above 4 GHz, the term $30 \log f$ in equations (1), (6a), and (10) of Report 238 be replaced by the term $20 \log f + 96$, where f is in GHz. However, calculations made at these higher frequencies should be used with extreme caution.

The value of basic transmission loss so found should be compared with that obtained from § 3 of this Report, and the lower value should be used to assess interference.

On overseas paths and for percentages of the time less than 1% only the prediction methods of this Report should be used. This would, in all cases, include an estimate of interference to be expected from scattering by hydrometeors, as discussed in § 5.

An alternative method of evaluating interference levels on overland and coastal paths has been suggested by the U.S.S.R. [Troitsky, 1981]. This provides, for temperate climates, worst month statistics for the combined effects of ducting and tropospheric scatter.

5. Hydrometeor scatter

In the types of propagation discussed in § 3 and 4, the signal is propagated in the forward direction in the great circle plane containing transmitter and receiver. On the other hand, scattering from hydrometeors (including rain, snow, hail, and ice clouds) can be considered to be isotropic. The important physical processes giving rise to precipitation scatter are considered in Report 882.

Scattering by hydrometeors may cause interference, even for large scattering angles and with antenna beams intersecting outside the great circle path. The main problem of importance is interference between earth stations and terrestrial radio-relay stations, but the possible interference arising between earth stations also needs to be evaluated.

There are several geometrical situations to consider. The first is when major portions of both main beams intersect in a rainstorm, and in this case coupling may occur between beams from stations at large separations (several hundred kilometres). The second is when near-intersection occurs, or when coupling occurs via main lobe/side-lobe or side lobe/side-lobe intersections. In these conditions, the effective antenna gains are smaller and so this interference is noticed at smaller distances. Finally, at short distances, say less than 100 km, main lobe/far side-lobe intersections occurring in a heavy rainstorm may cause interference.

The interference-path geometry also must take account of obstacles. If an obstacle partially or wholly obstructs a lobe of an antenna, then interference coupling by means of this lobe will be partially or wholly eliminated except insofar as diffraction may occur. Such obstacles of course are not necessarily on the great circle path between the stations.

The information in this present Report is limited to a transmission loss model representative of practical conditions as they may exist when an earth station and a terrestrial station or two earth stations, one receiving, the other transmitting, operate on the same frequency.

The method developed in this section assumes that the interference path contains at least one high-gain antenna beam the near field of which extends beyond the significant scatter volume. It does not, therefore, lend itself to the evaluation of rain scatter interference between relatively low-gain antennas. It is suggested that when the larger of the two antennas in a given case has a diameter-to-wavelength ratio of less than about 50 ($D/\lambda < 50$), a more detailed analysis such as referred to in Report 882 be undertaken.

A more general discussion of the basic analysis and radiometeorological concepts used is given by Crane [1974]. It must be emphasized that any rigorous evaluation of the effect of precipitation scatter covering all possible conditions would be extremely difficult and detailed. Such a treatment requires, for example, a knowledge of antenna polar diagrams, especially of the side lobes, and of the intensity and spatial distribution of heavy rain.

The treatment of rain scatter in this section assumes a time-invariant antenna pointing geometry. Interference problems involving an earth station operating with a non-geostationary satellite require further study.

5.1 Transmission loss equations for rain scatter

If L is the transmission loss for coupling due to scatter by rain, it has been shown [Crane, 1974] that, to a sufficient degree of accuracy,

$$L = 10 \log \left(\frac{p_T}{p_R} \right) = 10 \log \left(\frac{\lambda^2 10^{17} r^2}{g_T \cdot d_s \cdot Z \cdot M} \right) \quad \text{dB} \quad (5)$$

where:

p_R : received power (W),

p_T : transmitted power (W),

λ : wavelength (cm);

and

g_T , d_s , Z and M are described below.

If allowance is made for attenuation factors, divergence from Rayleigh law scattering, and considering that the zero isotherm may pass through the scattering volume, equation (5) may be rewritten as follows:

$$L = 199 + 20 \log r - 20 \log f - 10 \log M + 10 \log S - 10 \log C + A_g - 10 \log Z_R - 10 \log B \quad \text{dB} \quad (6)$$

where:

r : distance from terrestrial station to the scattering volume (km);

f : frequency (GHz);

M : polarization decoupling factor. This term is intended to allow for the fact that rain scatter is anisotropic and that the polarization of the scattered interfering signal may be different from that of the receiving antenna. The relation between these two polarizations will, in general, be complex, depending on the polarizations of the transmitting and receiving antennas, the shape of the scattering particles and the overall geometry of the system. If a preliminary calculation for cases of main beam-main beam coupling with $M = 1$ indicates the possibility of an interference situation, it would in theory be possible to evaluate M more precisely taking into account the above parameters [Awaka, 1979]. M should be taken equal to unity for cases of main beam side-lobe coupling.

S : an allowance for the deviation from Rayleigh law scattering at frequencies above 10 GHz:

$$10 \log S = R^{0.4} \times 10^{-3} \left[4(f-10)^{1.6} \left(\frac{1+\cos\alpha_T}{2} \right) + 5(f-10)^{1.7} \left(\frac{1-\cos\alpha_T}{2} \right) \right] \quad \text{dB} \quad \text{for } f > 10 \text{ GHz} \quad (7)$$

$$= 0 \text{ dB} \quad \text{for } f \leq 10 \text{ GHz}$$

R : the rainfall rate in the scatter volume (mm/h);

α_T : the azimuth of the terrestrial station relative to the earth-station beam azimuth, measured at the scatter volume ($\alpha_T = 0^\circ$: forward scatter; $\alpha_T = 180^\circ$: back scatter);

C : the rain attenuation in the scatter volume below the 0°C isotherm:

$$10 \log C = \left(\frac{1-\cos\alpha_T}{2} \right) 10 \log \left[\frac{2.17}{\gamma_R d_a} (1 - 10^{-\gamma_R d_a/5}) \right] - \gamma_R d_a \left(\frac{1+\cos\alpha_T}{2} \right) \quad \text{dB} \quad (8)$$

γ_R : kR^α , the rain attenuation coefficient in the rain cell (dB/km); (see Report 721);

d_a : the earth-station main beam section lying in the rain cell below the 0°C isotherm (km); (see Fig. 3);

r_a : the effective total atmospheric slant path from the terrestrial station through the scatter volume for gaseous absorption (km); (see Report 719);

A_g : the attenuation due to gases (dB). In this case A_g may be estimated by (see Report 719):

$$A_g = \gamma_a \left(r_a + \frac{H_a}{\sin \epsilon} \right) (1 - e^{-h_0/H_a}) \quad \text{dB}$$

ϵ : the earth-station main beam elevation angle (degrees);

γ_a : the specific composite gaseous absorption for oxygen and water vapour (dB/km); (see Report 719);

h_0 : the height of the intersection of the terrestrial station's horizon ray with the earth-station antenna main beam (km); (see Fig. 3);

Z_R : the unit volume rain scatter reflectivity factor below h_R (mm^6/m^3); (see Report 563);

$$Z_R = 400 R^{1.4} \quad (\text{mm}^6/\text{m}^3) \quad (h \leq h_R);$$

h : the altitude above ground of a common volume element dx used in the integration (km);

d_s : the axial length in km of the earth-station antenna main beam lying within the rain cell * of width d_c (km), (see equation (12), also Report 563);

The term $10 \log B$ is defined by:

$$10 \log B = 10 \log \left[10^{-\Gamma_1/10} \int_{D_0}^{D_a} g_T dx + 10^{-\Gamma_2/10} \int_{D_a}^D g_T 10^{-0.65(h-h_R)} dx \right] \quad \text{dB} \quad (9)$$

g_T : the numerical antenna gain component of the terrestrial station in the direction of an integration element dx along the earth-station main beam from $D_0 = 0$ to D ;

h_R : the rain ice-crystal transition height (km) (see Report 563) and above the height h_R the reflectivity is assumed to decrease by 6.5 dB per km of additional height.

Figure 3 shows the scatter geometry and the parameters associated with the calculation of transmission loss.

* A rain cell is here defined as one of several limited regions of relatively high rain rate embedded within a generally substantially greater area of lower rain intensity.

Note that when the antenna gain component g_T of the terrestrial station does not vary much between D_0 and D_a or between D_a and D , an average value g_T may be assumed and may be removed from the integral or integrals. The first integral would then simply assume the value d_a . Note also that when the entire common volume along d_s lies below h_R , only the first integral remains; the second becomes zero. Conversely, when the entire common volume along d_s lies above h_R , the first integral vanishes and only the second remains.

The terms Γ_1 and Γ_2 are intended to provide an estimate of rain attenuation outside the scatter volume. The terms are discussed in § 5.2.

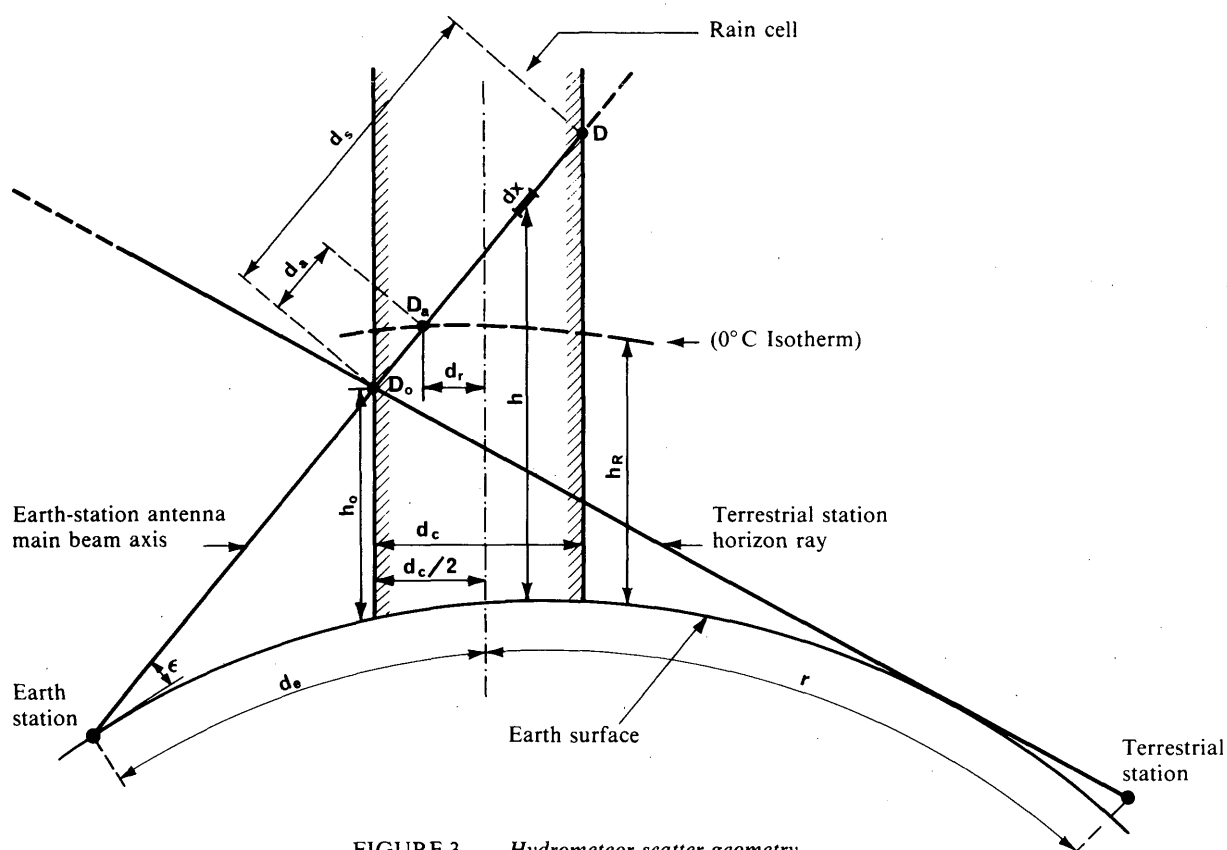


FIGURE 3 — Hydrometeor scatter geometry

5.2 Rain attenuation outside the scatter volume

Report 882 presents a model for estimating attenuation when the point rainfall rate statistics relevant to a path are known. Based on this model the two terms Γ_1 and Γ_2 are defined as follows:

$$\Gamma_1 = \frac{\gamma_R}{\alpha} \left[\frac{e^{u_{ad0}} - e^{u_{ad1}}}{u \cos \epsilon} + e^{b\alpha} \left(\frac{e^{c_{ad3}} - e^{c_{ad2}}}{c \cos \epsilon} + e^{c_{ad4}} - e^{22.5c\alpha} \right) \right] \quad \text{dB} \quad (10)$$

$$\Gamma_2 = \frac{\gamma_R}{\alpha \cos \epsilon} \left[\frac{e^{u_{ad0}} - e^{u_{ad5}}}{u} + e^{b\alpha} \left(\frac{e^{c_{ad3}} - e^{c_{ad6}}}{c} \right) \right] \quad \text{dB} \quad (11)$$

where

α : exponent in the specific attenuation expression $\gamma_R = kR^\alpha$. The values of k and α are given in Table I of Report 721.

$$u = \frac{b}{d_0} + c;$$

$$b = 0.83 - 0.39 \log R;$$

$$c = 0.026 - 0.069 \log R;$$

$$d_0 = 3.8 - 1.38 \log R;$$

d_1 : smaller of d_0 and $d_c/2$ (see Fig. 3);

d_2 : greater of d_0 and $d_c/2$;

$$d_3 = d_e \text{ when } d_e < 22.5 \text{ km} \\ = 22.5 \text{ km when } d_e \geq 22.5 \text{ km (see Fig. 3);}$$

$$d_4 = d_e + d_c/2 \text{ when } d_e + d_c/2 < 22.5 \text{ km} \\ = 22.5 \text{ km when } d_e + d_c/2 \geq 22.5 \text{ km;}$$

d_5 : greater of d_r and $d_c/2$ when $d_0 > d_r$ and $d_0 > d_c/2$;
 $= d_0$ when either $d_0 \leq d_r$ or $d_0 \leq d_c/2$;

d_6 : greatest among d_r , d_0 and $d_c/2$ when $d_r < d_e \leq 22.5 \text{ km}$;
 is the smaller of d_e and 22.5 km when $d_r \geq d_e$.

The distances $d_c/2$, d_a , d_s , d_r and d_e are identified in Fig. 3. The distance d_c is obtained as a function of rainfall rate from equation (12):

$$d_c \approx 3.3 R^{-0.08} \quad \text{km} \quad (12)$$

The other distances may be estimated as follows:

$$d_a \approx \left(h_R - \frac{(r + d_c/2)^2}{17\,000} \right) / \sin \epsilon \quad \text{km} \quad (13a)$$

$$d_s \approx d_c / \cos \epsilon \quad \text{km} \quad (13b)$$

$$d_e \approx \frac{r^2}{17\,000 \tan \epsilon} \quad \text{km} \quad (13c)$$

$$d_r \approx d_e - \frac{h_R}{\tan \epsilon} \quad \text{km} \quad (13d)$$

5.3 Cumulative distribution of transmission loss

Interference criteria are usually given in terms of a cumulative distribution of the permissible interfering signal level. Compliance with these criteria requires, first, the derivation of the cumulative distribution of transmission loss. It then has to be shown that, for all relevant percentages of time, the appropriate transmission loss exceeds the corresponding interference criteria.

5.4 Experimental measurements

Measurements over a period of one year in the Eastern United States have shown that, for intersecting main beams from an earth station and a terrestrial station 50 to 80 km apart, the experimental values of loss agree with those predicted using surface rainfall rates, for a scattering volume at a height of 3 km. For a scattering volume at 6 km, the predictions tended to underestimate the loss for 0.01% of the year. Other observations indicate that assumptions of Rayleigh scattering and negligible attenuation effects are both valid below 8 GHz [Crane, 1974].

Similar measurements at 12.3 GHz, over a 3-year period in the Federal Republic of Germany, with a common volume in the main beams at a height of 1-3 km showed good agreement between measured and calculated values of transmission loss for 0.01% of the time [CCIR, 1974-78].

5.5 General conclusions

The most serious case is that of intersecting main beams. Also, for frequencies greater than about 8 GHz, the distance for a given transmission loss does not continue to increase with increasing rainfall rate. At the higher frequencies attenuation increasingly outweighs the effects of scatter. Consequently, in such circumstances the maximum net signal can occur at light rainfall rates. The interference criteria must therefore be examined for a range of rainfall rates, i.e. for a range of time percentages for which the rates are exceeded.

For intersection of the earth-station beam and the first side lobe of the terrestrial station (i.e. for a beam displacement of the latter of about 3° away from exact intersection), the losses for storm-type rain increase by about 18 dB in most cases as compared with those for the intersecting condition.

Interference of objectionable magnitude could possibly be experienced due to rain scatter via an intersection of an earth-station main beam with the far side lobes of an interfering station.

6. Reflections from aircraft

Coupling between two antenna beams can be effected by reflections from aircraft. The probability of occurrence of such events depends on the frequency of aircraft movements through the intersections of the antenna main beams or side lobes. Their duration will depend on the speed of the aircraft and the overall geometry.

In an investigation made in the Federal Republic of Germany on a 1.9 GHz tropospheric scatter link of 420 km length, some 19 000 events attributed to aircraft reflections were observed during a period of 10 000 hours.

The percentages of these cases where a defined basic transmission loss was not exceeded are given in Table IV, and these provide an indication of the interference levels involved. During these measurements the average basic transmission loss due to tropospheric scatter was about 236 dB.

TABLE IV - Percentage of cases in which a defined value of the basic transmission loss is exceeded

Percentage of cases	50	10	1	0.1	0.02	0.005
Basic transmission loss (dB)	234	226	221	216	213	210

The measured results could be explained by the use of a model [CCIR, 1978-82b] which considers the aircraft as plane reflectors of equivalent effect.

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REPORT 724-1 *

**PROPAGATION DATA REQUIRED FOR THE EVALUATION OF COORDINATION
DISTANCE IN THE FREQUENCY RANGE 1 TO 40 GHz**

(Study Programme 5D/5)

(1978-1982)

1. Introduction

1.1 This Report sets out a straightforward method, based on a simplification and condensation of the information in Report 569 for the assessment of the propagation factors concerned in the determination of coordination distances. This Report provides propagation data for use in the calculation of a coordination area. In view of the provisional nature of some of the information, the Report is not at present being proposed as the basis for any changes in the Radio Regulations. Administrations are requested to compare results obtained using this Report with the standard methods of Appendix 28 of the Radio Regulations, and to forward the results of such comparison to Study Group 5. If the application of this method reveals that a potential coordination problem exists, then evaluation should be carried out as described in Report 569.

The determination of coordination distance propagation characteristics for an earth station is here based on the assumption that:

- the locations of terrestrial stations with which coordination is to be sought are not known;
- in the interference path geometry, only information pertaining to the earth station is available;
- for the geometry over the remainder of the interference path cautious limiting assumptions must be made as shown in the following text.

1.2 Because of the risk of error in predicting transmission loss over short distances when the exact path geometry is unknown, the minimum coordination distance in all cases is considered to be 100 km.

1.3 In this Report propagation phenomena are classified into two modes as follows:

- Mode A: propagation phenomena in clear air, and affected by the presence of the Earth's surface (diffraction, refraction, ducting). These phenomena are confined to propagation along the great-circle path,
- Mode B: rain scatter** which is not limited to the great-circle path, but is, as dealt with in this Report, limited to earth stations operating with geostationary satellites.

Modes A and B are illustrated in Fig. 4.

1.4 For each azimuth from the earth station, and for each of the above two modes of propagation, it is necessary to determine a distance corresponding to the required transmission loss. The greater of the two distances so obtained should be taken as the reference distance for that particular azimuth.

2. Mode A: great-circle path mechanisms

2.1 Definition of zones

For this calculation, the Earth is considered to be divided into three geographic zones:

- Zone A: land, excluding the coastal strip extending 50 km from Zone B and Zone C;
- Zone B: seas, oceans, and other substantial bodies of water (as a criterion, one which can encompass a circle of diameter 100 km) at latitudes greater than 23.5° N or S, but excepting the Black Sea and the Mediterranean and including the coastal strip extending 50 km inland;
- Zone C: seas, oceans and other substantial bodies of water (as a criterion, one which can encompass a circle of diameter 100 km) at latitudes less than 23.5° N or S, and including the Black Sea and the Mediterranean and the coastal strip extending 50 km inland.

* This Report is brought to the attention of Study Groups 1, 2, 4, 7, 8, 9, 10 and 11.

** Rain scatter is the predominant form of precipitation scatter in the context of the present problem.

2.2 Paths entirely in one zone

For Mode A, the basic transmission loss L_b in dB, is given by:

$$L_b = 92.5 + 20 \log f + 10 \log d + A_c + (\gamma_d + \gamma_o + \gamma_w) d + A_s \quad \text{dB} \quad (1)$$

where:

f : frequency (GHz),

d : length of the path (km),

A_c : coupling loss (dB) into the duct and is taken as 7.5 dB (Report 569),

γ_d : specific attenuation (dB/km), due to ducting and super-refraction, not including losses due to oxygen and water vapour and depends on the zone, frequency and time percentage (see Report 569):

$$\gamma_d = a(p) + b(p) g(f) \quad \text{dB/km} \quad (2)$$

where the values of $a(p)$, $b(p)$ and $g(f)$ may be evaluated for each zone using the expressions in Table I.

TABLE I - The values of $a(p)$, $b(p)$ and $g(f)$ of equation (2) for the different zones

	$a(p)$	$b(p)$	$g(f)$
Zone A	$0.052 + 0.020 (\log p + 3)^{1.3}$	$0.080 + 0.013 (\log p + 3)^{1.3}$	$\log f - 0.07 (\log f)^5 + 0.002 (\log f)^{10}$
Zone B	$0.013 + 0.009 (\log p + 3)^{1.5}$	$0.026 + 0.011 (\log p + 3)^{1.5}$	$\log f - 0.4 (\log f - 0.5)^3 + 0.001 (\log f)^{10}$
Zone C	$0.013 + 0.009 (\log p + 3)^{1.1}$	$0.026 + 0.011 (\log p + 3)^{1.3}$	$\log f - 0.4 (\log f - 0.5)^3 + 0.001 (\log f)^{10}$

p : time percentage ($0.001 \leq p \leq 1\%$),

γ_o : specific attenuation (dB/km) due to absorption by oxygen (see Report 719):

$$\gamma_o = \left[\frac{6.6}{f^2 + 0.33} + \frac{9}{(f - 57)^2 + 1.96} \right] f^2 \times 10^{-3} \quad \text{dB/km} \quad (3)$$

γ_w : specific attenuation (dB/km) due to water vapour, based on the following values of ρ , where ρ is the water vapour concentration in the air:

Zone A: $\rho = 1 \text{ g/m}^3$

Zone B: $\rho = 2 \text{ g/m}^3$

Zone C: $\rho = 5 \text{ g/m}^3$.

The following expression is used for γ_w (see Report 719):

$$\gamma_w = \left[0.067 + \frac{2.4}{(f - 22.3)^2 + 6.6} + \frac{7.33}{(f - 183.5)^2 + 5} \right] f^2 \cdot \rho \times 10^{-4} \quad \text{dB/km} \quad (4)$$

γ_w : may be neglected when $f < 10 \text{ GHz}$,

A_s : additional attenuation due to the elevation of the horizon *,

$$\begin{aligned} A_s &= 20 \log [1 + 4.5 \theta \times f^{0.5}] + \theta \cdot f^{0.33} \quad \text{dB} \quad \text{for } \theta \geq 0^\circ \\ A_s &= 0 \text{ dB} \quad \text{for } \theta < 0^\circ \end{aligned} \quad (5)$$

θ : horizon elevation angle (degrees).

Equation (1) allows d to be obtained for a defined value of L_b with the aid of an iterative computer program.

Experience of ducts occurring in practice shows that coordination distances predicted for Mode A should not exceed the limits shown in Table II.

* See Report 569, assuming in expression (4): $d_h = 0.5 \text{ km}$ and $C_r = 10 \text{ m}$.

TABLE II - Limit ducting distances*

Zone	Percentage of time		
	0.001	0.01	0.1 -
B and C (km)	2000	1500	1200

*These values are considered reasonable, but very little observed data are currently available.

The curves shown in Figs. 1, 2 and 3 have been drawn from the formula of § 2.2. The Mode A coordination distance is given for each of the three geographical zones as a function of frequency and $(L_b - A_s)$ exceeded for 0.01% of the time.

2.3 Mixed paths

If the distance being calculated extends through more than one zone (mixed path), the prediction is made as follows:

Designating the successive path sections in different zones by use of the suffix 1, 2, ... n it follows that:

$$L_b - 100 - 20 \log f - A_s = (\gamma_{d_1} + \gamma_{w_1} + \gamma_o) d_1 + 10 \log d_1 \quad \text{dB} \quad (6)$$

Now, in the direction considered, if the value d_1 is greater than the distance D_1 in the first zone, it follows that:

$$L_b - 100 - 20 \log f - A_s - (\gamma_{d_1} + \gamma_{w_1} + \gamma_o) D_1 = (\gamma_{d_2} + \gamma_{w_2} + \gamma_o) d_2 + 10 \log (D_1 + d_2) \quad \text{dB} \quad (7)$$

and so d_2 is found. If the value d_2 is greater than the distance D_2 of the path in the second zone, it can be stated that:

$$\begin{aligned} L_b - 100 - 20 \log f - A_s - (\gamma_{d_1} + \gamma_{w_1} + \gamma_o) D_1 - (\gamma_{d_2} + \gamma_{w_2} + \gamma_o) D_2 \\ = (\gamma_{d_3} + \gamma_{w_3} + \gamma_o) d_3 + 10 \log (D_1 + D_2 + d_3) \quad \text{dB} \end{aligned} \quad (8)$$

from which d_3 may be found. This method may be extended as necessary; the total distance D may now be expressed:

$$D = D_1 + D_2 + \dots + d_n \quad \text{km} \quad (9)$$

3. Mode B: rain scatter

In this mode, interference may result for quite large scattering angles and for beam intersections outside the great-circle path. It is assumed that on those azimuths on which the earth-station antenna has low horizon gain or if the earth station is screened by local hills from interference due to Mode A, the coordination distance may be determined by rain scatter. This effect is of course likely to be particularly important in monsoon climates.

The rainfall characteristics used in this Report are representative of wide-ranging actual observational data, deliberately chosen to be on the conservative side. Report 563 gives a first approach to theoretical consideration of the rainfall characteristics of various climates, but it should be understood that it has not yet been possible to choose the basic theoretical parameters to fit the characteristics of precipitation under all conditions encountered in practice. It is therefore considered that, at the present stage, the evaluation of the interference caused by precipitation when carried out on the basis of the data presented in this present Report will tend to yield conservative results.

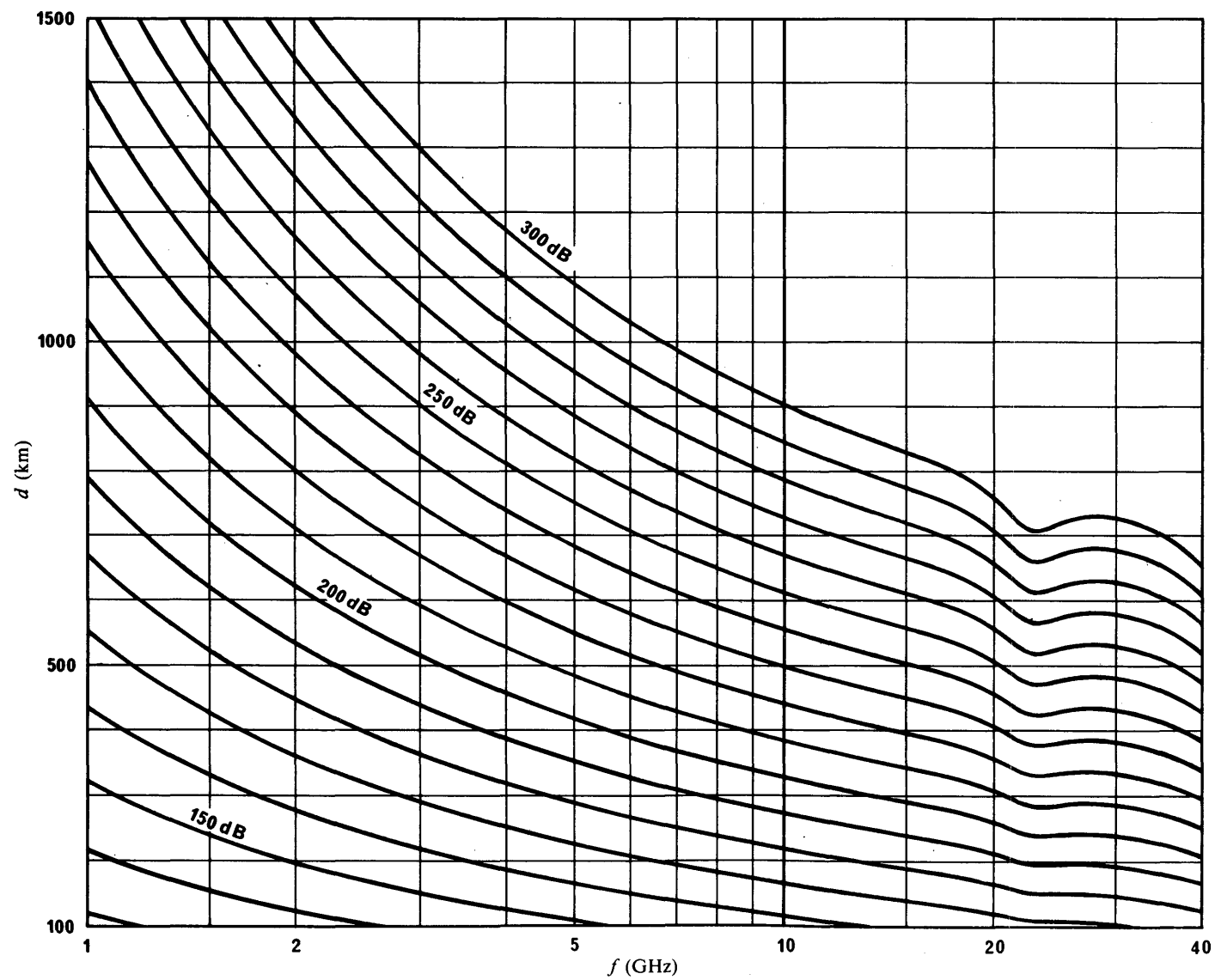


FIGURE 1 — The distance d in Zone A due to propagation Mode A as a function of the frequency and transmission loss $L_b - A_s$, exceeded for 0.01% of the time

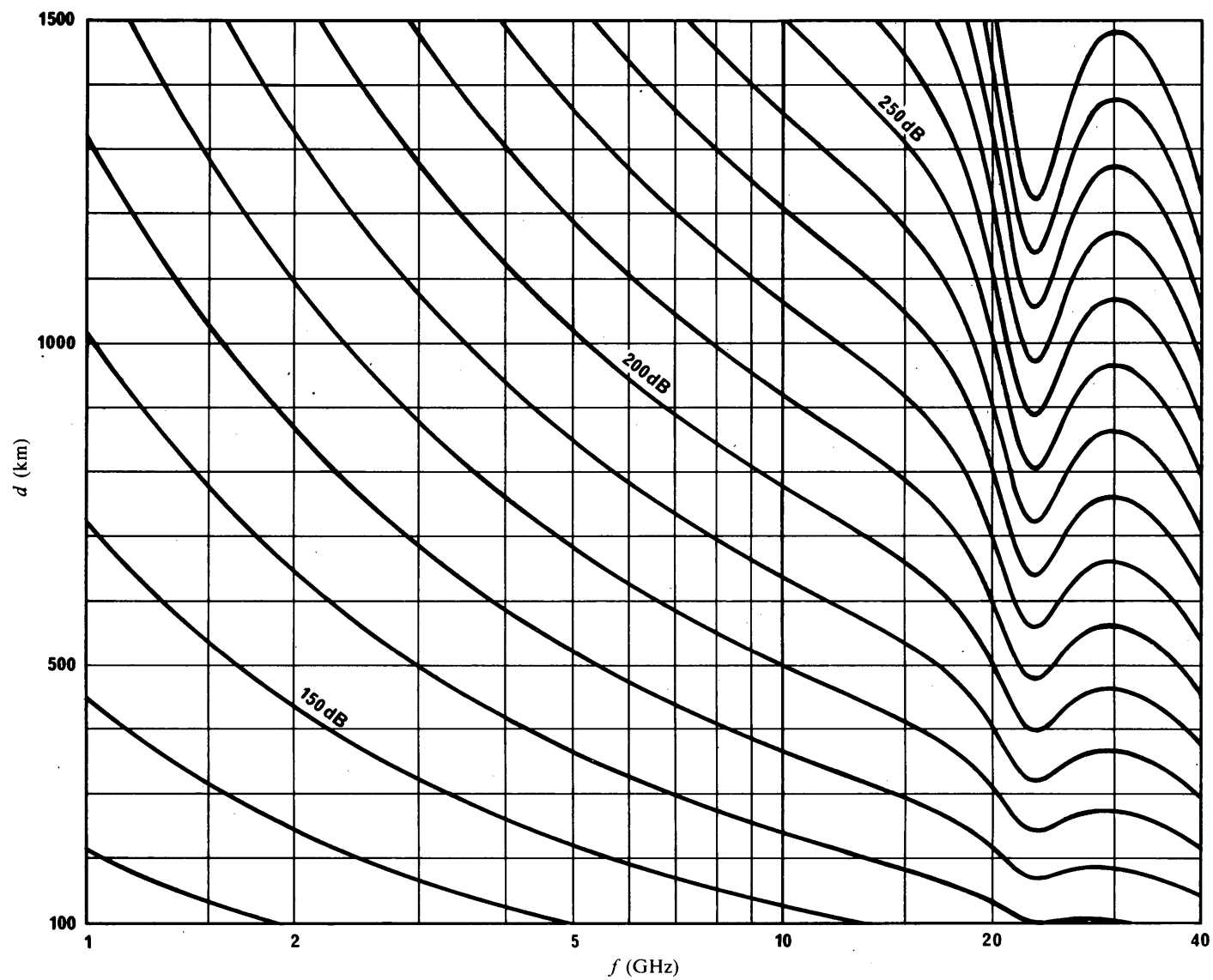


FIGURE 2 — The distance d in Zone B due to propagation Mode A as a function of the frequency and transmission loss $L_b - A_s$, exceeded for 0.01% of the time

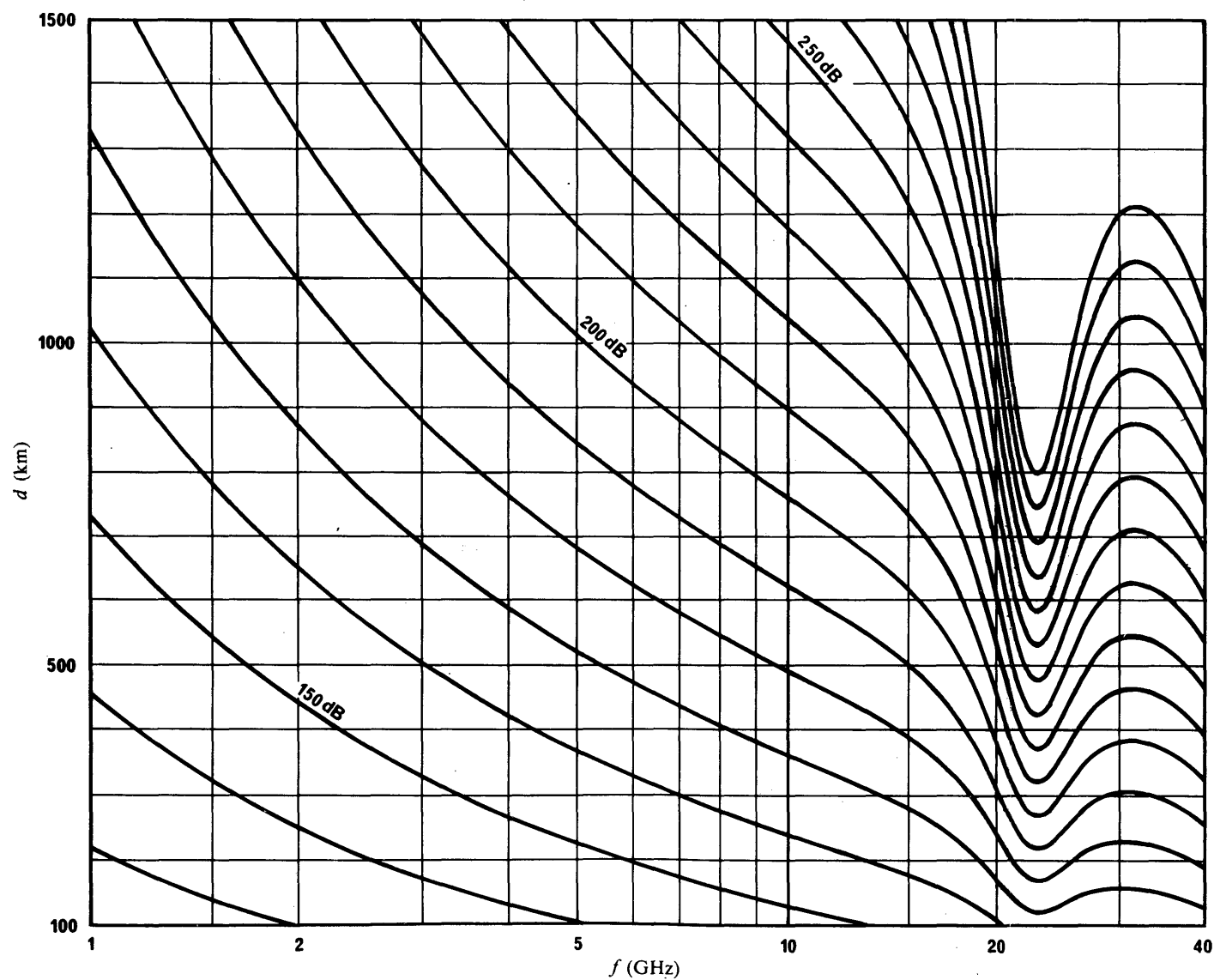


FIGURE 3 — The distance d in Zone C due to propagation Mode A as a function of the frequency and transmission loss $L_b - A_s$, exceeded for 0.01% of the time

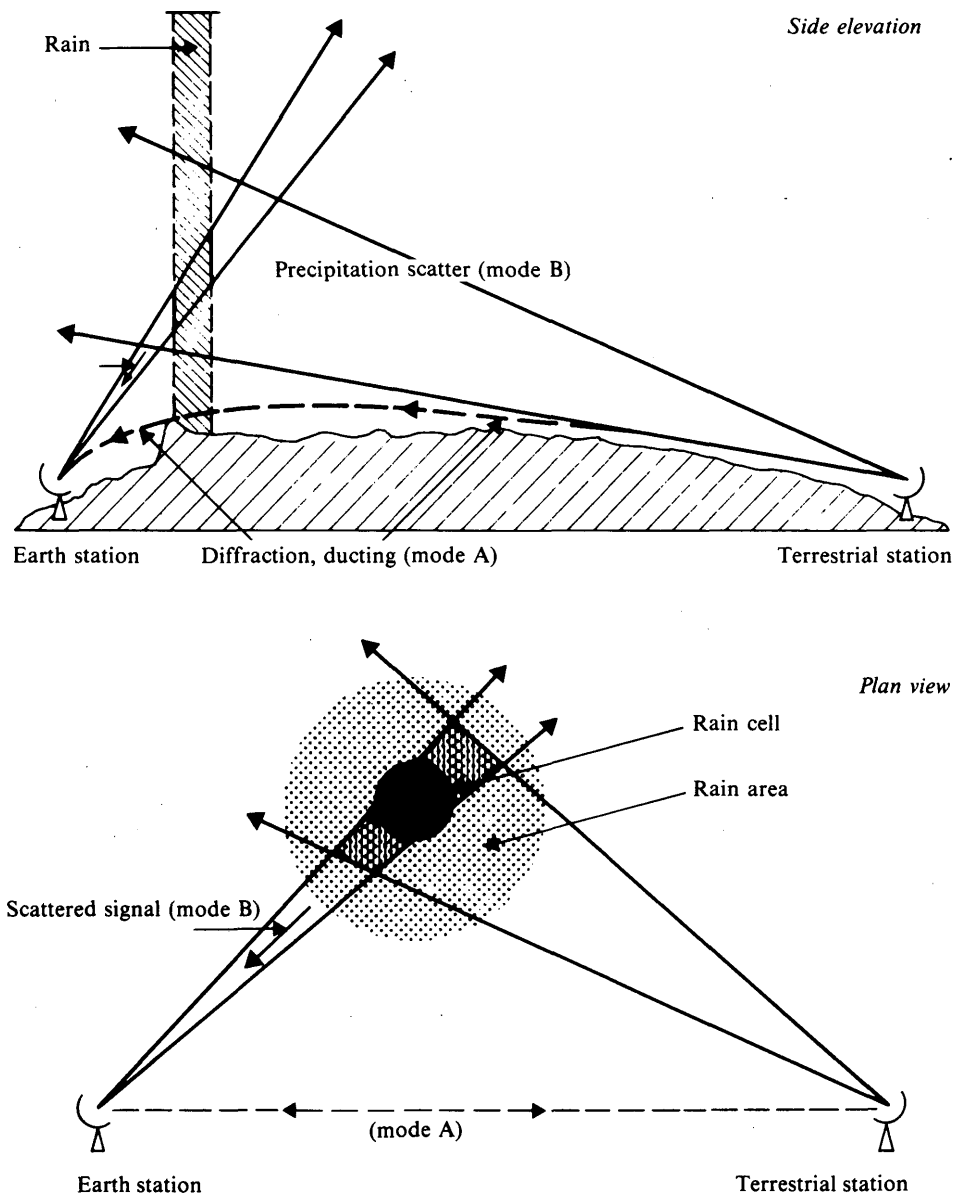


FIGURE 4 — Elevation and plan view of modes A and B

3.1 Evaluation method

3.1.1 General

For this propagation mode the previous classification of the terrain into Zones A, B and C is no longer appropriate.

The data presented herein are given in terms of rainfall rates. Annex I furnishes data by means of which rainfall rates may be related to a specific rain climatic zone, as well as to percentages of the time during which they are expected to be exceeded (see also Report 563).

The maximum heights h_R of the liquid-rain cells corresponding to precipitation rates not exceeded for four typical time percentages associated with the maximum rain rates are given in Table III as a function of geographic latitude of the location at which scattering takes place (see also Report 563).

TABLE III - Maximum rain heights h_R (km)

% of time	Latitude (degrees)				
	0-30	30-40	40-50	50-60	>60
1.0	4.6	3.7	2.1	1.1	0.5
0.1	4.8	4.0	2.8	1.9	1.0
0.01	5.1	4.6	3.8	2.8	1.7
0.001	5.4	5.1	4.6	3.8	2.5

The values for h_R of Table III are derived from Fig. 17 of Report 563.

The reflectivity of the rain within a rain cell is assumed to be constant below h_R and to decrease at the rate of 6.5 dB per kilometre above h_R .

To allow the rain scatter coordination contour to be drawn in the form of a circle, the transmission loss equation is solved for the back scatter distance only. This results in a slightly larger coordination contour than would be obtained by the exact procedure outlined in Report 569.

The transmission loss may be calculated as a function of distance r (km), frequency f (GHz) and surface rainfall rate R (mm/h) from:

$$L = 168 + 20 \log r - 20 \log f - 13.2 \log R - g_T + 10 \log A_b \quad (10)$$

$$- 10 \log C + \Gamma + \gamma_o r_o + \gamma_w r_w \quad \text{dB}$$

where:

R : the surface rainfall rate in mm/h, as given in Annex I for various rain climatic zones;

g_T : gain of the terrestrial station antenna (dB), assumed to be 42 dB.

$$10 \log A_b = 0.005 (f - 10)^{1.7} R^{0.4} \quad \text{dB} \quad \text{for } 10 \text{ GHz} \leq f < 40 \text{ GHz}$$

$$= 0 \quad \text{dB} \quad \text{for } f < 10 \text{ GHz}$$

$$C = \frac{2.17}{\gamma_R d_s} (1 - 10^{-\gamma_R d_s / 5}) \quad \text{for } f > 4 \text{ GHz}$$

$$= 1 \quad \text{for } f \leq 4 \text{ GHz}$$

where:

$$\gamma_R = k R^\alpha \quad \text{dB} \quad (11)$$

Table IV gives values for k and α for vertical polarization, which yield minimum specific attenuation (see Report 721).

TABLE IV - Values of k and α as a function of the frequency

Frequency (GHz)	k	α
1	0.000 035 2	0.880
4	0.000 591	1.07
6	0.001 55	1.27
8	0.003 95	1.31
10	0.008 87	1.26
12	0.016 8	1.20
14	0.029	1.15
18	0.055	1.09
20	0.069 1	1.07
22.4	0.090	1.05
25	0.113	1.03
28	0.150	1.01
30	0.167	1.00
35	0.233	0.963
40	0.310	0.929

Although d_s can be calculated from equation (13b) of Report 569 for any value of the earth-station main beam elevation angle ϵ , a value of $\epsilon = 20^\circ$ is considered to be sufficiently conservative, so:

$$d_s = 3.5 R^{-0.08} \quad \text{km} \quad (12)$$

$$\Gamma = \frac{\gamma_R}{\alpha} \left[\frac{e^{u\alpha d_0} - e^{u\alpha d_c/2}}{u} + e^{b\alpha} \left(\frac{e^{22.5c\alpha} - e^{c\alpha d_0}}{c} \right) \right] \quad \text{dB} \quad (13)$$

with:

$$d_0 = 3.8 - 1.38 \log R \quad \text{km}$$

$$b = 0.83 - 0.39 \log R$$

$$c = 0.026 - 0.069 \log R$$

$$u = c + b/d_0$$

$$d_c \approx 3.3 R^{-0.08} \quad \text{km}$$

The function Γ is shown in Fig. 5 as a function of the frequency f and rainfall rate R .

$$r_o = 0.7 r + 32 \quad \text{km} \quad \text{for } r < 340 \text{ km}$$

$$= 270 \text{ km} \quad \text{for } r \geq 340 \text{ km}$$

$$r_w = 0.7 r + 32 \quad \text{km} \quad \text{for } r < 240 \text{ km}$$

$$= 200 \text{ km} \quad \text{for } r \geq 240 \text{ km.}$$

The gaseous specific attenuation γ_o for (oxygen) and γ_w (for water vapour) are given in equations (3) and (4) above. The water vapour specific attenuation γ_w must be calculated for the appropriate water vapour concentration from Table V.

Equation (10) allows the distance r to be obtained as a function of the rain rate R with the transmission loss L_b as a parameter. Using this equation as a basis, the curves in Figs. 6 to 15 have been prepared and allow the rain scatter distance r_s for mode B to be easily obtained.

Note. — Figures 8 to 15 of this Report do not correspond precisely to Figs. 10 to 17 of Report 382 which however deal with the same subject (see also expression (10) of this Report and expression (21) of Report 382). In the curves presented in this Report the descending characteristic after the maximum of the rain scatter distance is not shown. In the case of higher rain rates, the interference levels and the probabilities of their occurrence are considerably lower. Hence these parts of the curves are not of practical importance.

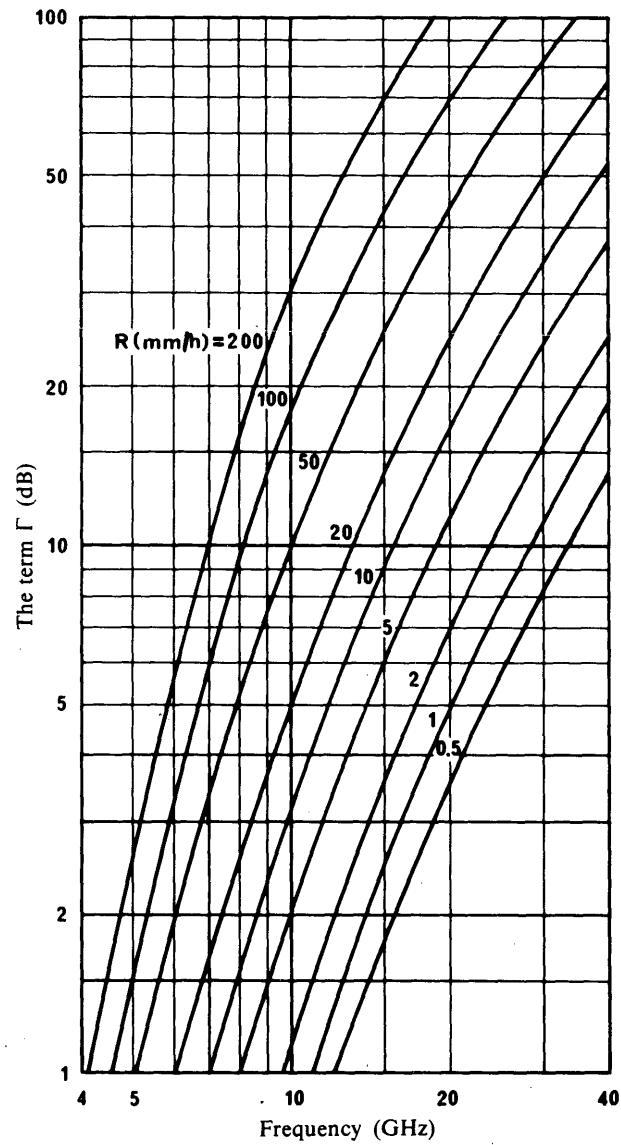


FIGURE 5 — The term Γ (dB) versus frequency and rainfall rate (R)

TABLE V — Water vapour concentration ρ assumed for the various rainfall rates

Rainfall rate R (mm/h)	>25	≤25
Water vapour concentration ρ (g/m ³)	5	2

3.1.2 Practical evaluation of rain scatter coordination distance

The procedure by which the curves of Figs. 6 to 15 are used to establish the rain scatter coordination distance r_c is as follows:

- determine, from Annex I, the rainfall rate for the appropriate percentage of time applicable to the rain climatic zone in which the earth station is situated;
- from Figs. 6 to 15 determine, for the appropriate frequency and for the rainfall rate obtained in step (a) above, the distance r_s for the desired transmission loss. The transmission loss will generally depend on the specified time percentage, and interference criteria may need to be considered for a range of time percentages;
- compare the distance r_s so found with the appropriate distance from Table VI; the smaller of the two compared distances is then the rain scatter coordination distance r_c ;
- determine a point at distance Δd along the earth-station beam azimuth. This can be obtained from Fig. 16 as a function of earth-station antenna main beam elevation angle and back scatter distance, r_c , or from the following formula:

$$\Delta d = \frac{(r_c - 40)^2}{17\,000} \cot \varepsilon \quad (14)$$

where:

ε : earth-station antenna main beam elevation angle;

- draw a circle of radius r_c around this point.

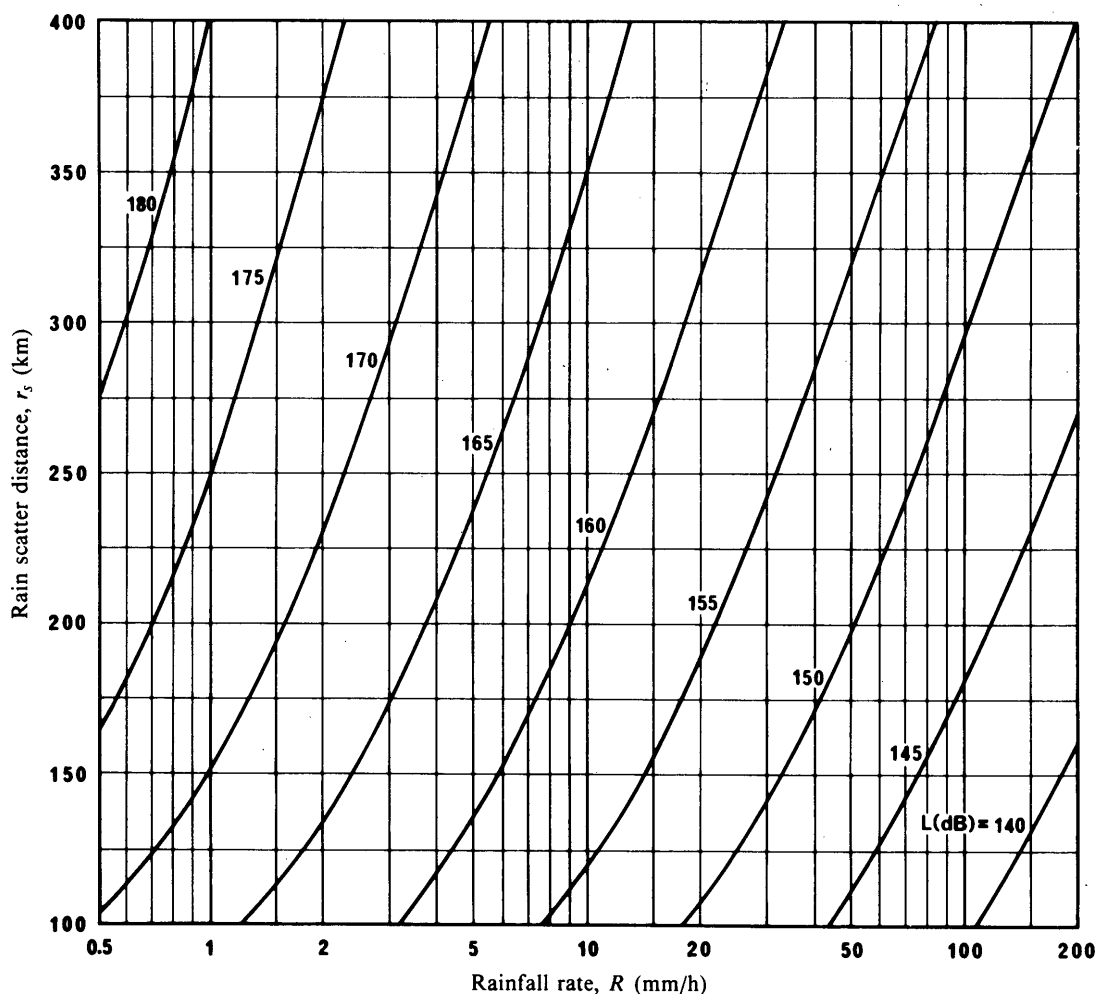


FIGURE 6 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$f = 1 \text{ GHz}$

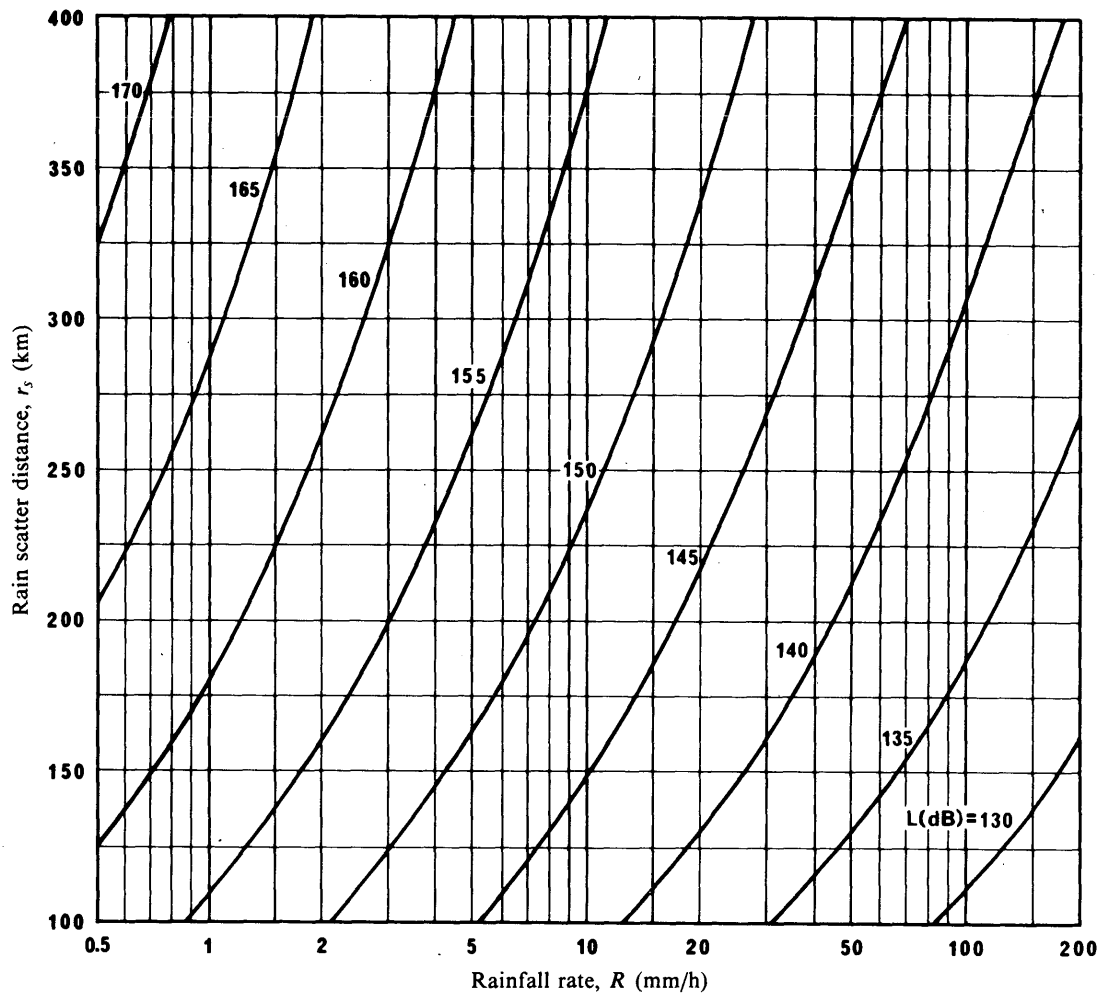


FIGURE 7 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$$f = 4 \text{ GHz}$$

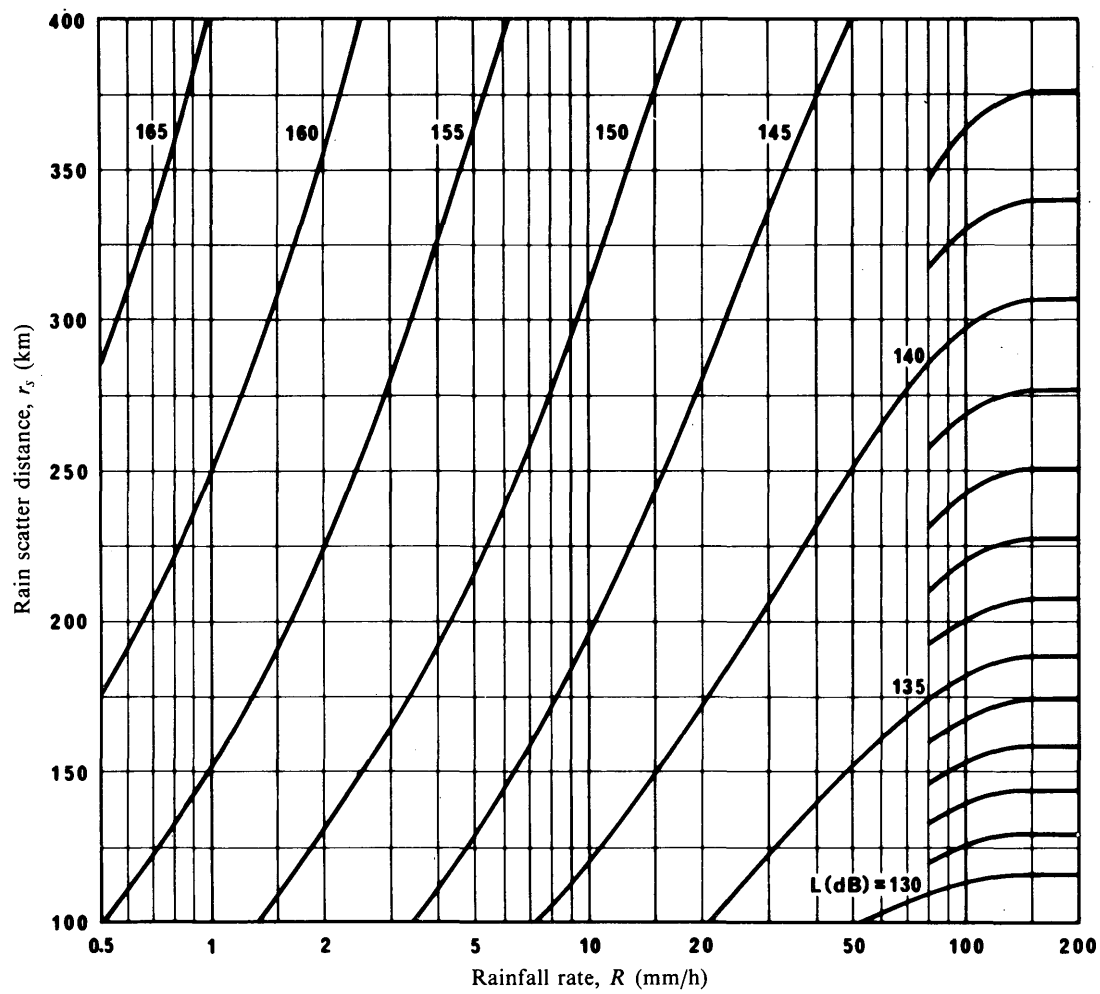


FIGURE 8 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$f = 6 \text{ GHz}$

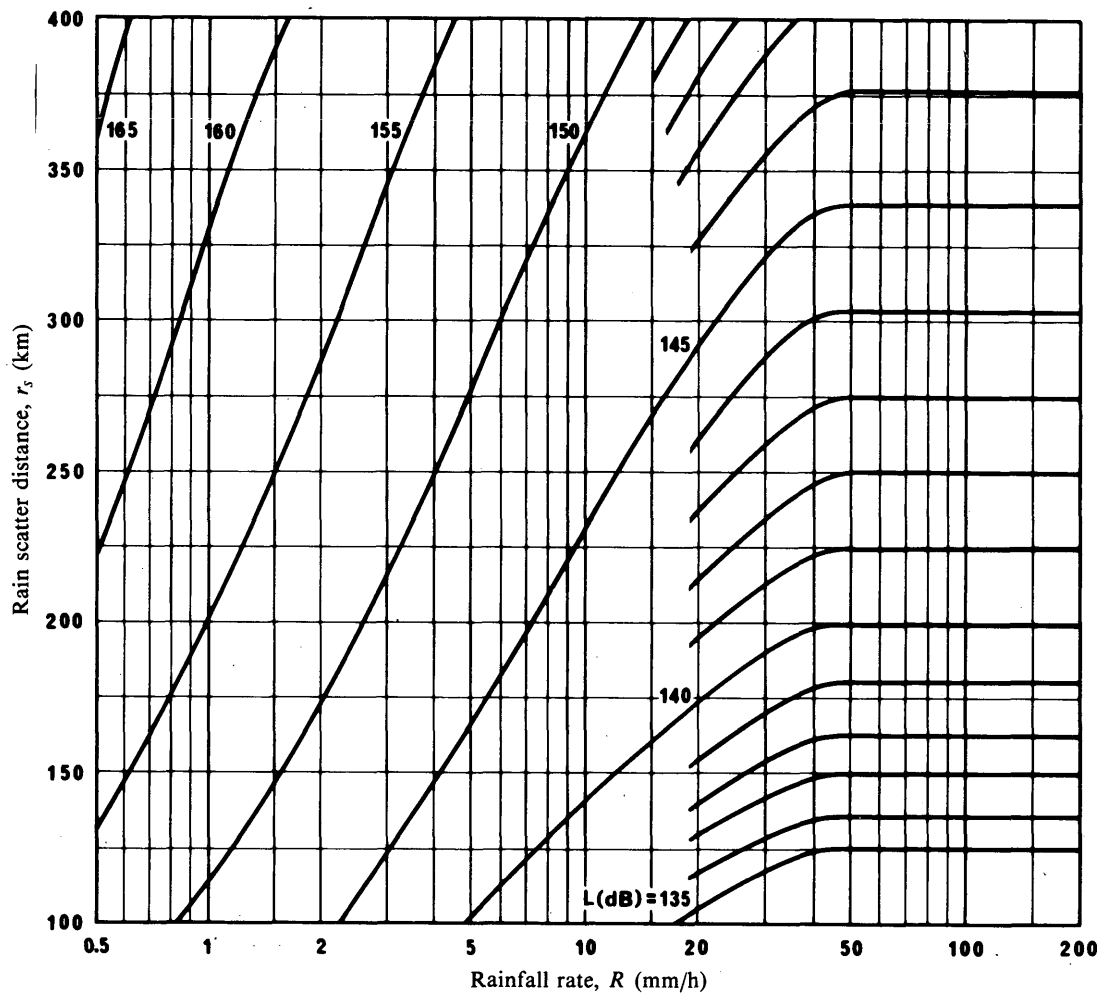


FIGURE 9 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$$f = 8 \text{ GHz}$$

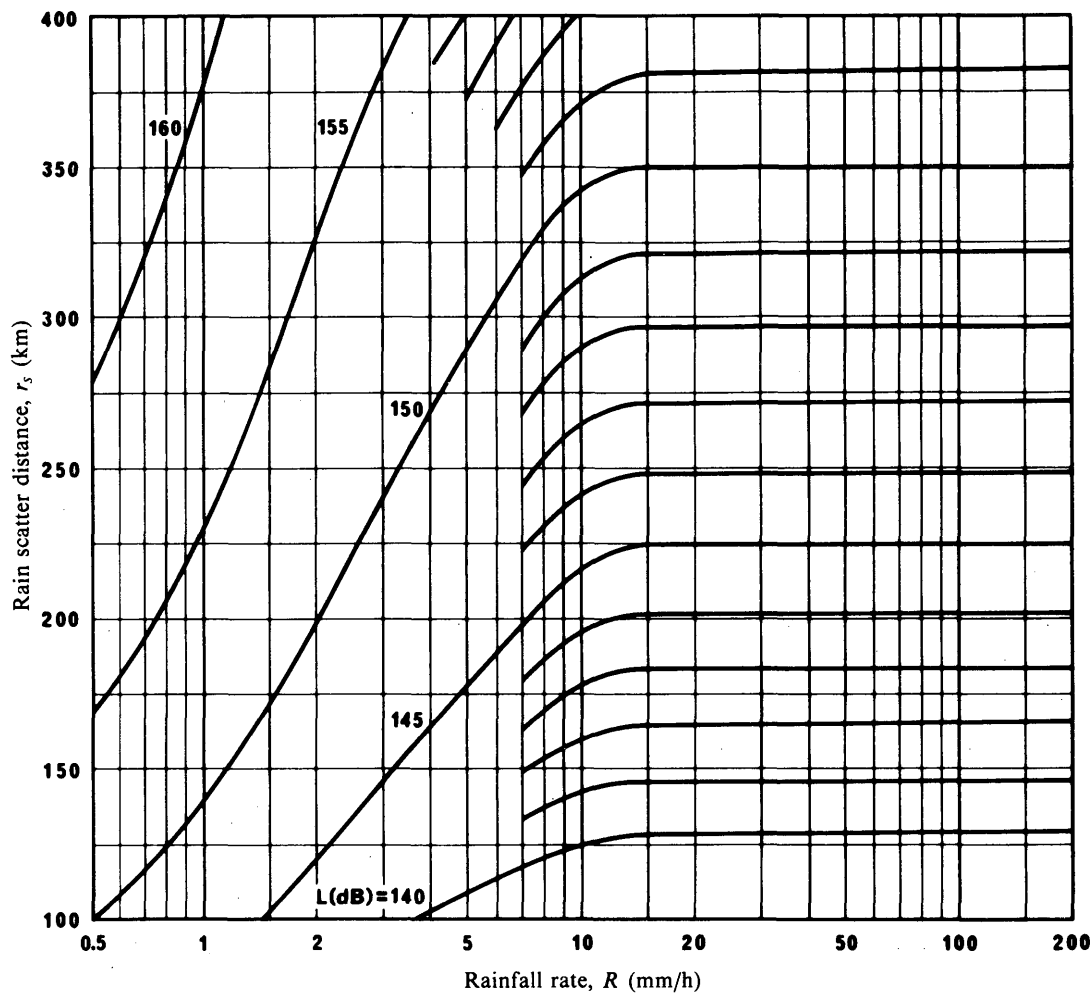


FIGURE 10 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$f = 12 \text{ GHz}$

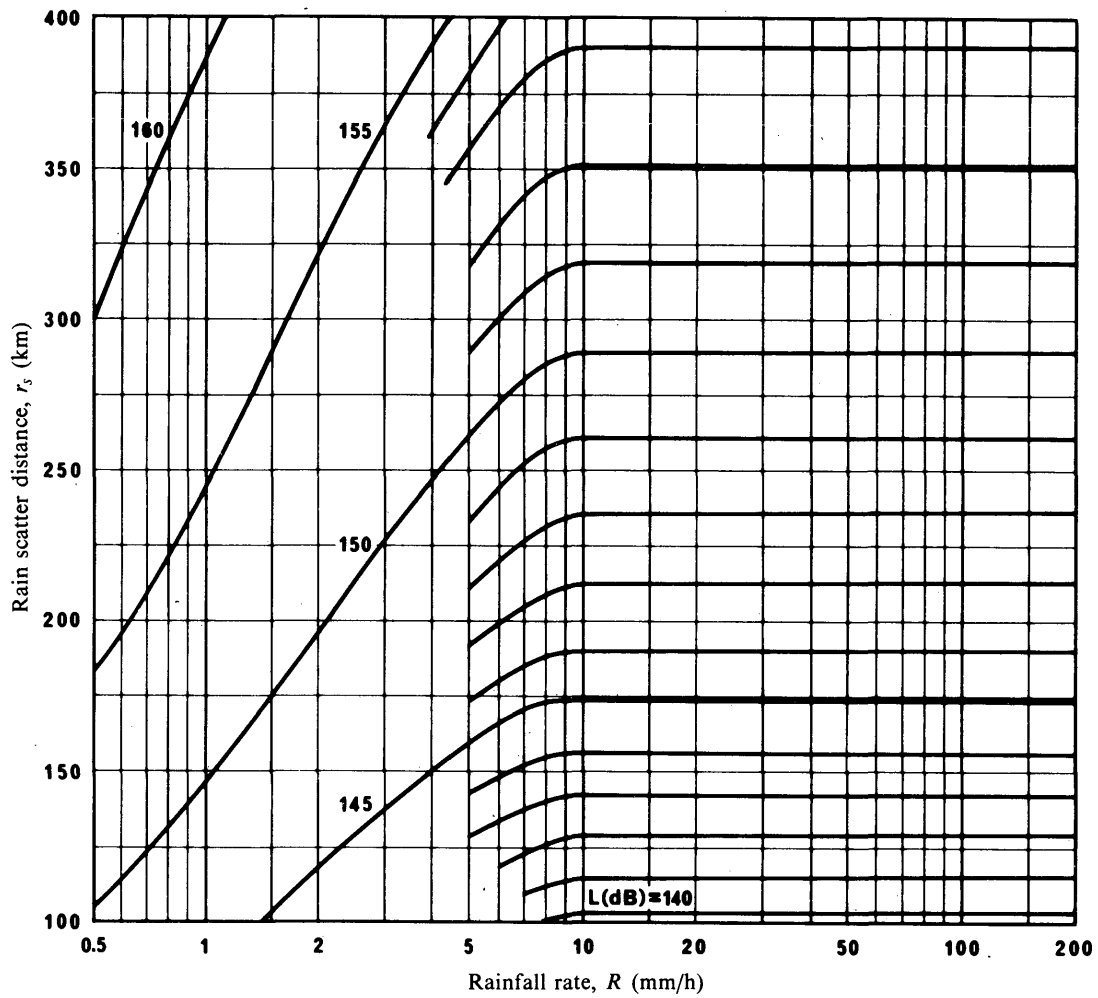


FIGURE 11 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$$f = 14 \text{ GHz}$$

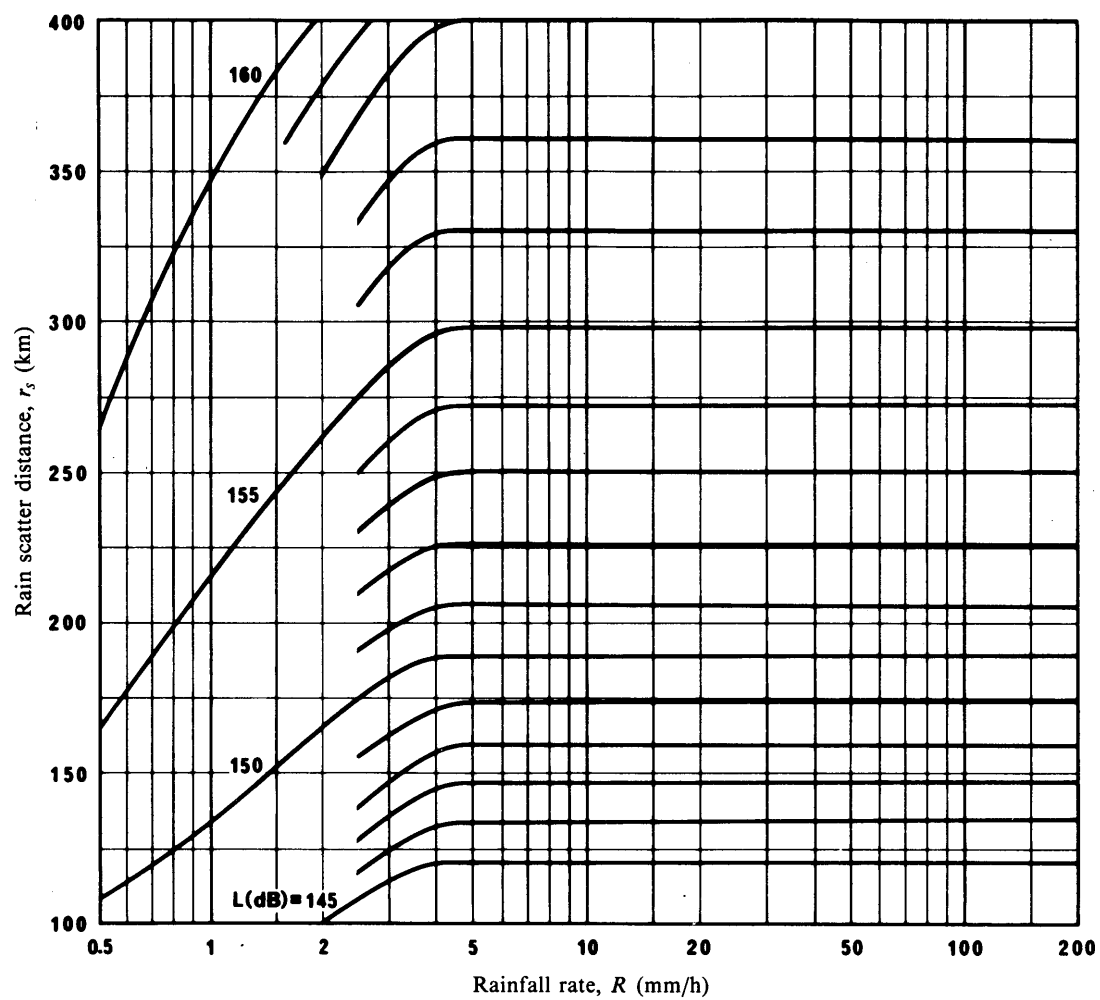


FIGURE 12 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$$f = 18 \text{ GHz}$$

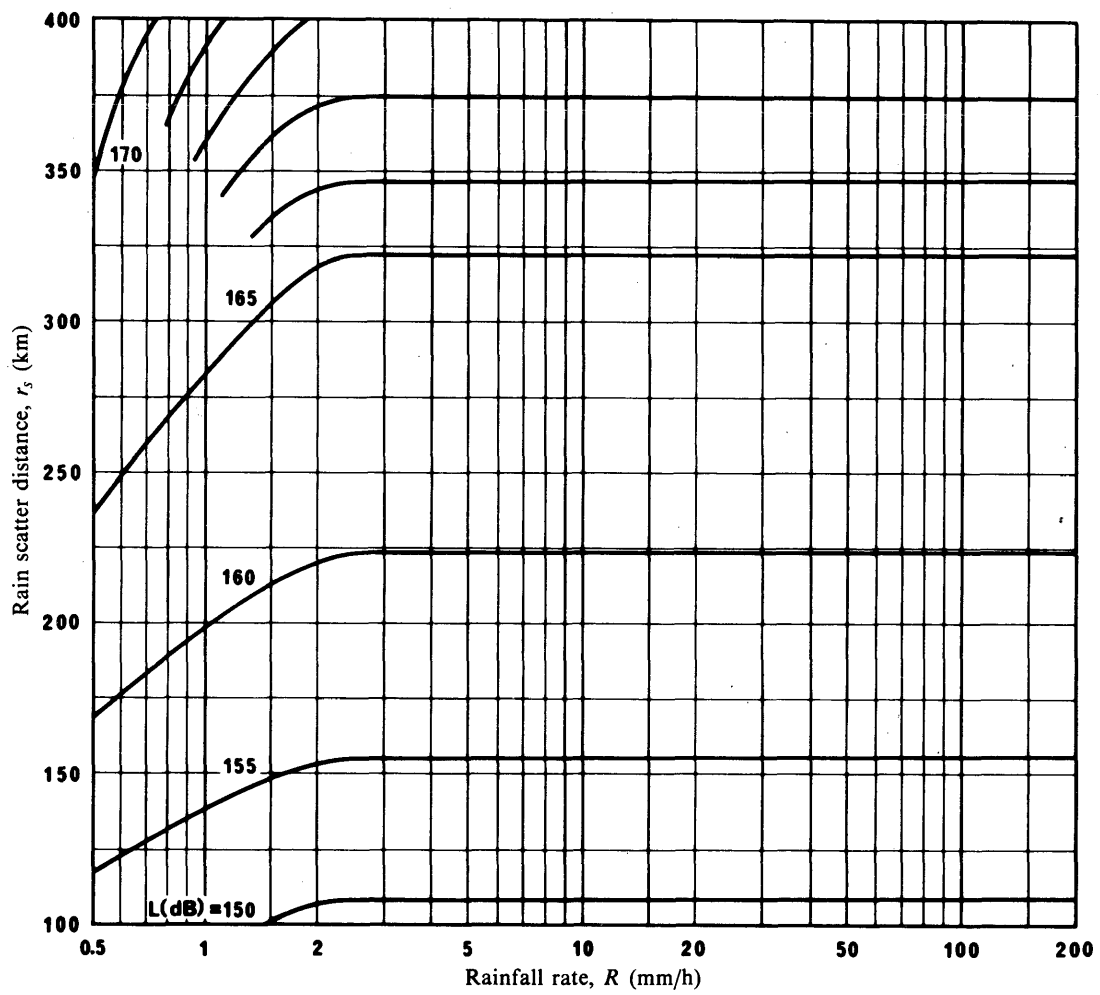


FIGURE 13 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$$f = 22.4 \text{ GHz}$$

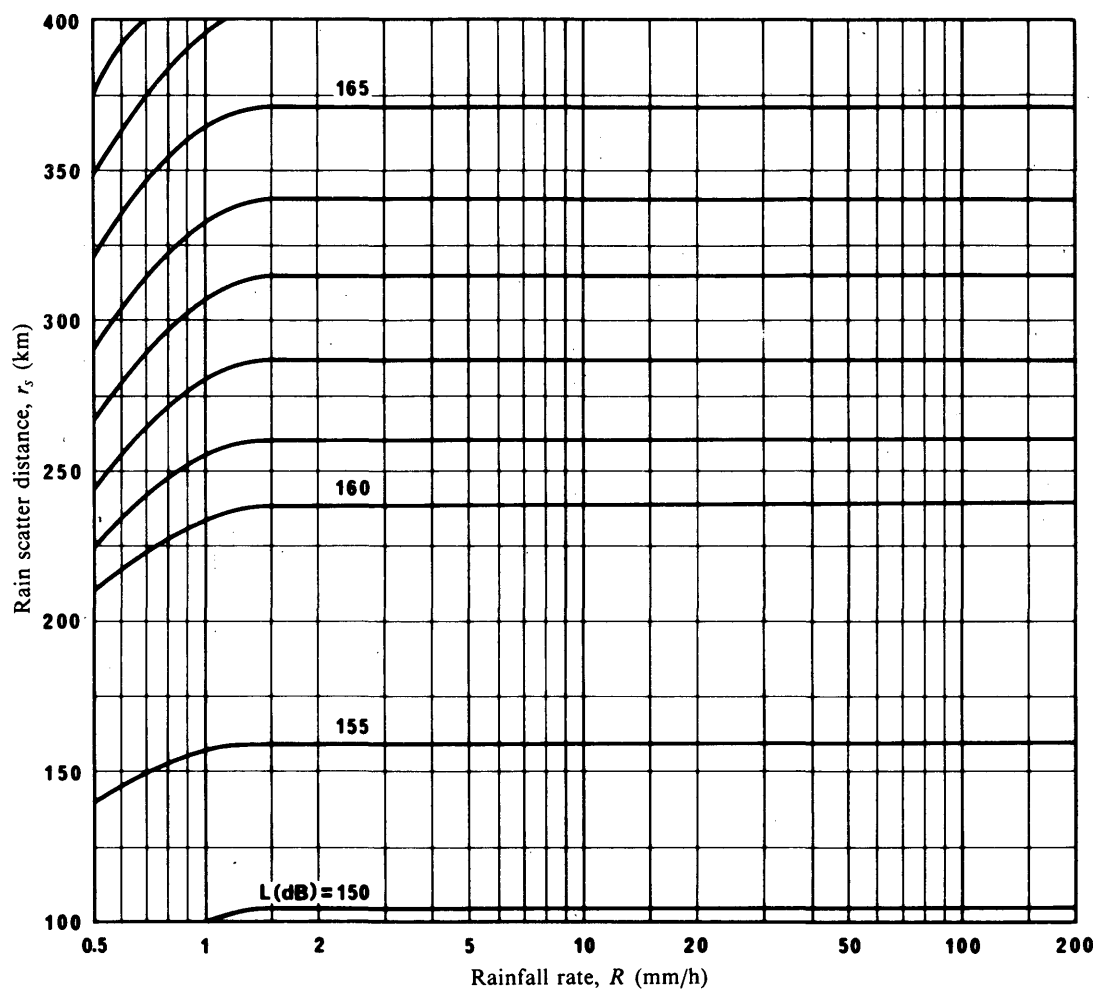


FIGURE 14 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$$f = 28 \text{ GHz}$$

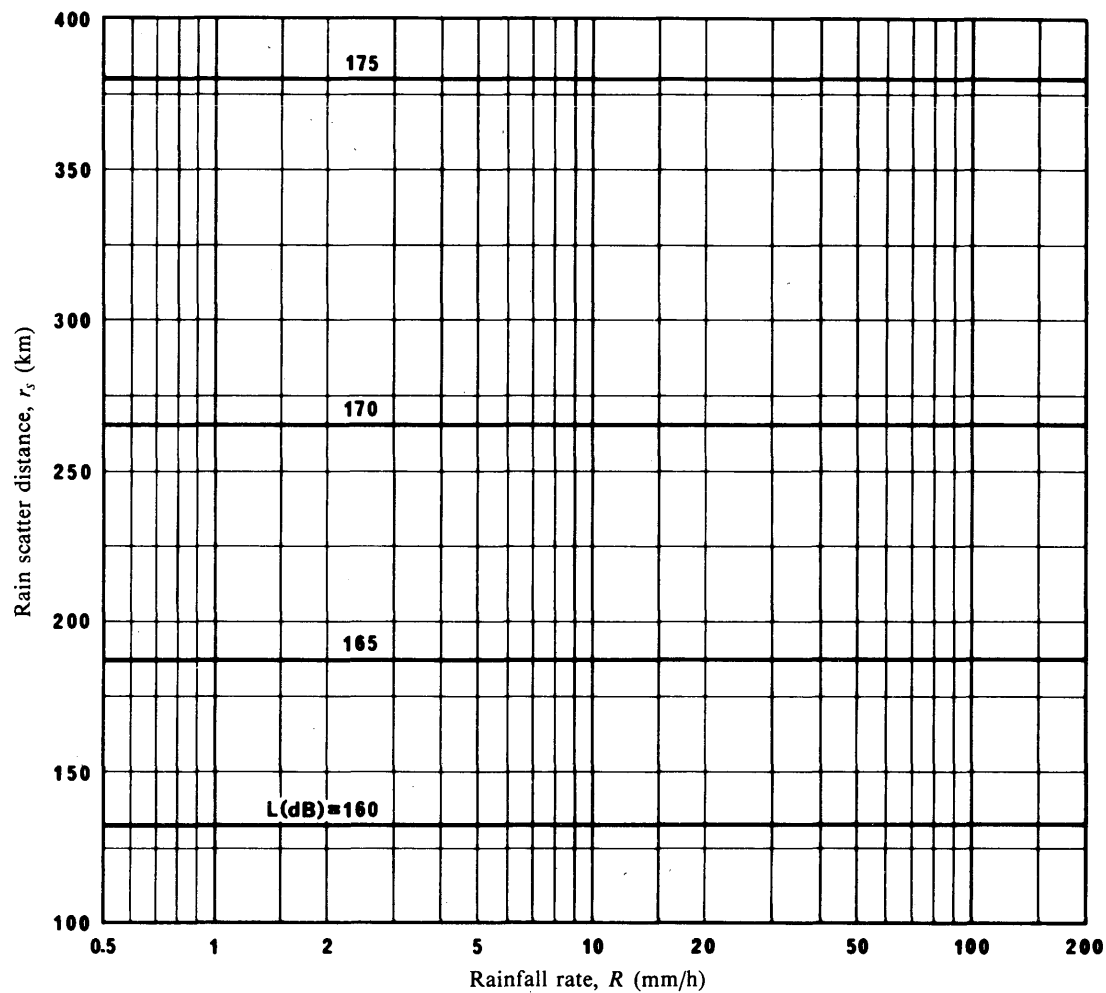


FIGURE 15 — Rain scatter distance (r_s) as a function of rainfall rate (R) with the transmission loss (L) as a parameter

$f = 40 \text{ GHz}$

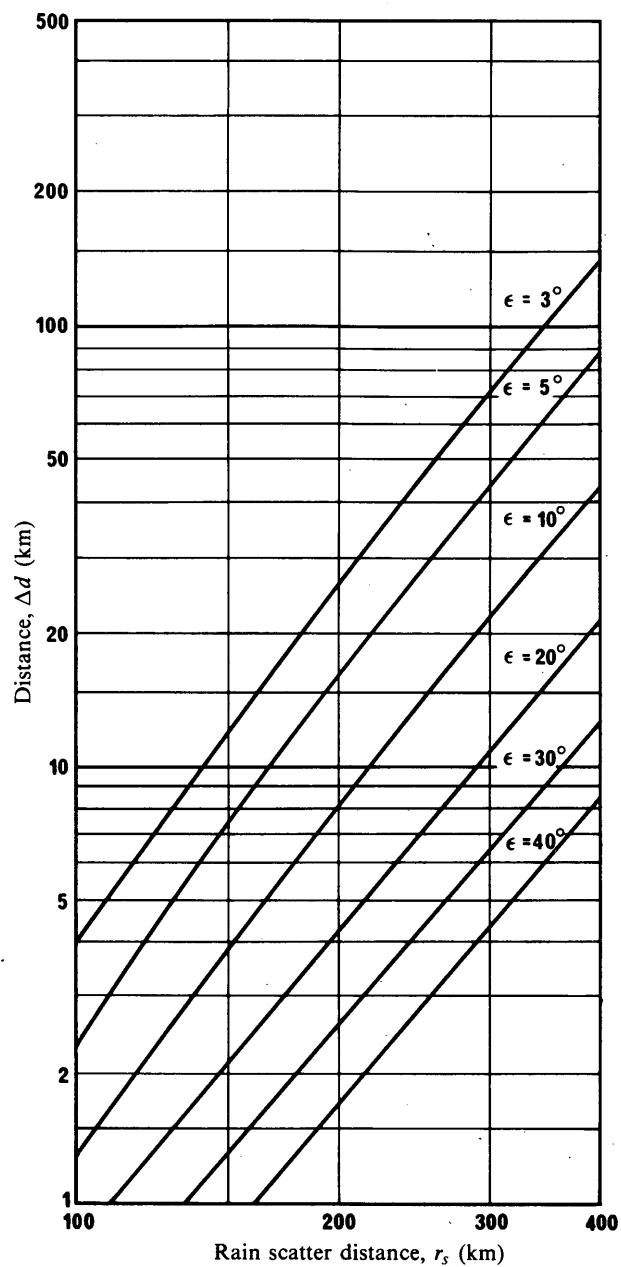


FIGURE 16 — Distance Δd as a function of rain scatter distance r_s and earth-station antenna beam elevation angle ϵ

3.1.3 *Maximum rain scatter distances*

Depending on latitude and percentage of the time, the greatest heights from which rain scatter returns are expected to be significant (due to the absence of significant liquid water above these heights) have been given in Table III, and result in the maximum rain scatter distances given in Table VI.

Although the transmission loss curves have been drawn as a standard procedure to a distance of 400 km, distances beyond those shown in Table VI should be ignored.

TABLE VI - *Maximum rain scatter distances (km)*

% of the time	Latitude (degrees)				
	0-30	30-40	40-50	50-60	>60
1.0	360	340	290	260	240
0.1	360	340	310	290	260
0.01	370	360	340	310	280
0.001	380	370	360	340	300

3.2 *Absence of mixed path effects*

As the only significant rain scatter is that occurring in the general area of the earth station, the question of a mixed path does not arise.

3.3 *Operational considerations at frequencies above 10 GHz*

At frequencies above 10 GHz rain attenuation will weaken the received signals at earth or terrestrial stations for small percentages of the time, increasingly so with increasing frequencies.

When power control is used in the up link to combat rain attenuation on the Earth-to-space path, the increased power will tend to produce greater potential interference to terrestrial systems towards which the attenuation may not have increased. It may therefore be necessary to determine coordination contours taking into account the maximum powers that may be radiated and the percentages of the time during which given levels of power control may have to be exercised.

When site diversity is used to combat attenuation, coordination contours will have to be determined for both sites. Since precipitation is the mechanism largely responsible for attenuation, each of the two sites will be operated, generally, only up to a given attenuation, i.e., a given rainfall rate, after which operation is transferred to the other site. As a consequence, rain scatter coordination distances need to be determined only for rain rates up to those corresponding to the attenuation at which switching to the other site is undertaken. Since the switching rain rates will be substantially lower than the maximum rain rates for the percentage of the time for which continuity of service must be maintained, the rain scatter coordination areas for the two sites may be significantly smaller than that for a single non-diversity site. It is worth noting that this advantage may accrue to both a transmitting and a receiving earth station.

ANNEX I

CLASSIFICATION OF RAIN CLIMATES

In Fig. 17 the world has been divided into a number of rain climatic zones which show different precipitation characteristics with respect to each other. The curves in Figs. 18a and 18b show the cumulative distribution of the surface rain rate in the rain climatic zones identified in Fig. 17. They are based on Table I of Report 563.

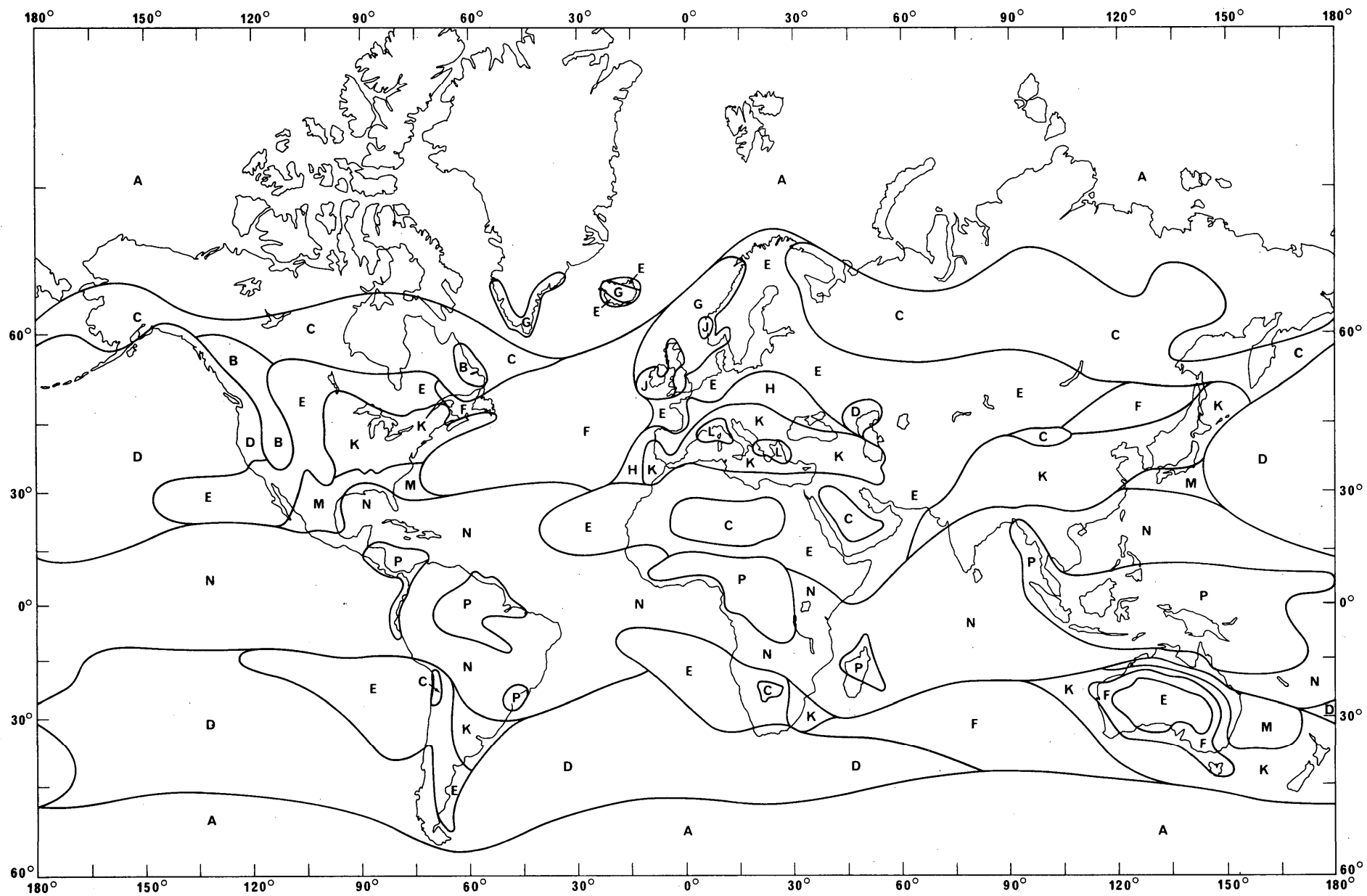


FIGURE 17 — Regions corresponding to rainfall rate distributions of Figs. 18a and 18b

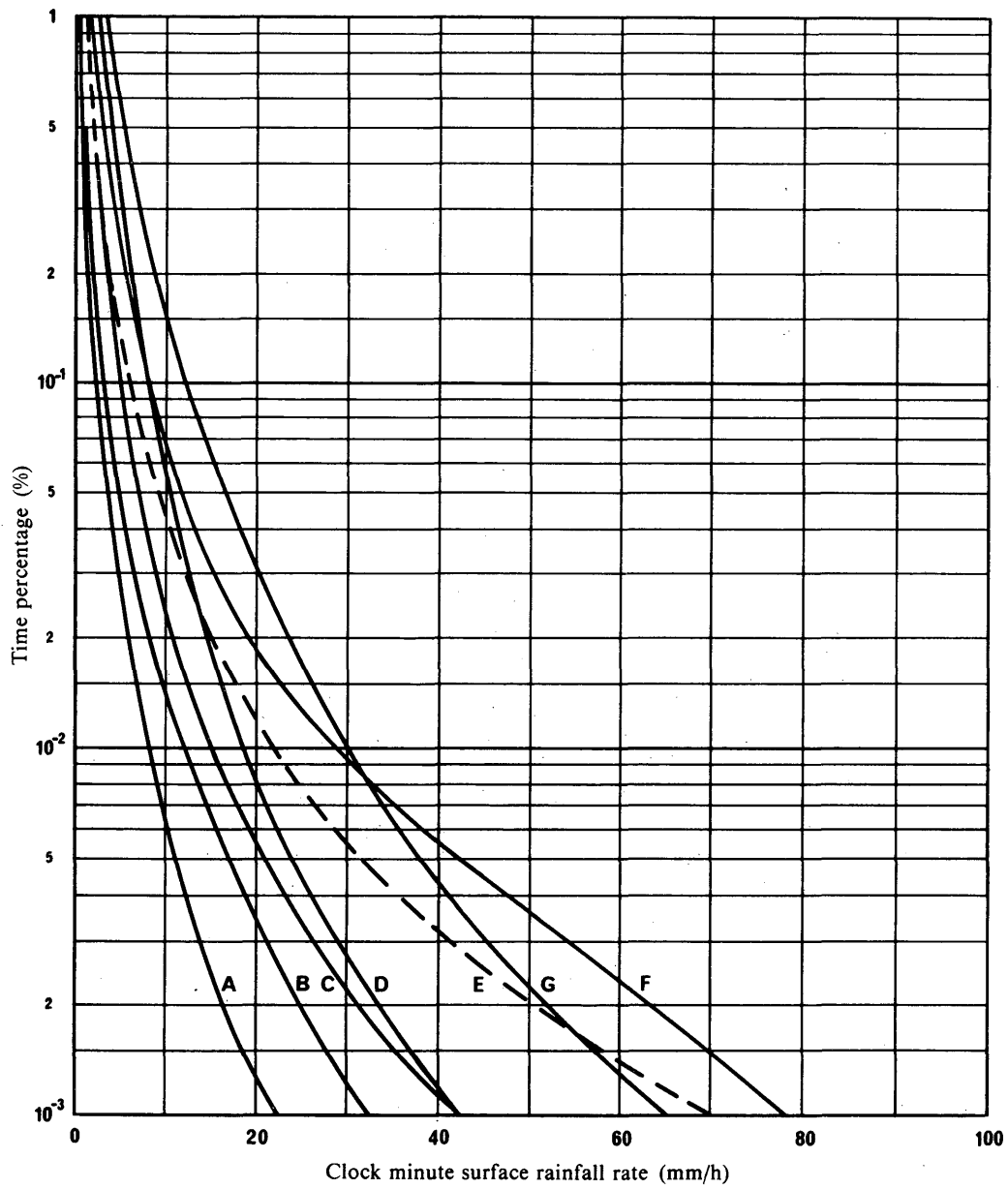


FIGURE 18a — *Percentage of an average year for which rainfall rate is exceeded for rain regions A — G*

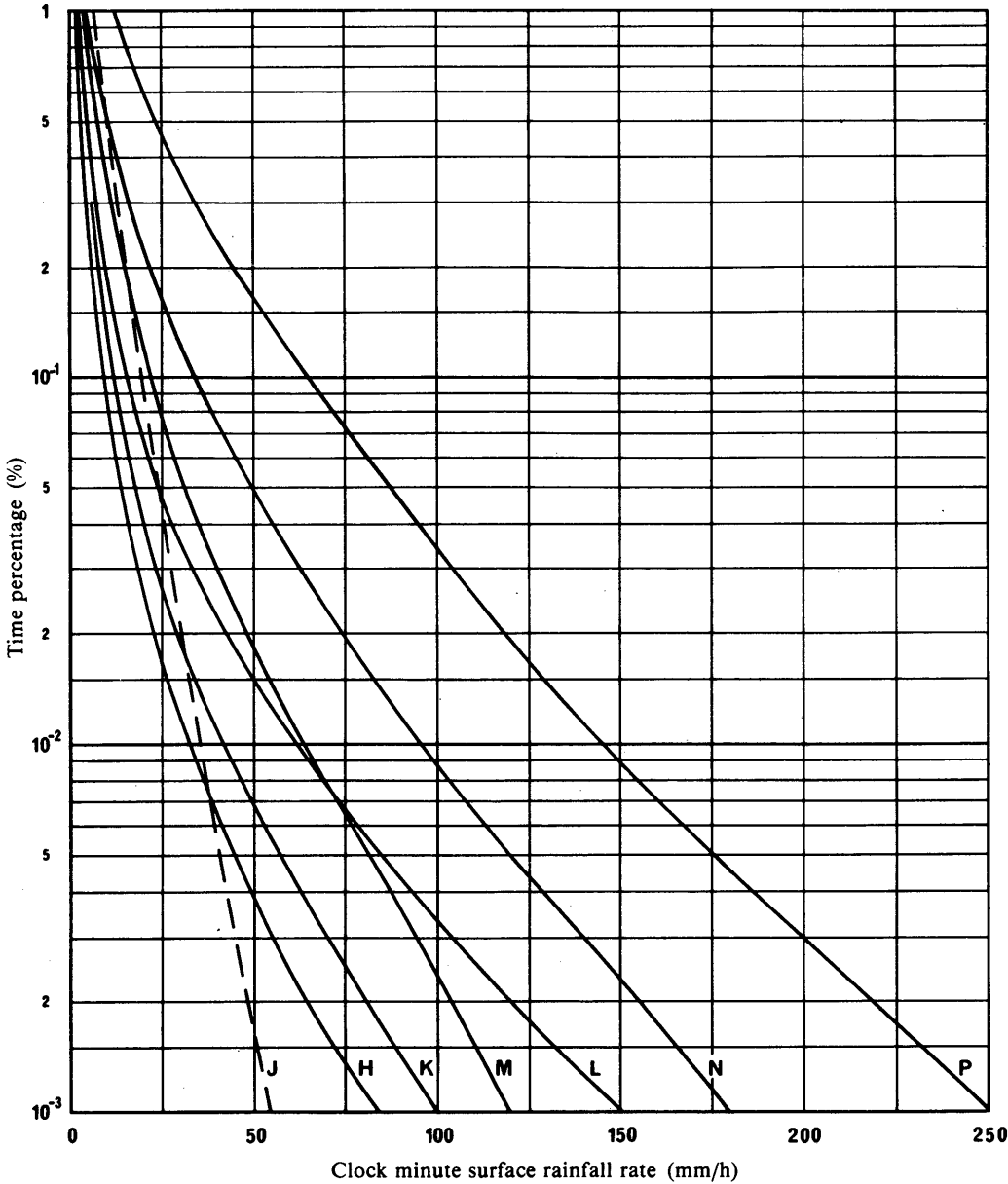


FIGURE 18b — *Percentage of an average year for which rainfall rate is exceeded for rain regions H–P*

ANNEX II

DERIVATION OF EQUATION (10)

Equation (10) was derived from equation (6) of Report 569 with the following assumptions:

1. The polarization decoupling factor M is assumed to be unity.
2. In the term $10 \log S$ only the backscatter component ($\alpha_T = 180^\circ$) was considered.
3. In the term $10 \log C$ only the backscatter component was considered ($\alpha_T = 180^\circ$) and d_a has been replaced by d_s under the assumption that for scatter heights up to and just above h_R attenuation would occur in the entire rain cell.
4. The term for gaseous absorption has been replaced by separate terms for oxygen ($\gamma_o r_o$) and water vapour ($\gamma_w r_w$) with simple expressions for r_o and r_w given. The formulae for equivalent path length for oxygen (r_o) and water vapour (r_w) were derived from those of Report 719 with the assumption of $r_h = 40$ km.
5. In the term containing the two integrals, g_T , assumed to be constant within the rain cell, was removed from the integral, and the second integral was neglected (conservative assumption). The entire term was, thus, replaced by:

$$10 \log g_T + 10 \log d_a - \Gamma_1 \quad \text{dB}$$

6. In the above expression, d_a was replaced by d_s (see item 3 above), with the assumption of a 20° earth station main beam elevation angle, so that:

$$d_a = d_s = \frac{d_c}{\cos 20^\circ} \approx 3.5 R^{-0.08} \quad \text{km}$$

7. The term Γ represents the term Γ_1 associated with the first integral. With the bounds on h_R and the assumption of a 20° earth station main beam elevation angle, $d_1 = d_c/2 < d_0$, $d_2 = d_0$ and $d_3 = 22.5$ km. The first of these three assumptions is not true at the highest rainfall rates ($R > 100$ mm/h), but these are of no concern at the higher frequencies while at the lower frequencies the error caused by this assumption may be neglected.

8. The maximum rain scatter distances of Table VI were derived under the assumption that when the scatter centre is at 3 km above the maximum liquid-rain bearing heights h_R of Table III, the reduction in reflectivity of 3×6.5 dB would reduce the coupling to acceptable levels. Hence, the maximum scatter distance is computed from:

$$d_{max} \approx \sqrt{17\,000 (h_R + 3)} \quad \text{km}$$

9. It is a peculiarity of the rain scatter model of Report 569 that for distances r which place the scatter height just above the liquid-rain height h_R , an increase in coupling occurs until the distances have increased sufficiently for the -6.5 dB/km reflectivity gradient to have overcome this coupling increase. It is likely that in practice this increase will not be of significance. However, even accepting its occurrence, it would be substantial only for high rain rates at the higher frequencies, but this condition does not produce the greatest coupling. Therefore, this coupling increase is expected to be negligible.

REPORT 885 *

**PROPAGATION DATA REQUIRED FOR EVALUATING INTERFERENCE
BETWEEN STATIONS IN SPACE AND THOSE
ON THE SURFACE OF THE EARTH**

(Question 5/5)

(1982)

1. Introduction

In interference between terrestrial and space stations (i.e. with an interfering signal traversing a slant path through the whole atmosphere) several propagation factors need to be considered. First, the values of absorption in a clear atmosphere, and not exceeded for small percentages of time, become important. Second, scatter from precipitation on the slant path can cause unwanted signals from a space station to be scattered into a terrestrial station. Possible interference from a solar power satellite by this mode of propagation is an important example.

In addition, differential rain attenuation between adjacent Earth-space paths can occur. The wanted signal may suffer a large attenuation due to heavy rain while, at the same time, the unwanted signal may experience a much lower attenuation in weaker rain – or even a much smaller attenuation in clear air.

These three main modes are discussed in the following sections.

2. Precipitation scatter on space-Earth paths

In this case, signals from the space station can be scattered from precipitation on the space-Earth path and cause interference at a terrestrial station. Scatter from a terrestrial to a space station is also possible. The scattering can be considered to be approximately isotropic and calculations of scattered power can be made using the expression for bistatic scattering (see Report 882). The maximum coupling will occur when the main beams (of the space station and terrestrial station) intersect in rain. Attenuation outside the common volume will have to be taken into account at frequencies above about 10 GHz and the problem is then rather complex.

An important problem in this context is possible interference from a solar power satellite. Some calculations for this situation are summarized in [CCIR, 1978-82]. Using available data on likely harmonic content, it can be shown that – even at the 4th harmonic – the interfering signal, at a distance of 50 km from the rain cell, can be comparable with the level of the received signal in the fixed-satellite service. At the fundamental frequency, however, direct radiation from the side lobes of the power satellite to the terrestrial station will probably exceed the signal due to precipitation scatter.

For limitations on the power flux-density on the surface of the Earth, reference is made to Report 369.

3. Clear-air propagation

In clear-air conditions, attenuation on an Earth-space or space-Earth path (in excess of the free-space loss) is due mainly to absorption by oxygen and water vapour but defocusing or beam spreading adds significantly to the loss at low elevation angles. At elevation angles below 5°, and for less than 1% of the time, tropospheric scintillation effects should be taken into consideration.

It should be noted that, for a space station located in a direction near the normal horizon of a terrestrial station, strong refraction in the lower atmosphere may appreciably increase the area on the Earth's surface within which mutual interference between the systems is possible.

The total attenuation in a clear air atmosphere, A , in excess of the free-space loss can be expressed as:

$$A = L_b - L_{bf} = A_g + A_D - G_S \quad \text{dB} \quad (1)$$

where:

- L_b : basic transmission loss (dB),
- L_{bf} : free-space loss (dB),
- A_g : attenuation due to atmospheric gases (dB),
- A_D : attenuation (dB) due to defocusing or beam spread,
- G_S : "gain" (dB) due to scintillation.

* This Report is brought to the attention of Study Groups 1, 2, 4, 7, 8, 9, 10 and 11.

The attenuation A_g due to atmospheric gases is described in Report 719. It is a function of the surface water vapour concentration p , the effective radius of the Earth $R_e = 10^6 (157 + \Delta N)^{-1}$ and, to a lesser extent, of the surface air temperature.

Average values of p for the months of February and August have been prepared and are reproduced in Figs. 9 and 10 of Report 563. To a first approximation the statistics of the temporal variations of p can be assumed to follow a Gaussian distribution having a standard deviation, σ , of about 0.25 times the mean value of p . For example, the absolute humidity likely to be exceeded for 99% of the time would be $1 - (0.25 \times 2.4) = 0.4$ times the mean value. Similarly the value exceeded for 99.99% of the time would be $1 - (0.25 \times 3.8) = 0.05$ times the mean value.

ΔN is the mean decrease (lapse) of the radio refractivity over a 1 km thick layer based at the surface. World maps of the monthly mean values of ΔN are given in Figs. 5 to 7 of Report 563.

The "gain" due to scintillation G_s may be assumed to be zero for elevation angles above 5° and for percentages of time greater than 1% (see Report 718). For low elevation angles and small percentages of time, scintillation may produce transmission loss values less than those of free space. Some measurements may be interpreted as showing that scintillation may decrease the transmission loss occurring by as much as 6 dB, this being for elevation angles between 1° and 2° and for less than 1% of the time at 7 GHz.

Assuming that defocusing or beam spreading is confined to the vertical plane then, at an elevation angle θ , the defocusing loss, A_D , is given by Fig. 1 as a function of ΔN .

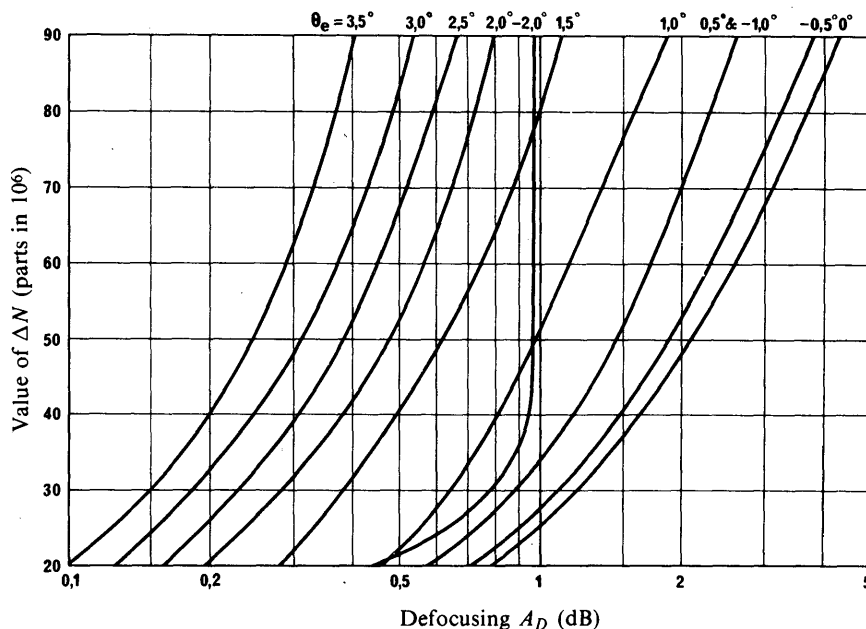


FIGURE 1 — Defocusing of near-horizontal radio waves

4. Rain attenuation on adjacent space-Earth paths

If two space stations operating at the same frequency are separated from one another by a small angle, situations can arise when rain attenuation on the path from a space station reduces the signal sufficiently to allow interference from a neighbouring space station.

It is essential to consider the joint effects of the rain attenuation A_c of the wanted signal and the rain attenuation A_i of the interfering signal.

For interference calculations the conditional distributions of $\Delta A = A_c - A_i$ and A_c must be used. As a basis for generating total exceedance statistics for various regions, in which the single path attenuation statistics are different, ΔA statistics exceeded for 1% of the time have been calculated under the condition: $0.5 \text{ dB} < A_c < A_m$, where A_m is the maximum allowed attenuation of the wanted signal [Rogers *et al.*, 1980]. The empirical formula:

$$\Delta A (1\%) = 0.036 (0.45f + \operatorname{cosec} \epsilon) \cdot \left[\log_e (\theta + 1) \cdot \log_e (A_m + 1) \right]^{1.15} \quad \text{dB} \quad (2)$$

where:

f : frequency (GHz): $11 \leq f \leq 30 \text{ GHz}$,

ϵ : earth-station elevation angle (degree): $5^\circ \leq \epsilon \leq 30^\circ$,

θ : angular separation (degree) of the two paths in the azimuth direction: $0^\circ \leq \theta \leq 10^\circ$,

was found to give a good fit to the data in the parameter ranges noted.

In order to determine the percentage of time that a particular value of ΔA is exceeded for a given value of A_m , the 1% figure must be multiplied by the probability that $0.5 \text{ dB} < A_c < A_m$. The latter can be obtained from a measured or predicted cumulative distribution for a single path (see Report 564).

Equation (2) is provisional and must be used with caution. The physical assumptions made in application of the data to other climatic regions are discussed in Report 721.

REFERENCES

ROGERS, R. R., YAU, M. K. and MASSAMBANI, O. [1980] Further studies of rain effects on Earth-space propagation. Scientific Report MW-93, Stormy Weather Group, McGill University, Montreal, Canada.

CCIR Documents

[1978-1982]: 5/219 (United Kingdom).

QUESTIONS AND STUDY PROGRAMMES, RESOLUTIONS, OPINIONS AND DECISIONS

QUESTION 1-3/5

INFLUENCE OF THE GROUND ON TROPOSPHERIC PROPAGATION

(1965-1966-1970-1974-1982)

The CCIR,

CONSIDERING

(a) that the problem of amplitude and phase variations in ground-wave propagation, resulting from the non-uniformity of the electrical characteristics of the ground, both vertically and horizontally, is of great importance in:

- the prediction of the service areas of radio transmitters;
- the accuracy of navigational aids and direction-finding equipment;
- the effect of coastal refraction on the use of such aids and equipment;

(b) that the rigorous mathematical analysis so far refers mainly to idealized models including:

- one or more boundaries between regions of different electrical characteristics normal to the path, with possible discontinuities in height;
- horizontal stratification;
- spherical earth;
- some forms of terrain irregularity;

(c) that full account of terrain irregularities of all kinds may be important,

UNANIMOUSLY DECIDES that the following question should be studied:

1. how should methods be refined for measuring the values of effective conductivity σ , and permittivity ϵ , for a path, for portions of a path or for local areas for various frequencies, and how should the results be presented for use;
2. how should more experimental results for amplitude and phase of the ground wave along the path, especially in combination with simultaneous measurements of ϵ and σ , be obtained;
3. how should further development be made of the mathematical analysis to include arbitrary variations of ϵ and σ , especially the cases where the line of propagation is oblique to a boundary and of non-horizontal stratification, and also the simultaneous treatment of surface irregularities and electrical characteristics of a non-homogeneous ground;
4. how may analytical methods be reduced to a form which is convenient for engineering computation, or, alternatively, how may the rigorous results be compared with the results of semi-empirical methods to define more closely the limitation of the latter;
5. how should the effects on ground-wave propagation of changes of such factors as the temperature, vegetation, climate or other causes be taken into consideration;
6. how should the effects of terrain irregularities of different kinds be taken into consideration;
7. what is the effect of irregularities of terrain on propagation characteristics such as fading in tropospheric propagation?

Note. — See Report 229.

STUDY PROGRAMME 1A-2/5

**INFLUENCE OF TERRAIN IRREGULARITIES AND VEGETATION
ON TROPOSPHERIC PROPAGATION**

(1951-1953-1956-1959-1963-1970-1974-1982)

The CCIR,

CONSIDERING

- (a) that it is of great importance to pursue studies concerning tropospheric propagation in environments having terrain irregularities;
- (b) that propagation over high mountain ridges is sometimes of great practical importance;
- (c) that the presence of obstacles on the path may modify, to a large extent, the mean value of the transmission loss, as well as the amplitude and fading characteristics;
- (d) that site shielding is of practical significance in interference studies,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. influence of more than one obstacle on a propagation path;
2. influence of the radius of curvature and of the nature of the ground at the summit of a mountain;
3. attenuation and variation in angle of arrival produced by terrain irregularities, and the existence of conducting structures, both for locations within the service area around a transmitter and for receiving sites at much greater distances;
4. propagation in urban areas;
5. the screening provided by obstacles near a terminal, taking into account the propagation mechanisms over the path;
6. influence of terrain irregularities and vegetation on both the short-term and long-term variations of transmission loss;
7. problems associated with the polarization of radio waves, as influenced by terrain irregularities and by the existence of conducting structures above the terrain;
8. attenuation and variations of phase, as a function of the distance;
9. conditions under which obstacle gain occurs and the short-term and long-term variations of transmission loss under these conditions.

Note. — See Reports 236 and 715.

QUESTION 2-4/5**INFLUENCE OF THE NON-IONIZED ATMOSPHERE
ON WAVE PROPAGATION****Radiometeorology for telecommunications**

(1966-1970-1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that the propagation of radio waves is a function of the conditions prevalent in the atmosphere;
- (b) that the propagation studies required for the establishment of a radio link, either Earth-to-Earth or Earth-to-space, necessitate a knowledge of the propagation medium, i.e., of the atmosphere,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what are the most appropriate methods and instruments for studying the variations of those parameters of the atmosphere which affect wave propagation (see Note);

2. what are the variations in space and time of the refractive index of the air and of its gradient, particularly in the vertical direction;
3. what is the influence on wave propagation of the various constituents of the atmosphere, such as water vapour, oxygen, cloud, rain, snow, fog, sand, etc., and in particular:
 - what are their statistical and geographical distributions;
 - what are the space and time correlation characteristics of each of the factors;
4. what are the radiometeorological parameters, other than those mentioned above, which may be useful in radio-wave propagation;
5. what are the statistical relationships between the different radiometeorological parameters in various climatological situations and the characteristics of radiowave propagation;
6. what are the best methods for the statistical prediction of the effects of the atmosphere on radio wave propagation? In addition, what is the minimum observation time required for establishing stable statistics and what are the confidence intervals to be applied to the statistics?

Note. — See Reports 563, 718 to 723, 881 and 882.

QUESTION 3-2/5

TROPOSPHERIC EFFECTS AT FREQUENCIES BELOW 30 MHz

(1951–1953–1956–1963–1966–1974–1978)

The CCIR,

CONSIDERING

- (a) that the ground-wave propagation curves below 30 MHz, included in Recommendation 368, take into account the effects of tropospheric refraction;
- (b) that allowance for tropospheric effects is likely to be important for frequencies well below 30 MHz and out to very large distances, in connection with the development of navigational aids employing pulse techniques which rely for their accuracy on the ground-wave mode of propagation,

UNANIMOUSLY DECIDES that the following question should be studied:

1. what further measurements of ground-wave field strengths are necessary to determine experimentally the effects of the troposphere at frequencies below 30 MHz;
2. what is the influence of the troposphere on the amplitude and phase of the ground wave, including anomalous effects?

QUESTION 5-3/5

PROPAGATION AND NOISE DATA REQUIRED FOR TERRESTRIAL AND SPACE TELECOMMUNICATION SYSTEMS

(1953–1956–1959–1966–1970–1974–1978)

The CCIR,

CONSIDERING

- (a) that the quality of communication by terrestrial radio-relay systems or by space telecommunication systems is determined by the propagation characteristics, especially as regards the highest values of transmission loss that may occur and the time variation of the transfer function or the impulse response of the propagation channel;
- (b) that interference between different systems may occasionally occur as a result of anomalous propagation either along Earth-to-space paths or over trans-horizon terrestrial paths,

UNANIMOUSLY DECIDES that the following question should be studied:

what are the propagation and noise characteristics to be taken into consideration in the planning of terrestrial and space telecommunication systems, to operate in conformity with Recommendations of the CCIR regarding system performance and mutual interference?

Note 1. — Other radio noise studies are treated by Study Groups 1 and 6 in connection with Questions 46/1 and 7/6.

Note 2. — See Report 885.

STUDY PROGRAMME 5A-4/5

PROPAGATION DATA REQUIRED FOR LINE-OF-SIGHT RADIO-RELAY SYSTEMS

(1963-1966-1970-1974-1978-1982)

The CCIR,

CONSIDERING

that a better knowledge of the characteristics of propagation contributes greatly to the design of economic line-of-sight radio-relay systems and to the improvement of system performance and in particular:

- (a) that the design of digital radio-relay systems is largely controlled by the availability required (as related to propagation) and that periods of adverse propagation as short as between 0.001% and 0.0001% of the time are significant over a 50 km hop to the design of digital radio-relay systems;
- (b) that the amplitude and group-delay distortion across a microwave radio channel have a profound effect on the bit error ratio of digital radio-relay systems,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the distribution with time of the value of basic transmission loss resulting from multipath propagation, diffraction and absorption, etc., in the VHF (metric), UHF (decimetric), SHF (centimetric) and EHF (millimetric) bands for each month of the year;
2. the propagation data to be used for station site selection and for determining the height of antennas and their radiation characteristics, including the distribution of refractive-index gradient or *k*-factor during subrefractive conditions averaged over a specified path length;
3. the concurrent statistical distributions of long-term attenuation and rainfall intensity;
4. data on multipath fading selectivity, in particular the number of rays during multipath propagation, their relative amplitudes, delays and probabilities of occurrence;
5. approximate models of the tropospheric channel which can be used to simplify the computation of system performance. These include:
 - the complex transfer function of the medium, and
 - restricted models of the impulse response (e.g. 2-ray, fixed delay, etc.);
6. the variation, due to multipath propagation, precipitation or any other cause, of the decoupling of two orthogonal polarizations, including:
 - cumulative distributions of cross-polar discrimination (XPD) (conditional and unconditional with respect to co-polar attenuation (CPA)), rate of change and duration statistics of XPD,
 - information concerning the relative importance of cross-polarization due to rain and multipath under various conditions,
 - comparison of design procedures based on unconditional distribution of XPD with procedures based on joint statistics of XPD and CPA;

7. the frequency of occurrence and duration of fades exceeding specified values and the rate of change of received signal in these fades;

Note. — Study Group 9 particularly requires:

- that the estimation be made in such a way that the distribution of the values of noise power (dependent on transmission loss and multipath propagation) at the output of a system, averaged over 5 ms, 1 s, and 1 min, can be derived;
- simultaneous measurements of path attenuation and depolarization with a measurement period of less than 1 s and preferably less than 100 ms, expressed in such a way that statistics relating to the "worst month" may be derived;

8. the improvement to be gained using diversity systems in the presence of rain or multipath;

9. the statistical properties of the propagation factors resulting in mutual interference between two links, the cumulative effects of these factors on the overall system performance of multi-hop radio-relay links and the dependence of these factors on path length, climate and the nature of the terrain over which the path passes.

STUDY PROGRAMME 5B-2/5

PROPAGATION DATA REQUIRED FOR TRANS-HORIZON RADIO-RELAY SYSTEMS

(1963-1970-1982)

The CCIR,

CONSIDERING

- (a) that, in the planning of a communication network, it is necessary to define the overall system performance achieved for a given percentage of the time;
- (b) that designers of radio systems in the VHF (metric), UHF (decimetric) and SHF (centimetric) bands require to know, from the viewpoint of sustained satisfactory operation, the tropospheric propagation characteristics and the resulting transmission loss that is not exceeded for a large percentage of the time for each particular frequency band, over the distance corresponding to the service range, which may extend from about 200 km to more than 500 km;
- (c) that the planning of systems requires a knowledge of the distribution curves, as functions of time, of the transmission loss for the most unfavourable month of the climatic zone under consideration;
- (d) that the bandwidth of the system may be limited by the nature of the mode of propagation employed,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the distribution in time of the basic transmission loss (see Recommendation 341), in the VHF (metric), UHF (decimetric) and SHF (centimetric) bands, for each month of the year (the value of the path antenna gain being specified). The recording should be performed with an instrument having a time constant of one minute (other time constants may be used, should it appear desirable, but in all cases the time constant used should be specified) and special importance should be attached to the quasi-maximum and quasi-minimum values of the transmission loss or field strength;
2. for given levels, the percentages of time corresponding to the worst month and corresponding to the whole year;
3. the hours of the day for which the greatest transmission loss may usually be expected;
4. the distribution in time of the fluctuation of the level of the received signal about its hourly median value (other periods of time may be used to define the median value, but these periods should be stated), when the recording is made with a time constant as short as possible;
5. the dependence of the distributions on the climatic zone in which the path under consideration is located, and which distinct climatic zones should be taken into consideration (in view of the paucity of data relating to propagation in climates other than temperate, administrations are urged to give special attention to the collection of data relating to other types of climate);

6. the dependence of the distributions on the frequency, the distance between the stations, the angle of elevation of the antennas at each terminal and on the nature of the terrain over which the path passes;
 7. the extent to which these distributions can be described by simple statistical laws;
 8. the limitations imposed on the bandwidth of the system by the propagation process (diffraction, partial reflection, scattering, etc.);
 9. the limitations imposed on the system by the effects of solar noise and noise from other external sources.
- Note.* — See Report 238.

STUDY PROGRAMME 5C-4/5

PROPAGATION AND NOISE DATA REQUIRED FOR SPACE TELECOMMUNICATION SYSTEMS

(1963-1970-1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that, in the design of space telecommunication systems, it is necessary to take into account various phenomena affecting the propagation of radio waves through the troposphere;
- (b) that a knowledge of the distributions in time of these phenomena, and of their dependence on various factors, is important to the determination of system performance and of interference to and from space stations,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the long-term statistical distribution in time and space of co-polar attenuation (CPA) and cross-polar discrimination (XPD) by atmospheric gases, precipitation and clouds, and sand and dust storms;
2. the distribution in time and space of refraction, scintillation, beam divergence, and wavefront coherence of radio waves passing through the troposphere;
3. the frequency of occurrence and duration of fades exceeding specified values and the rate of change of received signal in these fades;
4. the distribution in time and space of natural noise from the Earth and from atmospheric constituents as well as galactic and solar emissions above about 50 MHz (see Note 1);
5. the dependence of these distributions on the frequency, angle of elevation, geographic location, time and atmospheric composition;
6. the development of methods of prediction of these distributions and their dependence on the above parameters;
7. the cumulative effects of these phenomena on system performance including interference to or from a space station;
8. the extent to which site diversity or other techniques can be used to overcome the problems associated with:
 - attenuation and noise resulting from precipitation and cloud,
 - cross-polar discrimination, and
 - interference,
 i.e. the conditional probability of these variables at two separated sites;
9. the limitations imposed by precipitation and multipath effects on frequency re-use applying orthogonal polarization techniques;
10. correlation between up-link and down-link impairments over short time intervals (of the order of some seconds); both attenuation (for up-link power control) and depolarization (for up-link pre-compensation).

Note 1. — Other radio noise studies are within the competence of Study Groups 1 and 6 (see Questions 46/1 and 7/6).

Note 2. — See Reports 426, 564 and 722.

STUDY PROGRAMME 5D-4/5

**PROPAGATION FACTORS AFFECTING FREQUENCY-SHARING
ON TERRESTRIAL PATHS ***

(1963-1966-1970-1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that propagation data for terrestrial paths are required when planning the sharing of frequency channels in telecommunication systems;
- (b) that, in accordance with the Radio Regulations, a coordination distance or coordination area should be determined for earth stations in the frequency bands shared between space telecommunication services and the fixed and mobile terrestrial services;
- (c) that in the calculation of coordination distances, all pertinent propagation mechanisms should be taken into account;
- (d) that in the calculation of interference between systems, more detailed consideration of the contributing propagation mechanisms is required;
- (e) that in accordance with Recommendations Nos. 708 and 711 of the World Administrative Radio Conference (Geneva, 1979) the CCIR continues to study the possibility of improving and simplifying the method of determining coordination area and of extending the method to frequencies below 1 GHz and above 40 GHz,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of a suitable method by which contributions of known tropospheric propagation factors, including absorption by and scatter from precipitation, absorption due to atmospheric gases, reflections from aircraft and other phenomena both on and off the great circle path, can be taken into account when considering the signal received over trans-horizon paths, including the effects of site-shielding, particularly with reference to the signal strengths exceeded for small percentages of time, such as 0.001%, 0.01%, 0.1%, 1% and 20% of a month or a year; in particular, it should be determined to what extent the use of angular distance automatically allows for the high transmission loss usually associated with a high angle of elevation for the radio horizon at either end of the path;
2. determination of the distributions of signal amplitude and fading duration due to tropospheric mechanisms such as ducting, precipitation scatter and aircraft scatter as indicated below:
 - the amplitude distributions of greatest interest are the cumulative distributions of quasi-instantaneous values (a suggested averaging period is 1 minute) ranging from 0.001% to 20% of the time, during periods of at least one year and also during the worst months, when the wanted signal is low or when the unwanted signal is high;
 - path lengths of greatest interest are between 25 and 1000 km; however, over oceans in equatorial and tropical regions and other regions where ducting is prevalent, measurements could be useful up to much greater distances;
 - studies should be made through the whole frequency range, and simultaneous measurements at several frequencies over the same path would be of special interest;
3. the possibility of division of the world into broad zones to include the effects of different climatic conditions to take into account the relative importance of various tropospheric mechanisms;
4. determination of the losses to be expected over mixed paths (e.g. partly over land and partly over sea);
5. the effect of using high-gain antennas, taking into account the various extreme cases of interest, such as the following, which arise in considering communication-satellite and radio-relay services above 3 GHz;

* The propagation factors concerning the interfering paths between the satellite of a space telecommunication service and terrestrial systems are covered by Study Programme 5C/5.

- 5.1 the antenna at one end of the path may be assumed to have gain either close to unity, or about 40 dB, with the beam directed almost horizontally along the bearing of the other antenna;
- 5.2 the antenna at the other end of the path may have a gain of about 60 dB, with the beam directed either well above the horizon or towards the other antenna at an angle of elevation of about 3° above the horizontal. Radiation diagrams of large antennas at communication-satellite earth stations, for use in interference studies, are given in Report 391;
6. the losses due to coupling of the radio energy from the transmitting antenna into a duct and out of a duct into the receiving antenna, taking into account the effects of both site-shielding (when the antenna sees a positive horizon angle) and antenna height above the surrounding terrain (negative horizon angle);
7. the statistics of interference arising from the correlation of fading of the wanted signal and enhancement of an interfering co-frequency signal.
- Note.* — See Report 569.

STUDY PROGRAMME 5E-4/5

SCATTERING FROM PRECIPITATION AS A FACTOR IN INTERFERENCE FOR TERRESTRIAL AND SPACE SYSTEMS

(1966–1970–1974–1978–1982)

The CCIR,

CONSIDERING

- (a) that rain, hail, snow, and certain non-homogeneities in the refractive-index structure of the atmosphere may scatter radio waves more strongly and over wider angles than occurs under normal atmospheric conditions and that measurements have confirmed the importance of this effect;
- (b) that further studies of these phenomena need to be undertaken so that their effects may be considered in the selection of antenna sites of microwave stations operating on shared frequency channels,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. determination of the range of angles and distances in which the scattering from precipitation and other atmospheric inhomogeneities can be considered as likely to cause interference between microwave stations and, in general, determination of the relation between this range of angles and the scattering angle, distance, polarization and frequency, for frequencies above 1 GHz;
2. determination of the average distribution in time and space of observed values of effective scattering cross-section per unit volume, as a function of:
 - height above ground,
 - time of day,
 - season,
 - climatic region,
 - scattering angle,
 - polarization of transmitting and receiving antennas;
3. the possible existence of a simple dependence of scattering cross-section on the rainfall rate (mm of water per hour), and also for other forms of precipitation giving significant scattering;
4. methods of calculating the interference to be expected, including the case of microwave stations where the antenna beams do not intersect.

Note. — See Reports 569, 724 and 885.

QUESTION 7-2/5

**PROPAGATION CURVES AND DATA AT FREQUENCIES ABOVE 30 MHz FOR
BROADCASTING, MOBILE AND RADIODETERMINATION SERVICES****Terrestrial and space radiocommunications**

(1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that there is a requirement for methods to estimate the field strength or the transmission loss when planning broadcasting, mobile and radiodetermination services in the frequency bands above 30 MHz;
- (b) that propagation data may be required to determine the technical feasibility of frequency sharing between terrestrial broadcasting, mobile and radiodetermination services, and space radiocommunications;
- (c) that the provisional VHF and UHF curves for broadcasting services given in Recommendation 370 are based on a considerable amount of field-strength data, obtained mainly from measurements made in temperate climates;
- (d) that the provisional data given in Report 565 for broadcasting services using satellite transmitters are restricted to certain areas;
- (e) that further data to that given in Report 565 concerning sound broadcasting from satellite transmitters, particularly for portable receivers, are needed;
- (f) that the VHF, UHF and SHF propagation curves for the aeronautical mobile service given in Recommendation 528 are only valid for a continental temperate climate;
- (g) that there is a requirement for propagation data and modelling, especially at low elevation angles, for impairments to the slant propagation path for satellite to mobile communications and radiodetermination services;
- (h) that the provisional VHF and UHF curves for land mobile services given in Recommendation 529 and Report 567 are based on a considerable amount of field-strength data, obtained mainly from measurements made in temperate climates;
- (j) the importance of computer methods of field-strength prediction for broadcast and mobile services, which are referred to in Report 239,

UNANIMOUSLY DECIDES that the following question should be studied:

1. to what extent does the field strength or transmission loss depend on time, climate, frequency, polarization, distance, antenna heights, nature of terrain, the effects of vegetation and man-made structures; and, in the case of satellite communications, on the angle of elevation;
2. what is the most suitable method, for each radio service, of presenting the answers to § 1 for use in the preparation of national and international frequency plans;
3. what are the preferred methods of presenting the answers to § 1 for use in computer methods of field-strength prediction?

Note. — See Report 227.

STUDY PROGRAMME 7B-2/5

**PROPAGATION DATA REQUIRED FOR SATELLITE BROADCASTING IN
THE FREQUENCY BANDS ABOVE 0.5 GHz, AND FOR TERRESTRIAL
BROADCASTING ABOVE 10 GHz**

(1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that, in future, frequencies above 10 GHz will be used for sound and television broadcasting with terrestrial or satellite transmitters;
- (b) that, in future, frequencies below 3 GHz may be used for sound and television broadcasting with satellite transmitters;
- (c) that the propagation phenomena occurring in these frequency bands will have a decisive effect on the planning of broadcasting services;
- (d) that the data given in Reports 562 and 565 have been collected in certain areas of the world,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. recordings of field strength or transmission loss from terrestrial or satellite transmitters, over periods of up to several years, in as many parts of the world as possible;
2. investigations of the statistical distributions of the field strength with time and location;
3. in the case of terrestrial transmitters, the statistical field-strength distribution with time outside the service area up to several hundred kilometres;
4. effects of climate, terrain and vegetation on terrestrial paths;
5. the influence of buildings on terrestrial as well as satellite paths;
6. the attenuation by atmospheric gases and precipitation, presented in statistical form;
7. the effects of the directivity of the antennas;
8. in the case of terrestrial transmitters, the minimum height of the receiving antenna under urban and rural conditions;
9. development of computer methods for calculating reliability and interference.

Note. — See Reports 562 and 565.

STUDY PROGRAMME 7C-1/5 *

**PROPAGATION DATA REQUIRED BY MOBILE SERVICES
USING COMMUNICATION OR RADIODETERMINATION
SATELLITE SYSTEMS**

(1974-1982)

The CCIR,

CONSIDERING

- (a) that a number of administrations are studying satellite systems for aeronautical and maritime safety, radiodetermination, communication and control;
- (b) that maritime mobile-satellite communication services have been instituted;
- (c) that several administrations are also considering satellite systems for land mobile purposes;
- (d) that for VHF, UHF and SHF systems involving satellites, both the ionosphere and troposphere may affect propagation as well as reflections from the ground, sea and/or man-made structures,

* This Study Programme is brought to the attention of Study Groups 6 and 8.

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. investigation of the propagation factors affecting the selection of frequencies for such systems, taking into account the case where the satellite is near the horizon;
2. investigation of the characteristics and effects of land- or sea-reflection and multipath fading on communication or radiodetermination signals transmitted by satellites, both geostationary and otherwise, for the use of land vehicles, aircraft and ships;
3. collection of propagation data for and modelling of tropospheric and multipath-induced impairments, especially for low elevation angle slant paths, as a function of sea or land surface state (wave height or terrain irregularity), satellite elevation angle, antenna radiation pattern, local site clearance and environment and frequency;
4. investigation of the question of optimum polarization through joint consideration of propagation and terrain effects and the characteristics of realizable antennas.

Note. — See Report 884.

STUDY PROGRAMME 7D-1/5

VHF AND UHF PROPAGATION CURVES IN THE FREQUENCY RANGE 30 MHz TO 1 GHz FOR THE BROADCASTING SERVICES

(1974-1982)

The CCIR,

CONSIDERING

that the provisional propagation curves given in Recommendation 370 are based on data obtained mainly in Europe and North America, using transmitting and receiving antennas generally of the order of 300 m and 10 m respectively above ground level, and that information is required not only for other regions but for other antenna heights,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. recordings of field strength or transmission loss at frequencies between 30 MHz and 1 GHz, over periods of up to several years, in as many parts of the world as possible and for distances up to about 1000 km, covering as wide a range of climatic conditions as possible;
2. determination of additions and modifications to the curves of Recommendation 370, to allow for the effects of other conditions of climate, terrain and vegetation;
3. the influence of buildings on reception at low heights;
4. particular investigation of overseas paths and of mixed land and overseas paths;
5. investigations, over various transmission distances of the effect of using directional antennas and also of using antennas with beams inclined to the horizontal plane, including the inclination which may be associated with an elevated or depressed horizon;
6. investigation of the statistical distribution of field strength as a function of location and height of the point of reception within a specified zone;
7. statistical analyses of the results of such experiments, according to Recommendation 311, to extend the range of application of the curve of Recommendation 370;
8. development of computer methods for estimating field strength or transmission loss for application to the planning of broadcasting services.

Note. — See Report 239.

STUDY PROGRAMME 7E-2/5

**PROPAGATION DATA FOR FREQUENCIES ABOVE
30 MHz FOR LAND MOBILE SERVICES**

(1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that there is a requirement for methods to estimate the field strength or the transmission loss when planning land mobile services at frequencies between approximately 30 MHz and 10 GHz;
- (b) that although there is available a considerable amount of measured field-strength data applicable to this requirement, some of which has been incorporated in Recommendation 529 and Report 567, these data relate mainly to temperate climates or certain other areas;
- (c) that there is a need to have available for system planning more detailed propagation data appropriate to the conditions for land mobile services, particularly because of the antenna heights being different from those in the broadcasting services,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the recording of field strength at frequencies between 30 MHz and 10 GHz and especially between 1 and 10 GHz over periods of up to several years, in as many parts of the world as possible and for distances of less than 1 km up to about 300 km for overland paths and up to about 1000 km for overseas paths. Location probability distributions for the particular antenna heights and statistical distributions for field-strength variations as a function of height should be derived from existing and new measured data. The antenna heights above ground to be considered are: between 10 and 600 m for the base stations and 1 and 10 m for the mobile stations;
2. the development of methods for estimating field strength or transmission loss for the planning of frequency assignments for mobile services at frequencies between 30 MHz and 10 GHz taking into account the dependence on frequency, polarization, distance, antenna heights, nature of terrain, vegetation, buildings and climate and also the statistical distribution of field strength or transmission loss with time and location. In particular, methods are required which can be used with computers. The possible requirements for frequency sharing with the stations of space telecommunication services should also be considered.

Note 1. — This Study Programme also covers radiocommunication links with helicopters.*Note 2.* — See Report 567.

STUDY PROGRAMME 7F-2/5

**PROPAGATION DATA FOR FREQUENCIES ABOVE 30 MHz FOR THE AERONAUTICAL,
MARITIME MOBILE AND RADIODETERMINATION SERVICES**

(1974-1978-1982)

The CCIR,

CONSIDERING

- (a) that there is a requirement for methods to estimate the field strength or the transmission loss when planning aeronautical, maritime mobile and radiodetermination services at frequencies above 30 MHz;
- (b) that although there is available a considerable amount of measured field strength data applicable to this requirement, some of which has been incorporated in Recommendations 370 and 528 and in Report 884 these data relate mainly to temperate climates,

UNANIMOUSLY DECIDES that the following studies should be carried out:

1. the recording of field strength at frequencies above 30 MHz and especially between 1.5 and 16 GHz over periods of up to several years, in as many parts of the world as possible and for distances up to about 500 km for overland paths and up to about 1000 km for overseas paths. The base station and mobile antenna heights above ground should be between 10 and 1000 m and between 5 m and 20 000 m respectively;
2. the development of methods for estimating field strength or transmission loss for the planning of frequency assignments for aeronautical, maritime mobile and radiodetermination services at frequencies above 30 MHz, taking into account the dependence on frequency, polarization, distance, antenna heights, nature of terrain and sea state, vegetation, buildings and climate and also the statistical distribution of field strength or transmission loss with time and location. In particular, methods are required which can be used with computers. The possible requirements for frequency sharing with the stations of space telecommunication services should also be considered.

Note. — See Recommendation 528.

STUDY PROGRAMME 8A/5 *

PROPAGATION CHARACTERISTICS OF ELECTROMAGNETIC WAVES IN THE HIGHEST RADIO-FREQUENCY REGION, AS WELL AS IN THE INFRA-RED AND VISIBLE LIGHT REGIONS

(1978)

The CCIR,

CONSIDERING

that Question 53/1 envisages the possible use of frequencies very much higher than 300 GHz for telecommunication purposes,

UNANIMOUSLY DECIDES that the following studies should be carried out:

investigation of the propagation factors affecting the suitability of such frequencies for systems involving transmissions in space or through the atmosphere.

Note. — See Report 883.

RESOLUTION 72

HANDBOOK OF GROUND-WAVE PROPAGATION CURVES

(1982)

The CCIR,

CONSIDERING

- (a) that there is still a need to provide ground-wave propagation curves for frequencies above 10 MHz relative in particular to different antenna heights and polarizations;
- (b) that the computer program GRWAVE is now available to revise the curves found in the Handbook of Ground-Wave Propagation Curves to account for the CCIR refractive profile described in Recommendation 369;
- (c) that formal maintenance of computer programs can be a standard practice for the CCIR Secretariat,

* This Study Programme is derived from Question 53/1.

UNANIMOUSLY DECIDES

1. that the Director, CCIR, should be requested:
 - 1.1 to calculate and publish ground-wave propagation curves using the GRWAVE program for the frequencies, terminal heights, refractive index profile and ground conditions specified by Study Group 5;
 - 1.2 to provide maintenance for the GRWAVE computer program in accordance with commonly accepted procedures;
 - 1.3 to make such comparisons with other existing programs as may be considered appropriate by Study Group 5.

RESOLUTION 73

WORLD ATLAS OF GROUND CONDUCTIVITIES

(1982)

The CCIR,

CONSIDERING

the needs of administrations for suitable conductivity charts when planning all types of radiocommunication, including navigational services, in the VLF, LF and MF bands,

UNANIMOUSLY DECIDES

1. that the Director of the CCIR should continue with the preparation of a World Atlas of effective ground conductivity values, using the most up-to-date information as it becomes available;
2. that when published as an ITU sales document, the Atlas shall contain at least the VLF information at present set out in Report 717, as well as the information relative to MF;
3. that prior to publication the manuscript shall be approved by Study Group 5;
4. that such Study Group 5 approval be given in time to enable publication at the earliest possible date and in any case before the XVIth Plenary Assembly of the CCIR,

AND REQUESTS ADMINISTRATIONS

to supply information in the form of suitable maps and correct as necessary information already provided (see Report 717); in all such cases the frequency concerned should be mentioned. It is particularly emphasized that data relative to the MF part of the spectrum, standardized to 1 MHz, is urgently needed.

RESOLUTION 79

RADIO PROPAGATION STUDIES IN TROPICAL REGIONS

(1982)

This Resolution is published in Volume XIV.

DECISION 3-4

PREDICTION OF PHASE AND AMPLITUDE OF GROUND WAVES

(1970-1974-1976-1978-1980-1981)

CCIR Study Group 5,

CONSIDERING

- (a) that there is need to develop improved methods of predicting the phase and amplitude of ground-waves propagated over the Earth (see Questions 1/5 and 3/5);
- (b) that tropospheric effects are of importance in the prediction of the phase (time-of-arrival) of signals used in radionavigation and radiolocation services,

DECIDES

1. that Interim Working Party 5/1 (see Resolution 24) should be maintained to examine the practical application of meteorological, topographical and geological data to the prediction of the phase and amplitude of radio waves especially at frequencies below about 30 MHz propagated over the surface of the Earth and through the non-ionized regions of the atmosphere;
 2. that the Interim Working Party should propose amendments to existing Study Group 5 texts, or new ones, as appropriate;
 3. that the Interim Working Party should propose desirable revisions and amendments to the Handbook of Ground-Wave Propagation Curves, which is then to be published separately by the ITU;
 4. that the Interim Working Party should seek to provide conductivity maps with consistent and convenient scales for use in a world Atlas of ground conductivity taking account of its variation with frequency and with season of the year, where it is appropriate;
 5. that the Interim Working Party be composed of members from the following Administrations: Algeria, Argentine, Canada, the United States of America, Finland, France, India, Iran, Norway, New Zealand, the United Kingdom, Sweden and Yugoslavia (Socialist Federal Republic of), as well as the EBU;
 6. that the coordination of the Interim Working Party be undertaken by a representative designated by the Administration of Sweden;
 7. that this Interim Working Party collaborate with Interim Working Parties 5/2, 5/3 and 5/5 established under Decisions 4-3, 5-3 and 50 concerning matters of mutual interest.
- Note.* — See Reports 716 and 717.

DECISION 4-3

**TROPOSPHERIC PROPAGATION DATA FOR PLANNING SPACE AND
POINT-TO-POINT TERRESTRIAL TELECOMMUNICATION SYSTEMS
AND DETERMINING LIKELY INTERFERENCE BETWEEN SYSTEMS**

(1963-1970-1974-1976-1980-1981-1982)

CCIR Study Group 5,

CONSIDERING

that there is a need to keep under review current information on the tropospheric propagation factors affecting the design of satellite-based broadcasting and mobile services, Earth-to-space and terrestrial point-to-point telecommunication systems and the sharing of the radio-frequency spectrum between them (see Study Programme 5D/5),

DECIDES

1. that Interim Working Party 5/2 should continue to study all methods of determining, as accurately and concisely as possible, and in a form readily usable by radiocommunication engineers, the degradation and impairments to signals that arise on the propagation path for satellite-based broadcasting and mobile systems, space and terrestrial point-to-point communication systems, bearing in mind the need to determine their availability and also their susceptibility to interference;
2. that the Working Party should propose amendments to existing Study Group 5 texts, or new ones as appropriate;
3. that the Working Party should be composed of members nominated by the Administrations of the Federal Republic of Germany, Australia, Canada, Denmark, the United States of America, France, India, Italy, Japan, Norway, the Netherlands, the United Kingdom, Sweden and the U.S.S.R., as well as the European Space Agency and the IFRB, INTELSAT and L.M. Ericsson and that the coordination of the work of the Party should be undertaken by the Administration of the United Kingdom;
4. that the Working Party should work in close collaboration with Interim Working Parties 5/3 and 5/5 established under Decisions 5 and 50;
5. that, as far as possible, the work of the Party should be conducted by correspondence;
6. that the Working Party should prepare Reports for Study Group 5 as appropriate prior to Plenary Assemblies of the CCIR.

 DECISION 5-3

**INFLUENCE OF THE NON-IONIZED REGIONS OF THE
ATMOSPHERE ON WAVE PROPAGATION**

(1963-1970-1974-1976-1978-1980-1982)

CCIR Study Group 5,

CONSIDERING

- (a) that the data presented in Reports in Section C of this Volume should be kept under review in the light of new measurements;
- (b) that there is a need to examine the usefulness of other parameters in radiometeorological studies (see Question 2/5) for various climates;
- (c) that there is a need to know the characteristics of absorption, refraction and sky noise in relation to space telecommunication systems (see Study Programme 5A/5),

DECIDES

1. that Interim Working Party 5/3 should continue the examination of all meteorological data relevant to the propagation of radio waves through the non-ionized regions of the atmosphere;
 2. that the Working Party should propose amendments to existing Reports in Section C of this Volume, or propose new ones, as appropriate;
 3. that the Working Party be composed of members nominated by the Administrations of the Federal Republic of Germany, Canada, Denmark, the United States of America, France, India, Italy, Japan, the Netherlands, United Kingdom, Sweden, Switzerland, and the U.S.S.R., as well as the European Space Agency and INTELSAT, and that the coordination of the work of the Party be undertaken by a member designated by the Administration of Italy;
 4. that the Working Party should continue to work in close collaboration with Interim Working Parties 5/2 and 5/5 established under Decisions 4 and 50;
 5. that, as far as possible, the work of the Party should be conducted by correspondence;
 6. that the Working Party should prepare Reports as appropriate prior to the Plenary Assemblies of the CCIR.
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DECISION 50

**TROPOSPHERIC PROPAGATION DATA FOR TERRESTRIAL BROADCASTING
AND MOBILE SERVICES**

(1981-1982)

CCIR Study Group 5,

CONSIDERING

that propagation data for the planning of terrestrial broadcasting and mobile services should be kept under review,

DECIDES

1. to establish Interim Working Party 5/5 to study all methods of determining, as accurately and concisely as possible, and in a form readily usable by radiocommunication engineers, the degradation and impairment to signals that arise on the propagation path for terrestrial broadcasting and mobile services, bearing in mind the need to determine their availability and also their susceptibility to interference;
 2. that the Working Party should propose amendments to existing Study Group 5 texts, or new ones as appropriate;
 3. that the Working Party should be composed of members nominated by the Administrations of Canada, Congo (People's Republic of the), the United States, France, India, Iran, Italy, Japan, the Netherlands, the United Kingdom, Sweden, the U.S.S.R. and the EBU and that the coordination of the work of the Party should be undertaken by the Administration of France;
 4. that the Working Party should work in close collaboration with the Interim Working Parties 5/1, 5/2 and 5/3 established under Decisions 3, 4 and 5;
 5. that, as far as possible, the work of the Party should be conducted by correspondence;
 6. that the Working Party should prepare Reports for Study Group 5 as appropriate prior to Plenary Assemblies of the CCIR.
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