RECOMMENDATION ITU-R P.620-4

PROPAGATION DATA REQUIRED FOR THE EVALUATION OF COORDINATION DISTANCES IN THE FREQUENCY RANGE 100 MHz TO 105 GHz

(Question ITU-R 208/3)

(1986-1992-1995-1997-1999)

The ITU Radiocommunication Assembly,

considering

a) the terms of Resolution 60 of the World Administrative Radio Conference (Geneva, 1979) (WARC-79);

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 should be adequately conservative,

recommends

1 that, for the determination of the coordination area with respect to frequencies above 100 MHz, administrations use the propagation calculation methods set out in Annex 1.

ANNEX 1

1 Introduction

This Annex provides propagation data for use in the calculation of a coordination area and sets out a straightforward method for the assessment of the propagation factors concerned in the determination of coordination distances.

The coordination area represents the area outside of which interference between an earth station and terrestrial stations (or between bidirectionally operating earth stations), operating within the conservative assumptions given elsewhere, may be considered negligible. In the remainder of this Recommendation the words terrestrial stations may also represent bidirectionally operating earth stations. The determination of coordination distance therefore necessitates the comparison of the required transmission loss (minimum permissible basic transmission loss, $L_b(p)$ (dB), not exceeded for a given annual percentage time p), based on system and interference model considerations, with the transmission loss contributed by the propagation medium. The required coordination distance is that at which these two losses become equal.

Various propagation models are provided to cover different frequency ranges and to take account of different propagation mechanisms. These models predict propagation loss as a function of distance. Coordination distances are determined by calculating propagation loss iteratively for increasing distance until either the required transmission loss is achieved or a maximum distance (d_{max1} (km) or d_{max2} (km)) is reached.

The iteration method always starts at a defined value of minimum distance (d_{min} (km)), and iteration may proceed using a uniform step size (s (km)) for increasing distance, a step size of 1 km being recommended. All propagation models give propagation loss as a monotonic function of distance, and thus more advanced iteration methods may be used.

It is important to note that the coordination area does not represent a zone within which the sharing of frequencies between the earth station and the terrestrial station is excluded. Such sharing is often possible, and the coordination area serves to assist this arrangement by indicating where the potential for interference between the earth station and any terrestrial stations needs to be evaluated using a more detailed analysis based on the relevant ITU-R Recommendations.

In addition to providing the method of calculation for the coordination contour, this Recommendation also provides information that enables the preparation of auxiliary contours to assist in the rapid elimination of the majority of potential interference cases during the subsequent coordination analysis for terrestrial stations falling within the coordination contour.

2 Structure of the Recommendation

The structure of the Recommendation is as follows:

Annex 1:	The overall methodology for determining the coordination area
Appendix 1 to Annex 1:	The definition of the input parameters
Appendices 2 and 3 to Annex 1:	The equations required to calculate the coordination contours
Appendix 4 to Annex 1:	A reference radiation pattern for line-of-sight radio-relay system antennas
Appendix 5 to Annex 1:	The definition of all parameters.

3 General considerations

3.1 Assumptions

The determination of coordination distance propagation characteristics for an earth station is 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.

In this Annex propagation phenomena are classified into two modes as follows:

– *mode (1)*: propagation phenomena in clear air:
  – affected by the presence of the Earth's surface (diffraction, refraction, ducting and layer reflection/refraction) and
  – via tropospheric scatter. These phenomena are confined to propagation along the great-circle path;

– *mode (2)*: hydrometeor scatter, which is not limited to the great-circle path, but is, as dealt with in this Annex, limited to earth stations operating with geostationary satellites.

For each azimuth from the earth station, and for each of the above two modes of propagation, it is necessary to determine a distance which gives a propagation loss equal to the required minimum permissible basic transmission loss. This distance (coordination distance) will be the greater of the two distances found.

3.2 Overview of propagation models

For the determination of coordination distances for propagation mode (1), the applicable frequency range has been divided into three parts:

– For VHF/UHF frequencies between 100 MHz and 850 MHz the model is based on an empirical fit to measured data.

– From 850 MHz to 60 GHz a propagation model taking account of tropospheric scatter, ducting and layer reflection/refraction is used.

– From 60 GHz to 105 GHz a millimetric model, based upon free-space loss and a conservative estimate of gaseous absorption, plus an allowance for signal enhancements at small time percentages, is used.

The parameter input ranges for each of the propagation mode (1) model mechanisms are in general different.

For the determination of coordination distances for propagation mode (2), isotropic scattering from hydrometeors in the common volume formed by the main beams of the potentially interfering stations is modelled. For the purposes of frequency coordination at frequencies below 4 GHz and above 40 GHz interference produced by hydrometeor scatter can be ignored. Below 4 GHz the level of the scattered signal is very low and above 40 GHz, although significant scattering occurs, the scattered signal is then highly attenuated on the path from the scatter volume to the terrestrial station.

As discussed in § 1 the iterative calculation of the coordination distance starts at a specified minimum distance which varies according to the propagation factors relevant to each frequency band, and which is always the lowest value of coordination distance under any circumstances.

The loss due to shielding by terrain around an earth station should be calculated by the method described in § 1 of Appendix 2 according to the horizon elevation angles along different radials from the earth station. For all frequencies between 100 MHz and 105 GHz this additional loss should be taken into account.

4 Radio-climatic information

4.1 Radio-climatic data

For the calculation of the coordination distance for propagation mode (1), the world has been classified in terms of radio-climatic zones (see § 4.2) and a radiometeorological parameter, β_p, which reflects the relative incidence of clear-air anomalous propagation conditions.

The value of β_p is latitude dependent. The latitude to be used in determining the correct value for β_p is given by:

$$\zeta_r = \begin{cases} |\zeta| - 1.8 & \text{for} \quad |\zeta| > 1.8° \quad (1a) \\ 0 & \text{for} \quad |\zeta| \le 1.8° \quad (1b) \end{cases}$$

where ζ is earth station latitude (degrees).

β_p is then determined using:

$$\beta_p = \begin{cases} 10^{1.67-0.015\,\zeta_r} & \text{for} \quad \zeta_r \le 70° \quad (2a) \\ 4.17 & \text{for} \quad \zeta_r > 70° \quad (2b) \end{cases}$$

For frequencies between 850 MHz and 60 GHz the path centre sea level surface refractivity (N_0) is used in the propagation mode (1) calculations. This can be calculated using:

$$N_0 = 330 + 62.6\,e^{-\left(\frac{\zeta-2}{32.7}\right)^2} \quad (3)$$

4.2 Radio-climatic zones

In the calculation of coordination distance for propagation mode (1), the world is divided into four basic radio-climatic zones. These zones are defined as follows:

– *Zone A1:* coastal land and shore areas, i.e. land adjacent to a Zone B or Zone C area (see below), up to an altitude of 100 m relative to mean sea or water level, but limited to a maximum distance of 50 km from the nearest Zone B or Zone C area as the case may be; in the absence of precise information on the 100 m contour, an approximation (e.g. 300 feet) may be used;

– *Zone A2:* all land, other than coastal land and shore defined as Zone A1 above;

– *Zone B:* cold seas, oceans and large bodies of inland water situated at latitudes above 30°, with the exception of the Mediterranean and the Black Sea;

– *Zone C:* warm seas, oceans and large bodies of inland water situated at latitudes below 30°, as well as the Mediterranean and the Black Sea.

The following zone distance parameters are required in the various frequency models:

- d_t (km): current aggregate land distance, Zone A1 + Zone A2, within the current path distance;
- d_{lm} (km): longest continuous inland distance, Zone A2, within the current path distance;
- d_{tm} (km): longest continuous land (i.e. inland + coastal) distance, Zone A1 + Zone A2 within the current path distance.

Where necessary, these distances must be re-evaluated for each total path distance within the iteration loops of the propagation models.

Large bodies of inland water

A large body of inland water, to be considered as lying in Zone B or Zone C as appropriate, is defined for the administrative purpose of coordination as one having an area of at least 7 800 km^2, but excluding the area of rivers. Islands within such bodies of water are to be included as water within the calculation of this area if they have elevations lower than 100 m above the mean water level for more than 90% of their area. Islands that do not meet these criteria should be classified as land for the purposes of the water area calculation.

Large inland lake or wetland areas

Large inland areas of greater than 7 800 km^2 which contain many small lakes or a river network should be declared as coastal Zone A1 by administrations if the area comprises more than 50% water, and more than 90% of the land is less than 100 m above the mean water level.

Climatic regions pertaining to Zone A1, large inland bodies of water and large inland lake and wetland regions are difficult to determine unambiguously. Therefore administrations are invited to register with the ITU Radiocommunication Bureau (BR) those regions within their territorial boundaries that they wish identified as belonging to one of these categories. In the absence of registered information to the contrary, all land areas will be considered to pertain to climate Zone A2.

5 Distance limits

5.1 Minimum distance limits

The coordination distance in any given direction is determined by a number of factors set out above and, based on propagation factors alone, the distances could extend from relatively close-in to the earth station to many hundreds of kilometres. However, for practical reasons and also to take account of assumptions which have to be made about the radio path, it is necessary to set lower limits to coordination distances (d_{min}), calculated as follows:

As a preliminary first step, calculate the minimum coordination distance as a function of frequency, f (GHz), up to 40 GHz, using:

$$d'_{min}(f) = 100 + \frac{(\beta_p - f)}{2} \qquad \text{km} \tag{4}$$

Then calculate the minimum coordination distance at any frequency in the range 100 MHz to 105 GHz using:

$$d_{min}(f) = \begin{cases} d'_{min}(f) & \text{km} \quad \text{for} \quad f < 40\ \text{GHz} & \text{(5a)} \\ \dfrac{(54-f)d'_{min}(40) + 10(f-40)}{14} & \text{km} \quad \text{for} \quad 40\ \text{GHz} \le f < 54\ \text{GHz} & \text{(5b)} \\ 10 & \text{km} \quad \text{for} \quad 54\ \text{GHz} \le f < 66\ \text{GHz} & \text{(5c)} \\ \dfrac{10(75-f) + 45(f-66)}{9} & \text{km} \quad \text{for} \quad 66\ \text{GHz} \le f < 75\ \text{GHz} & \text{(5d)} \\ 45 & \text{km} \quad \text{for} \quad 75\ \text{GHz} \le f < 90\ \text{GHz} & \text{(5e)} \\ 45 - \dfrac{(f-90)}{1.5} & \text{km} \quad \text{for} \quad 90\ \text{GHz} \le f \le 105\ \text{GHz} & \text{(5f)} \end{cases}$$

Note that in equation (5b) d'_{min} (40) is evaluated using equation (4) with $f = 40$.

The distance from which all iterative calculations should start (for both propagation mode (1) and propagation mode (2)) is the minimum coordination distance ($d_{min}(f)$) as given in equations (5a) to (5f).

5.2 Maximum distance limits

It is also necessary to set upper limits (d_{max1} and d_{max2}) to the maximum distance used in the iterative calculations for propagation modes (1) and (2) respectively. The maximum calculation distance limit for propagation mode (1) (d_{max1}) is given by the following equation:

$$d_{max1} = \begin{cases} 1\,200 & \text{km} \quad \text{for} \quad f \le 60\ \text{GHz} \quad (6a) \\ 80 - 10\log\left(\dfrac{p_1}{50}\right) & \text{km} \quad \text{for} \quad f > 60\ \text{GHz} \quad (6b) \end{cases}$$

The maximum calculation distance limits for propagation mode (2) (d_{max2}) are given in Table 2.

6 Determination of the coordination distance for propagation mode (1) – Great circle propagation mechanisms

6.1 Coordination distances based on worst-month time percentages

The calculation of coordination distance is based on a level of interference which must not be exceeded for more than a specified average annual time percentage, p_1. For cases where the coordination needs to be based on a worst-month time percentage, p_{w1}, the equivalent annual time percentage, p_1, required by the method can be determined as follows:

Let:

$$G_L = \begin{cases} \sqrt{1.1 + |\cos 2\zeta_r|^{0.7}} & \text{for} \quad \zeta_r \le 45° \quad (7a) \\ \sqrt{1.1 - |\cos 2\zeta_r|^{0.7}} & \text{for} \quad \zeta_r > 45° \quad (7b) \end{cases}$$

then:

$$p_1 = 10^{\frac{\log(p_{w1}) + \log(G_L) - 0.444}{0.816}} \qquad (8)$$

where p_1 (%) is the average annual time percentage for propagation mode (1).

If necessary the value of p_1 must be limited such that $12p_1 \ge p_{w1}$.

6.2 Calculation of the coordination distance for propagation mode (1)

The following methods should be used to determine the coordination distances for propagation mode (1):

– for frequencies between 100 MHz and 850 MHz the method described in § 2 of Appendix 2;

– for frequencies between 850 MHz and 60 GHz the method described in § 3 of Appendix 2;

– for frequencies between 60 GHz and 105 GHz the method described in § 4 of Appendix 2.

7 Determination of the coordination distance for propagation mode (2) – Scattering from hydrometeors

7.1 General

The determination of the coordination contour for scattering from hydrometeors (e.g. rain scatter) is predicted on a path geometry which is substantially different from that of the great-circle propagation mechanisms. As a first approximation, energy is scattered isotropically by rain, so that interference may result for large scattering angles, and for beam intersections away from the great-circle path.

For this propagation mode the previous classification of the Earth's surface into inland, coastal and sea zones is no longer used.

7.2 Coordination distances based on worst-month time percentages

The calculation of coordination distance is based on a level of interference which must not be exceeded for more than a specified average annual time percentage, p_2. For cases where the coordination needs to be based on a worst-month time percentage, p_{w2}, the equivalent annual time percentage, p_2, required by the method can be determined as follows:

$$p_2 = 0.30 (p_{w2})^{1.15} \tag{9}$$

where:

$1.9 \times 10^{-4} < p_{w2} < 7.8$

7.3 Calculation of contours for propagation mode (2)

In the case of propagation mode (2) coordination distances should be calculated using the method described in Appendix 3. This calculation is only necessary in the frequency range 4 GHz to 40 GHz. Outside this frequency range, rain scatter interference can be neglected and the mode (2) coordination distance is equal to the minimum coordination distance given by equation (5). This method also requires iteration for distance, starting at the same minimum distance defined for mode (1) until either the required minimum transmission loss or a latitude-dependent maximum propagation mode (2) distance is achieved.

8 Auxiliary contours

8.1 General

Coordination contours are based upon worst-case assumptions regarding interference. Such assumptions do not necessarily apply in practice, and under certain conditions auxiliary contours can be drawn to eliminate terrestrial stations from further consideration.

For propagation mode (1), the derivation of auxiliary contours requires no additional propagation information. For propagation mode (2), auxiliary contours are generated for different values of the avoidance angle, this angle being the offset azimuth angle of the terrestrial station main beam axis away from the direction of the earth station. This involves additional propagation considerations which are addressed in § 8.2 below.

8.2 Hydrometeor scatter (propagation mode (2))

The coordination contour for mode (2) propagation around an earth station is calculated assuming a worst-case geometry, i.e. the two main beams intersect exactly in the great-circle plane containing both stations. This produces a large coordination area within which detailed calculations of hydrometeor scatter interference levels need to be performed. In practice, mode (2) propagation is far more likely to occur outside this great-circle plane than on it, and, furthermore, the antenna main lobes are unlikely to intersect exactly. In either case, it is possible to generate auxiliary contours which would yield areas that are smaller than the coordination area. Propagation mode (2) auxiliary contours, which take account of the azimuthal offset φ of a terrestrial station antenna beam from the direction of the earth station, should be calculated according to the method described in § 4 of Appendix 3. Any station which lies outside the relevant contour for its avoidance angle need not be considered as a significant source of interference.

The minimum coordination distance for propagation mode (2) is the same as that for propagation mode (1) i.e. d_{min}. The propagation mode (2) auxiliary contours should be prepared for avoidance angles of 2°, 5°, 10°, 20° and 30°, with additional angles as appropriate. It is essential that every effort be made to utilize the actual antenna pattern when determining the auxiliary contours; however, if this is not available the reference antenna pattern given in Appendix 4 may be used.

APPENDIX 1

TO ANNEX 1

TABLE 1

Input parameters

Parameter	Units	Definition	Where defined	Status
d_c	km	The distance from the earth station to the coast in the direction being considered, used in calculating the propagation mode (1) coordination distance	Equation (24)	Input
d_h	km	The distance of the radio horizon, as viewed from the centre of the earth station antenna	§ 1 of Appendix 2	Input or derived
d_{lm}	km	The longest continuous inland distance, Zone A2, within the distance d_i, used in the iterative calculation of the propagation mode (1) coordination distance	Equation (33)	Input
d_t	km	The current aggregate land distance, Zone A1 + Zone A2, within the distance d_i, used in the iterative calculation of the mode (1) coordination distance	Equation (32)	Input
d_{tm}	km	The longest continuous land (i.e. inland + coastal) distance, Zone A1 + Zone A2, within the distance d_i used in the iterative calculation of the mode (1) coordination distance	Equation (34)	Input
D	m	The antenna diameter used in determining the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input
f	GHz	Frequency, 100 MHz to 105 GHz	–	Input
G_{max}	dB	The antenna on-axis gain used in the antenna reference radiation pattern (Appendix 4)	Equation (98)	Input or derived
G_T	dB	The gain of the terrestrial station antenna, assumed to be 42 dB, used in the calculation of the mode (2) coordination distance	Equation (65)	Input
$L_b(p)$	dB	The minimum permissible basic transmission loss required for p_1% (mode (1)) or p_2% (mode(2)) of the time	§ 1	Input
p_1	%	The average annual time percentage for propagation mode (1), where p_1 is in the range: 1% to 50% for f between 100 MHz and 850 MHz 0.001% to 50% for f between 850 MHz and 105 GHz	Equation (8) § 6.1	Input or derived
p_{w1}	%	The worst-month time percentage for propagation mode (1)	§ 6.1	Input
p_2	%	The average annual time percentage for propagation mode (2) 0.001% to 10%	Equation (9) § 7.2	Input or derived
p_{w2}	%	The worst-month time percentage for propagation mode (2)	§ 7.2	Input
s	km	The distance increment used in the iterative calculation of the coordination distance (the recommended value is 1 km)	§ 1	Input
ε_s	degree	The earth station antenna main beam elevation angle	Equation (73)	Input

TABLE 1 (*end*)

Parameter	Units	Definition	Where defined	Status
φ	degree	An angular offset from the axis of the antenna main beam used in the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input
Φ	degree	The avoidance angle used to determine auxiliary contours applicable to propagation mode (2)	§ 4.1 of Appendix 3	Input
λ	m	The wavelength used in determining the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input
θ_h	degree	The earth station horizon elevation angle	§ 1 of Appendix 2	Input
θ_{bw}	degree	The antenna 3 dB beamwidth used in the antenna reference radiation pattern (Appendix 4)	Equations (97) and (98)	Input
ρ	g/m^3	Atmospheric water vapour density	Equation (21)	Input
ω	degree	The polar angle of the terrestrial station with respect to the centre of the common volume, used in calculating the auxiliary contours for propagation mode (2)	§ 4.1 and 4.2 of Appendix 3	Input
ψ	degree	The angle subtended by *b* at the terrestrial station (look angle), used in calculating the auxiliary contours for propagation mode (2)	§ 4.1 of Appendix 3 Equations (76), (77) and (78)	Input
ζ	degree	The earth station latitude (North positive, South negative)	Equations (1a) and (1b)	Input

APPENDIX 2

TO ANNEX 1

Calculation of the coordination distance for propagation mode (1)

1 Site shielding

For propagation mode (1) some shielding of the earth station (site shielding) can be produced by the terrain surrounding the earth station. A term A_h is used in the propagation mode (1) model to take account of this. The additional loss due to site shielding in the vicinity of the earth station along each radial direction is calculated as follows.

The distance of the radio horizon (d_h), as viewed from the centre of the earth station antenna, is determined by:

$$d_h = \begin{cases} 0.5\ \text{km} & \text{if no information is available about the horizon distance,} \\ & \text{or if the distance is} < 0.5\ \text{km} \\ \text{horizon distance (km)} & \text{if this is within the range } 0.5\ \text{km} \le \text{horizon distance} \le 5.0\ \text{km} \\ 5.0\ \text{km} & \text{if the horizon distance is } > 5.0\ \text{km} \end{cases}$$

The horizon angle, θ_h (degrees), is calculated. This is defined here as the angle, viewed from the centre of the earth station antenna, between the horizontal plane and a ray that grazes the physical horizon in the direction concerned. The value of θ_h is positive when the physical horizon is above the horizontal. It is necessary to determine horizon angles for all azimuths around an earth station. In practice it will generally suffice to do this in azimuth increments of 5°. However, every attempt should be made to identify, and take into consideration, minimum horizon angles that may occur between those azimuths examined in 5° increments.

The correction for horizon distance A_d (dB) along each azimuth from an earth station is then calculated using:

$$A_d = 15\left[1 - \exp\left(\frac{0.5 - d_h}{5}\right)\right]\left[1 - \exp\left(-\theta_h\, f^{1/3}\right)\right] \quad \text{dB} \qquad (10)$$

The total loss due to terrain shielding along each azimuth from an earth station is given by:

$$A_h = \begin{cases} 20\log\left(1 + 4.5\theta_h\, f^{1/2}\right) + \theta_h\, f^{1/3} + A_d & \text{dB} \quad \text{for} \quad \theta_h \geq 0° \qquad (11a) \\ 3\left[(f+1)^{1/2} - 0.0001 f - 1.0487\right]\theta_h & \text{dB} \quad \text{for} \quad 0° > \theta_h \geq -0.5° \qquad (11b) \\ -1.5\left[(f+1)^{1/2} - 0.0001 f - 1.0487\right] & \text{dB} \quad \text{for} \quad \theta_h < -0.5° \qquad (11c) \end{cases}$$

The value of A_h must be limited to satisfy the conditions:

$$A_h \leq (30 + \theta_h)$$

and (12)

$$A_h \geq -10$$

Note that in equations (10), (11) and (12) the value of θ_h must always be expressed in degrees. Note that the limits defined in equation (12) are specified because protection outside these limits may not be realized in practical situations.

2 Frequencies from 100 MHz up to and including 850 MHz

The propagation model given in this section is limited to an average annual time percentage (p_1) in the range 1% to 50%.

An iterative process must be used, as described in § 1 of Annex 1. Equation (14) is evaluated and then commencing at the minimum coordination distance, d_{min}, given by the method described in § 5.1, equations (15) to (18) are iterated for distances d_i, where $i = 0, 1, 2$ ... etc., incremented in suitable steps. In each iteration d_i is referred to as the current distance. This process is continued until either of the following expressions becomes true:

$$L_2(p_1) \geq L_1(p_1) \qquad (13a)$$

or

$$d_i \geq d_{max1} \qquad (13b)$$

The required coordination distance, d_1, is then given by the current distance for the last iteration.

The recommended distance increment, s (km), is 1 km. Equations (16), (17a) and (17b) provide only for paths that are wholly of one path classification. Where the path includes sections in more than one zone (land and/or cold sea and/or warm sea, see § 4.2) the coordination distance can be found by an interpolation of the results calculated if the path is assumed to be all land and all sea. Where a sea path includes sections of warm sea zone all the sea along that path should be assumed to be warm sea.

$$L_1(p_1) = L_b(p_1) - A_h \qquad (14)$$

where $L_b(p_1)$ (dB) is the minimum permissible basic transmission loss required for p_1% of the time.

Iterative calculations

At the start of each iteration calculate the current distance for $i = 0, 1, 2 ...$ etc.:

$$d_i = d_{min} + i \cdot s \tag{15}$$

The losses, $L_{bl}(p_1)$ and $L_{bs}(p_1)$, for the assumption of the path being wholly land (Zones A1 or A2) or wholly cold (Zone B) or warm sea (Zone C) respectively, are evaluated successively from:

$$L_{bl}(p_1) = 142.8 + 20 \log f + 10 \log p_1 + 0.1\, d_i \qquad \text{for paths wholly in Zone A1 or A2} \tag{16}$$

$$L_{bs}(p_1) = \begin{cases} 49.91 \log\left(d_i + 1840 f^{1.76}\right) + 1.195 f^{0.393} (\log p_1)^{1.38} d_i^{0.597} \\ + (0.01\, d_i - 70)(f - 0.1581) + \left(0.02 - 2 \times 10^{-5} p_1^2\right) d_i + 9.72 \times 10^{-9} d_i^2 p_1^2 \\ + 20.2 & \text{paths wholly in Zone B} \quad (17a) \\ 49.343 \log\left(d_i + 1840 f^{1.58}\right) + 1.266 (\log p_1)^{(0.468 + 2.598 f)} d_i^{0.453} \\ + (0.037\, d_i - 70)(f - 0.1581) + 1.95 \times 10^{-10} d_i^2 p_1^3 + 20.2 & \text{paths wholly in Zone C} \quad (17b) \end{cases}$$

The basic transmission loss at the current distance is given by:

$$L_2(p_1) = L_{bs}(p_1) + \left[1 - \exp\left(-5.5\left(\frac{d_{tm}}{d_i}\right)^{1.1}\right)\right] \left(L_{bl}(p_1) - L_{bs}(p_1)\right) \tag{18}$$

where d_{tm} is defined in § 4.2 of Annex 1.

3 Frequencies between 850 MHz and 60 GHz

The propagation model given in this section is limited to an average annual time percentage (p_1) in the range 0.001% to 50%.

An iterative process must be used, as described in § 1 of Annex 1. Equations (20) to (30) are evaluated and then commencing at the minimum coordination distance, d_{min}, given by the method described in § 5.1, equations (31) to (41) are iterated for distances d_i, where $i = 0, 1, 2 ...$ etc., incremented in suitable steps. In each iteration d_i is referred to as the current distance. This process is continued until either of the following expressions becomes true:

$$\left(L_5(p_1) \geq L_3(p_1)\right)$$

and

$$\left(L_6(p_1) \geq L_4(p_1)\right) \tag{19a}$$

or

$$d_i \geq d_{max1} \tag{19b}$$

The required coordination distance, d_1, is then given by the current distance for the last iteration.

The recommended distance increment, s (km), is 1 km.

Calculate the specific attenuation (dB/km) due to dry air:

$$\gamma_o = \begin{cases} \left[7.19 \times 10^{-3} + \dfrac{6.09}{f^2 + 0.227} + \dfrac{4.81}{(f - 57)^2 + 1.50}\right] f^2 \times 10^{-3} & \text{for } f \leq 56.77 \quad (20a) \\ 10 & \text{for } f > 56.77 \quad (20b) \end{cases}$$

The specific attenuation due to water vapour is given as a function of ρ, the water vapour density in units of g/m^3 by the following equation:

$$\gamma_w(\rho) = \left(0.050 + 0.0021\rho + \frac{3.6}{(f - 22.2)^2 + 8.5} \right) f^2 \rho \times 10^{-4} \tag{21}$$

Calculate the specific attenuation (dB/km) due to water vapour for the troposcatter propagation model using a water vapour density of 3.0 g/m^3:

$$\gamma_{wt} = \gamma_w (3.0) \tag{22a}$$

Calculate the specific attenuation (dB/km) due to water vapour for the ducting propagation model using a water vapour density of 7.5 g/m^3 for paths over land, Zones A1 and A2, using:

$$\gamma_{wdl} = \gamma_w (7.5) \tag{22b}$$

Calculate the specific attenuation (dB/km) due to water vapour for the ducting propagation model using a water vapour density of 10.0 g/m^3 for paths over sea, Zones B and C, using:

$$\gamma_{wds} = \gamma_w (10.0) \tag{22c}$$

Note that the value of 10 g/m^3 is used for both Zones B and C in view of the lack of data on the variability of water vapour density on a global basis, particularly the minimum values.

Calculate the frequency-dependent ducting specific attenuation (dB/km):

$$\gamma_d = 0.05 f^{1/3} \tag{23}$$

For the ducting model

Calculate the correction for direct coupling into over-sea ducts (dB):

$$A_c = \frac{-6}{(1 + d_c)} \tag{24}$$

where d_c (km) is the distance from a land-based earth station to the coast in the direction being considered.

d_c is zero in other circumstances.

Calculate the non-distance-dependent part of the losses (dB):

$$A_1 = 122.43 + 16.5 \log f + A_h + A_c \tag{25}$$

Calculate the minimum required value for the distance-dependent losses (dB):

$$L_3(p_1) = L_b(p_1) - A_1 \tag{26}$$

Set a factor controlling an allowance for additional path-dependent and other losses, including those associated with terrain height:

$$\varepsilon = 8.5 \tag{27}$$

For the tropospheric scatter model

Calculate the frequency-dependent part of the losses (dB):

$$L_f = 25 \log(f) - 2.5 \left[\log\left(\frac{f}{2} \right) \right]^2 \tag{28}$$

Calculate the non-distance-dependent part of the losses (dB):

$$A_2 = 187.36 + 10\,\theta_h + L_f - 0.15\,N_0 - 10.1\left(-\log\left(\frac{p_1}{50}\right)\right)^{0.7} \qquad (29)$$

where:

θ_h: earth station horizon elevation angle (degrees)

N_0: path centre sea level surface refractivity.

Calculate the minimum required value for the distance dependent losses (dB):

$$L_4(p_1) = L_b(p_1) - A_2 \qquad (30)$$

Iterative calculations

At the start of each iteration calculate the current distance for i = 0, 1, 2 ... etc.:

$$d_i = d_{min} + i \cdot s \qquad (31)$$

Calculate the specific attenuation due to gaseous absorption (dB/km):

$$\gamma_g = \gamma_o + \gamma_{wdl}\left(\frac{d_t}{d_i}\right) + \gamma_{wds}\left(1 - \frac{d_t}{d_i}\right) \qquad (32)$$

where d_t is defined in § 4.2 of Annex 1.

Calculate the following zone-dependent parameters:

$$\tau = 1 - \exp\left[-\left(4.12 \times 10^{-4}\, d_{lm}^{2.41}\right)\right] \qquad (33)$$

where d_{lm} is defined in § 4.2 of Annex 1.

$$\mu_1 = \left[10^{\frac{-d_{tm}}{16 - 6.6\,\tau}} + \left[10^{-(0.496 + 0.354\,\tau)}\right]^5\right]^{0.2} \qquad (34)$$

where d_{tm} is defined in § 4.2 of Annex 1.

μ_1 shall be limited to $\mu_1 \leq 1$.

$$\sigma = -0.6 - \varepsilon \times 10^{-9}\, d_i^{3.1}\, \tau \qquad (35)$$

σ shall be limited to $\sigma \geq -3.4$.

$$\mu_2 = \left(2.48 \times 10^{-4}\, d_i^2\right)^{\sigma} \qquad (36)$$

μ_2 shall be limited to $\mu_2 \leq 1$.

$$\mu_4 = \begin{cases} 10^{(-0.935 + 0.0176\zeta_r)\log \mu_1} & \text{for} \quad \zeta_r \leq 70^\circ \qquad (37a) \\ 10^{0.3 \log \mu_1} & \text{for} \quad \zeta_r > 70^\circ \qquad (37b) \end{cases}$$

Calculate the path-dependent incidence of ducting, β, and a related parameter, Γ_1, used to calculate the time dependency of the basic transmission loss:

$$\beta = \beta_p \cdot \mu_1 \cdot \mu_2 \cdot \mu_4 \tag{38}$$

$$\Gamma_1 = \frac{1.076}{(2.0058 - \log\beta)^{1.012}} \exp\left[-\left(9.51 - 4.8\log\beta + 0.198(\log\beta)^2\right) \times 10^{-6} d_i^{1.13}\right] \tag{39}$$

Calculate the distance-dependent part of the losses (dB) for ducting:

$$L_5(p_1) = (\gamma_d + \gamma_g) d_i + (1.2 + 3.7 \times 10^{-3} d_i)\log\left(\frac{p_1}{\beta}\right) + 12\left(\frac{p_1}{\beta}\right)^{\Gamma_1} \tag{40}$$

and for tropospheric scatter:

$$L_6(p_1) = 20\log(d_i) + 5.73 \times 10^{-4}\left(112 - 15\cos(2\zeta)\right) d_i + (\gamma_o + \gamma_{wt})\, d_i \tag{41}$$

4 Frequencies between 60 GHz and 105 GHz

In the millimetric frequency range from 60 GHz to 105 GHz the propagation model is based upon free-space loss and a conservative estimate of gaseous absorption, plus an allowance for signal enhancements at small time percentages. This propagation model is valid for annual percentage times, p_1, in the range from 0.001% to 50%.

An iterative process must be used, as described in § 1 of Annex 1. Equations (43) to (47) are evaluated and then commencing at the minimum coordination distance, d_{min}, given by the method described in § 5.1, equations (48) and (49) are iterated for distances d_i, where $i = 0, 1, 2$ ... etc., incremented in suitable steps. In each iteration d_i is referred to as the current distance.

This process is continued until either of the following expressions becomes true:

$$L_9(p_1) \geq L_8(p_1) \tag{42a}$$

or

$$d_i \geq d_{max1} \tag{42b}$$

The required coordination distance, d_1, is then given by the current distance for the last iteration.

The recommended distance increment, s (km), is 1 km.

Calculate the specific absorption (dB/km) for dry air in the frequency range 60-105 GHz using:

$$\gamma_{om} = \begin{cases} \left[2 \times 10^{-4}\left(1 - 1.2 \times 10^{-5} f^{1.5}\right) + \dfrac{4}{(f - 63)^2 + 0.936} + \right. \\ \left. + \dfrac{0.28}{(f - 118.75)^2 + 1.771}\right] f^2 6.24 \times 10^{-4} & \text{for } f > 63.26\ \text{GHz} \quad (43a) \\ 10\ \text{dB/km} & \text{for } f \leq 63.26\ \text{GHz} \quad (43b) \end{cases}$$

Calculate the specific water vapour absorption (dB/km) for an atmospheric water vapour content of 3 g/m^3 using:

$$\gamma_{wm} = \left(0.039 + 7.7 \times 10^{-4} f^{0.5}\right) f^2 2.369 \times 10^{-4} \tag{44}$$

Calculate a conservative estimate of the specific gaseous absorption using:

$$\gamma_{gm} = \gamma_{om} + \gamma_{wm} \qquad \text{dB/km} \tag{45}$$

For the required frequency, and the value of earth station site shielding, A_h(dB), as calculated using the method described in § 1 of this Appendix, calculate the non-distance-dependent part of the basic transmission loss using:

$$L_7 = 92.5 + 20 \log(f) + A_h \qquad \text{dB} \tag{46}$$

Calculate the minimum required value for the distance-dependent losses (dB):

$$L_8(p_1) = L_b(p_1) - L_7 \qquad \text{dB} \tag{47}$$

Iterative calculations

At the start of each iteration calculate the current distance for $i = 0, 1, 2$ ... etc.:

$$d_i = d_{min} + i \cdot s \tag{48}$$

Calculate the distance-dependent losses for the current distance:

$$L_9(p_1) = \gamma_{gm}\, d_i + 20 \log(d_i) + 2.6\left[1 - \exp\left(\frac{-d_i}{10}\right)\right] \log\left(\frac{p_1}{50}\right) \tag{49}$$

APPENDIX 3

TO ANNEX 1

Calculation of the coordination distance for propagation mode (2)

1 Overview

The algorithm given below allows transmission loss, $L_r(p_2)$ (dB), to be obtained as a monotonic function of rainfall rate, $R(p_2)$ (mm/h), and with the hydrometeor scatter distance, r_i (km), as a parameter. The procedure to determine the hydrometeor scatter contour is as follows:

a) The value of $R(p_2)$, should be found for the required average annual time percentage, p_2 (0.001% to 10%), and the appropriate rain climate A to Q.

b) Values of $L_r(p_2)$, are then calculated for incremental values of r_i, starting at the minimum coordination distance d_{min}. The recommended distance increment, s (km), is 1 km. The correct value of r_i is that for which the corresponding value of $L_r(p_2)$, equals or exceeds the required transmission loss $L(p_2)$. This value of r_i is denoted d_r.

c) If the iterative calculation results in r_i equalling or exceeding the appropriate maximum calculation distance (d_{max2}) given in Table 2, then the calculation is terminated and d_r is assumed to have this maximum value i.e. the iteration stops when either of the following expressions becomes true:

$$L_r(p_2) \geq L(p_2) \tag{50a}$$

or

$$r_i \geq d_{max2} \tag{50b}$$

d) The coordination contour for propagation mode (2) is a circle of radius d_r (km) centred on a point along the azimuth of the earth station antenna main beam at a horizontal distance of Δd (km) from the earth station.

2 Maximum calculation distance

As discussed in § 5.2 of Annex 1, it is necessary to set upper limits to the maximum distance used in the iterative calculation of coordination distance. The maximum calculation distance to be used for propagation mode (2) (d_{max2}) is latitude dependent and is given in Table 2.

TABLE 2

Propagation mode (2) maximum calculation distances (d_{max2}) (km)

Latitude (degrees)	0-30	30-40	40-50	50-60	> 60
Distance (km)	350	360	340	310	280

3 Calculation of the propagation mode (2) coordination contour

Determine $R(p_2)$:

$R(p_2)$ is the surface rainfall rate (mm/h) exceeded on average for p_2% of a year. p_2% is the average annual percentage time applicable to propagation mode (2).

The world has been divided into a number of rain climatic zones (see Figs. 1, 2 and 3) which show different precipitation characteristics. The curves shown in Fig. 4 represent consolidated rainfall-rate distributions, each applicable to several of these rain climates.

Determine which rain climate is appropriate for the location of the earth station:

– For $0.001\% < p_2 < 0.3\%$ and the appropriate rain climate:

  Determine $R(p_2)$ either from Fig. 4 or from equations (51), (52), (53), (54) and (55).

– For $p_2 \geq 0.3\%$:

  Use equation (56) with values of $R(0.3\%)$ and p_c obtained from Table 3.

FIGURE 1

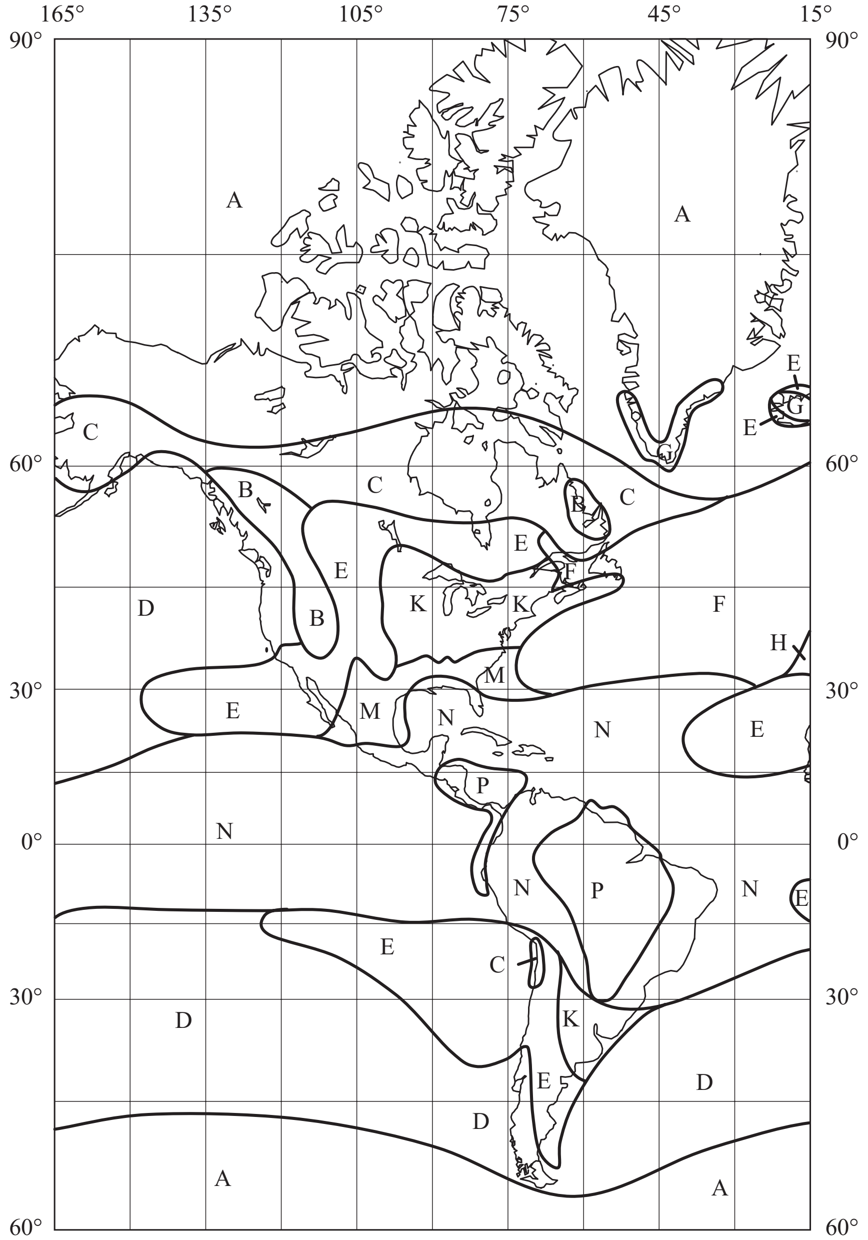

FIGURE 2

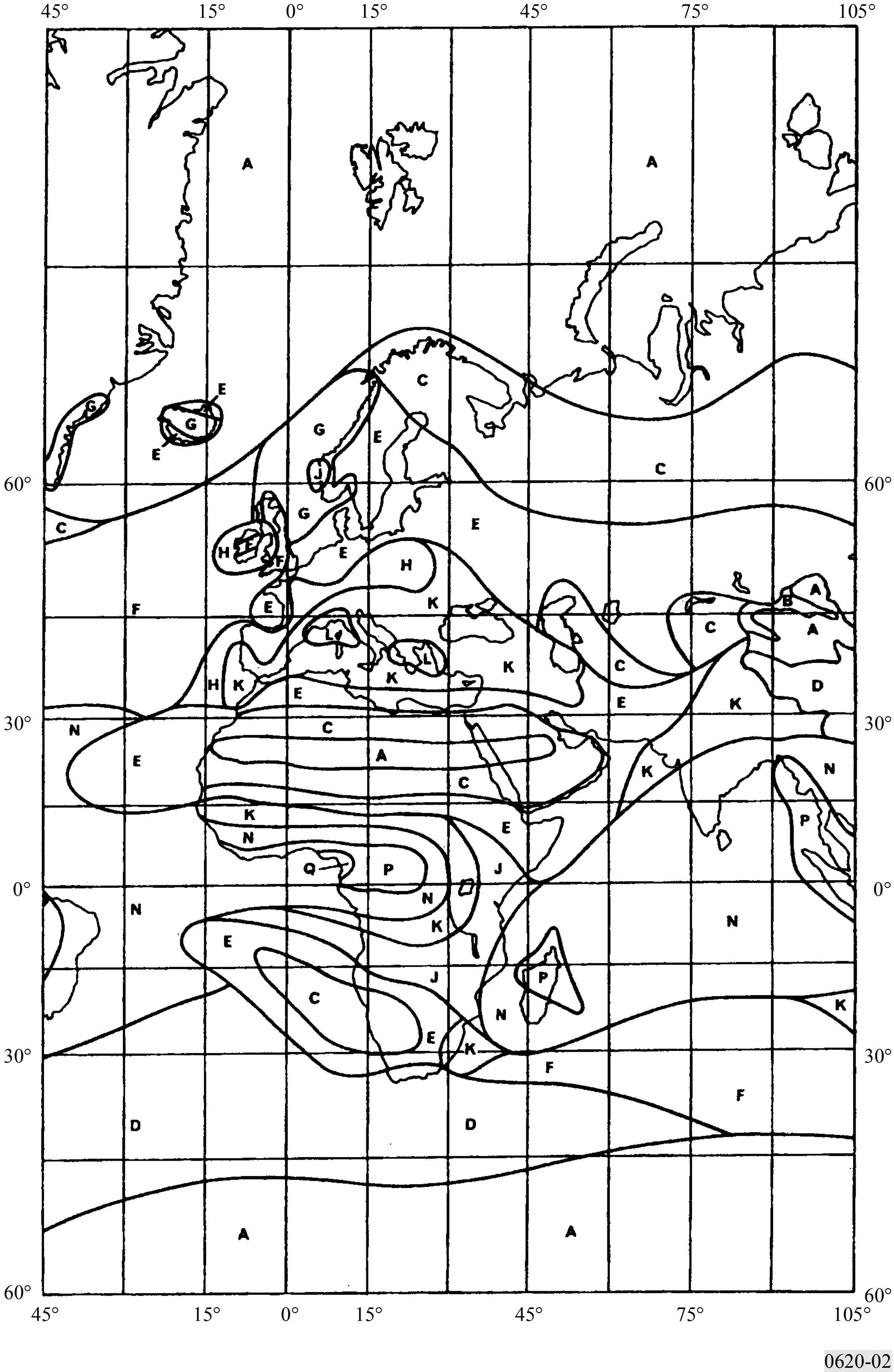

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FIGURE 3

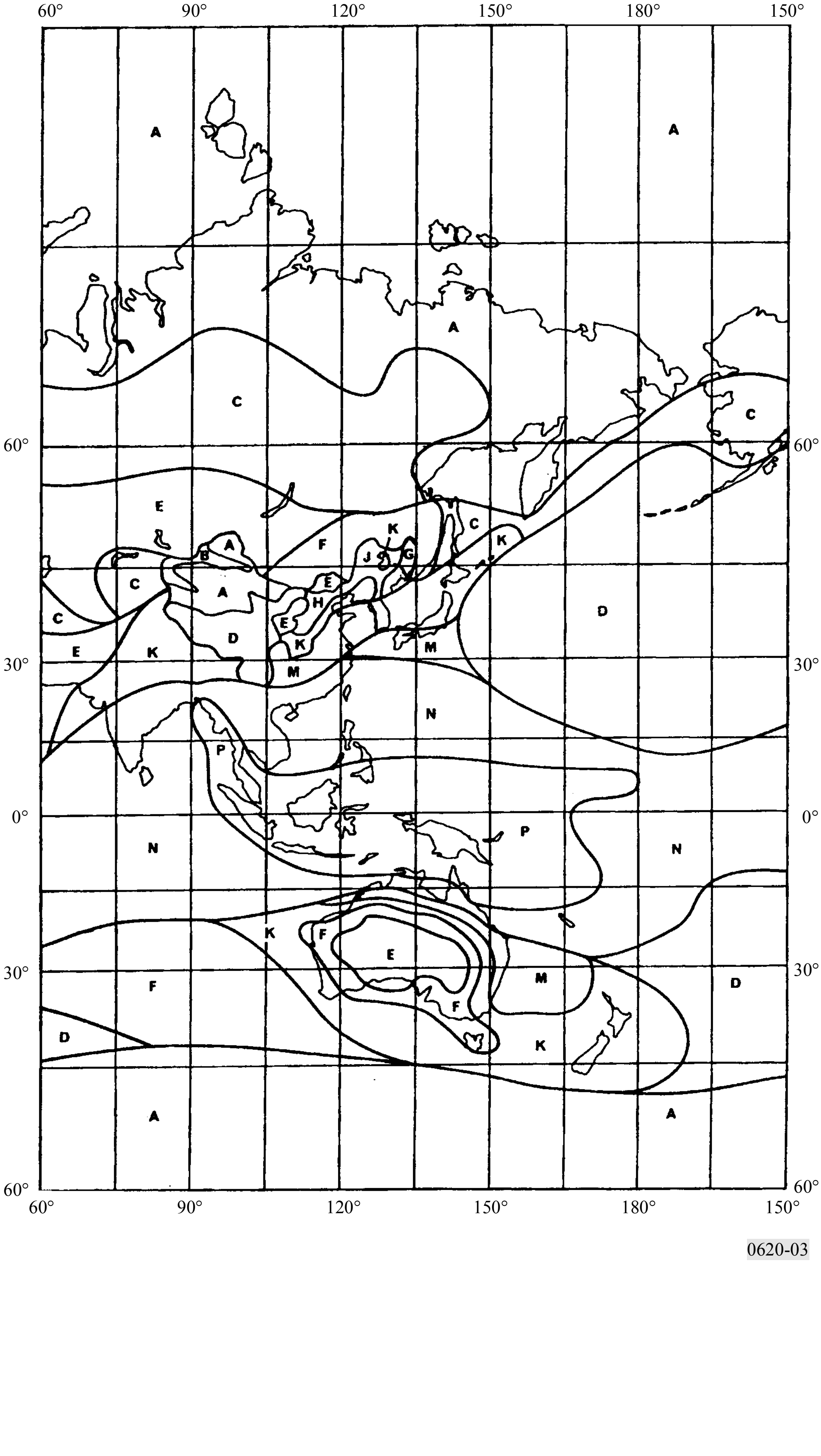
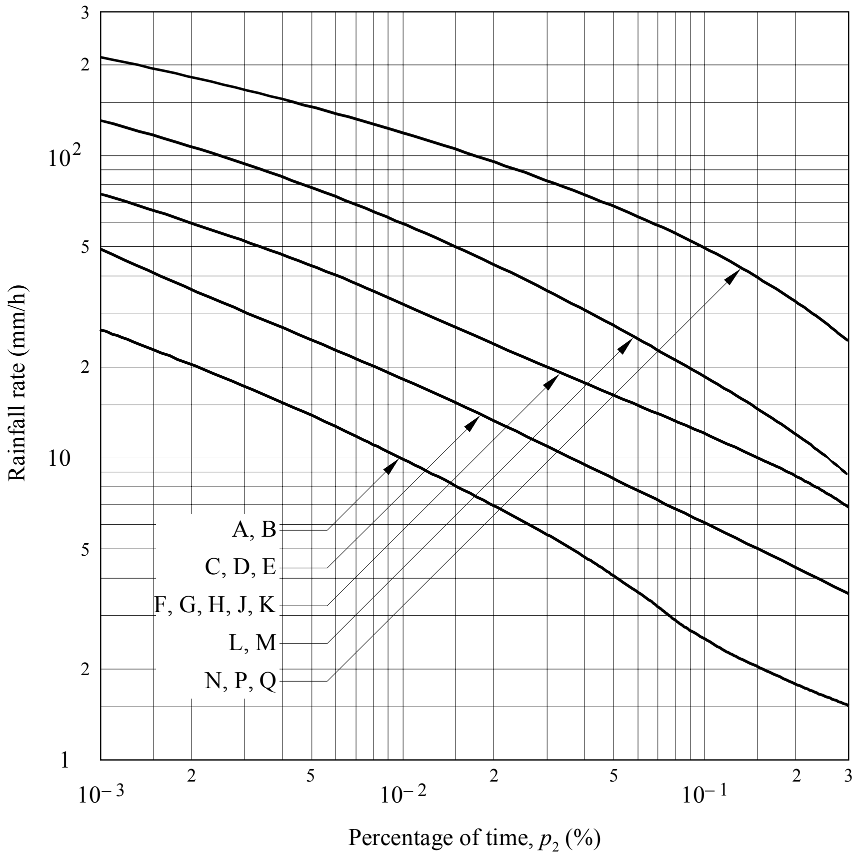


FIGURE 4

Consolidated cumulative distributions of rainfall rate for the rain climatic zones shown in Figs. 1, 2 and 3



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Rain climatic zones A, B

$$R(p_2) = 1.1\, p_2^{-0.465} + 0.25\left[\log\left(p_2/0.001\right)\log^3\left(0.3/p_2\right)\right] - \left[\left|\log\left(p_2/0.1\right)\right| + 1.1\right]^{-2} \quad \text{mm/h} \quad (51)$$

Rain climatic zones C, D, E

$$R(p_2) = 2\, p_2^{-0.466} + 0.5\left[\log\left(p_2/0.001\right)\log^3\left(0.3/p_2\right)\right] \quad \text{mm/h} \quad (52)$$

Rain climatic zones F, G, H, J, K

$$R(p_2) = 4.17\, p_2^{-0.418} + 1.6\left[\log\left(p_2/0.001\right)\log^3\left(0.3/p_2\right)\right] \quad \text{mm/h} \quad (53)$$

Rain climatic zones L, M

$$R(p_2) = 4.9\, p_2^{-0.48} + 6.5\left[\log\left(p_2/0.001\right)\log^2\left(0.3/p_2\right)\right] \quad \text{mm/h} \quad (54)$$

Rain climatic zones N, P, Q

$$R(p_2) = 15.6\left(p_2^{-0.383} + \left[\log\left(p_2/0.001\right)\log^{1.5}\left(0.3/p_2\right)\right]\right) \quad \text{mm/h} \quad (55)$$

TABLE 3

Rain climatic zone	R(0.3%) (mm/h)	p_c (%)
A, B	1.5	2
C, D, E	3.5	3
F, G, H, J, K	7.0	5
L, M	9.0	7.5
N, P, Q	25.0	10

where p_c% is the percentage time at which the rainfall rate $R(p_2)$ can be assumed to approach zero.

$$R(p_2) = R(0.3\%)\left[\frac{\log(p_c/p_2)}{\log(p_c/0.3)}\right]^2 \quad \text{mm/h} \tag{56}$$

Determine the specific attenuation (dB/km) due to rain using values of k and α from Table 4 in equation (58). Values of k and α at frequencies other than those in Table 4 can be obtained by interpolation using a logarithmic scale for frequency, a logarithmic scale for k and a linear scale for α.

TABLE 4

Values of k and α for vertical polarization as a function of the frequency

Frequency (GHz)	k	α
4	0.000591	1.075
6	0.00155	1.265
8	0.00395	1.31
10	0.00887	1.264
12	0.0168	1.20
14	0.029	1.15
18	0.055	1.09
20	0.0691	1.065
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

Let:

$$R = R(p_2) \tag{57}$$

Then the specific attenuation (dB/km) due to rain is given by:

$$\gamma_R = k \; R^{\alpha} \tag{58}$$

Let:

$$d_s = 3.5\, R^{-0.08} \tag{59}$$

$$C = \frac{2.17}{\gamma_R \, d_s}\left(1 - 10^{\frac{-\gamma_R \, d_s}{5}}\right) \tag{60}$$

$$\Gamma_2 = 631\, k \, R^{(\alpha - 0.5)} \times 10^{-(R + 1)^{0.19}} \tag{61}$$

Determine the mean rain height above ground, h_R (km):

For North America and Europe west of 60° E longitude:

$$h_R = 3.2 - 0.075\,(\zeta - 35) \qquad \text{for} \qquad 35 \le \zeta \le 70 \tag{62}$$

For all other areas of the world:

$$h_R = \begin{cases} 5 - 0.075\left(\zeta - 23\right) & \text{for} \quad \zeta > 23 \quad \text{Northern hemisphere} & (63a) \\ 5 & \text{for} \quad 0 \le \zeta \le 23 \quad \text{Northern hemisphere} & (63b) \\ 5 & \text{for} \quad 0 \ge \zeta \ge -21 \quad \text{Southern hemisphere} & (63c) \\ 5 + 0.1\left(\zeta + 21\right) & \text{for} \quad -71 \le \zeta < -21 \quad \text{Southern hemisphere} & (63d) \\ 0 & \text{for} \quad \zeta < -71 \quad \text{Southern hemisphere} & (63e) \end{cases}$$

Determine the specific attenuation due to water vapour absorption (a water vapour density of 7.5 g/m^3 is used):

$$\gamma_{wr} = \left[0.06575 + \frac{3.6}{\left(f - 22.2\right)^2 + 8.5}\right] f^2 \, 7.5 \times 10^{-4} \tag{64}$$

Set the gain of the terrestrial station antenna (assumed to be 42 dBi):

$$G_T = 42 \tag{65}$$

Iterative calculations

Carry out the iterative calculation for increasing values of r_i, where r_i is the current distance (km) between the region of maximum scattering and the possible location of a terrestrial station and $i = 0, 1, 2$ ... etc.:

$$r_i = d_{min} + i \cdot s \tag{66}$$

Determine the loss above the melting layer, E (dB), applicable to scatter coupling:

$$E = \begin{cases} 6.5\left[6\,(r_i - 50)^2 \times 10^{-5} - h_R\right] & \text{for} \quad 6\,(r_i - 50)^2 \times 10^{-5} > h_R & \text{(67a)} \\ 0 & \text{for} \quad 6\,(r_i - 50)^2 \times 10^{-5} \leq h_R & \text{(67b)} \end{cases}$$

Let:

$$10 \log A_b = \begin{cases} 0.005\,(f - 10)^{1.7}\,R^{0.4} & \text{for} \quad 10\,\text{GHz} < f < 40\,\text{GHz} & \text{(68a)} \\ 0 & \text{for} \quad f \leq 10\,\text{GHz} \text{ or when } E \neq 0 & \text{(68b)} \end{cases}$$

and

$$d_o = \begin{cases} 0.7\,r_i + 32 & \text{for } r_i < 340\,\text{km} & \text{(69a)} \\ 270 & \text{for } r_i \geq 340\,\text{km} & \text{(69b)} \end{cases}$$

and

$$d_v = \begin{cases} 0.7\,r_i + 32 & \text{for } r_i < 240\,\text{km} & \text{(70a)} \\ 200 & \text{for } r_i \geq 240\,\text{km} & \text{(70b)} \end{cases}$$

Determine the propagation mode (2) path loss, L_r (dB):

$$L_r = 168 + 20 \log r_i - 20 \log f - 13.2 \log R - G_T + 10 \log A_b - 10 \log C + \Gamma_2 + E + \gamma_o d_o + \gamma_{wr} d_v \qquad (71)$$

where γ_o is given in equation (20).

In order to determine the centre of the circular propagation mode (2) coordination contour, it is necessary to calculate the horizontal distance to this point from the earth station, along the azimuth of the earth station antenna main beam. This horizontal distance, Δd (km), is given by:

$$\Delta d = \frac{h_R}{2 \tan \varepsilon_s} \qquad (72)$$

where ε_s is the earth station antenna main beam elevation angle (degrees) and Δd shall be limited to the distance (d_r – 50) to ensure that the earth station location does not fall outside the propagation mode (2) coordination contour for small values of ε_s.

Draw a circle of radius d_r (km) around the point determined above. The hydrometeor scatter coordination contour (coordination contour for propagation mode (2)) is the locus of points on this circle bounded by the minimum and maximum coordination distances.

As the only significant hydrometeor scatter is that occurring in the general vicinity of the earth station, the question of a mixed path loss does not arise.

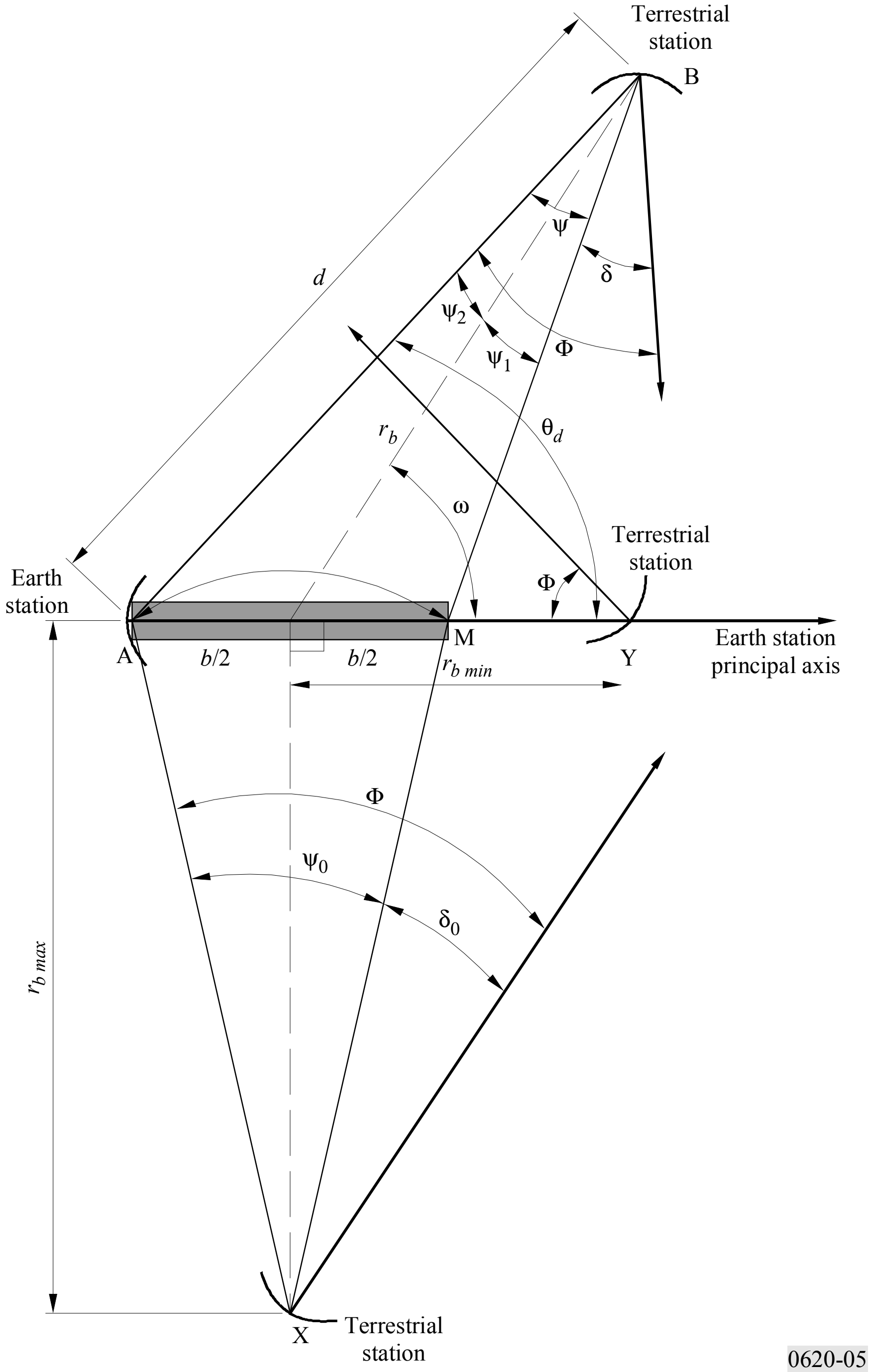
4 Calculation of auxiliary contours for propagation mode (2)

4.1 Overview

Figure 5 shows the plan view of the hydrometeor scatter projected on to the horizontal plane, where A is the earth station, B is the terrestrial station at an arbitrary position, X and Y represent the locations of the terrestrial station that correspond to the maximum and minimum distance away from the centre of the contour, defined by equation (72), respectively and M is at the maximum horizontal extent of the potential common volume (CV). The shaded area in Fig. 5 represents the critical region along the earth station beam which, if intersected by the terrestrial station main beam, would result in significant hydrometeor scatter interference via main lobe to main lobe coupling. This critical region, whose extent is annotated by b in the Figure, is bounded by the earth station on one side and the rain height, h_R, on the other. For a given point within the coordination zone, the angle subtended by this region is termed the look angle, ψ. The protection angle, δ, represents the angle of the terrestrial station beam away from the critical region. The avoidance angle, Φ, is the sum of these two angles ψ and δ and it is this quantity Φ which will remain fixed along its own auxiliary contour.

FIGURE 5

Propagation geometry in the horizontal plane



The reference point of the contour is at the centre of the common volume (at a distance $b/2$ away from the earth station). Each contour is generated by varying the polar angle, ω, and deriving corresponding values of r_b, as ω changes from 0° to 360°, the angles ψ and δ will rise and fall, but their sum remains the same. The most favourable position for a terrestrial station occurs when ω = 0 (position Y), at which point the protection angle reaches its maximum. The distance from the centre of the common volume to the terrestrial station is then a minimum, denoted by $r_{b\,min}$ in the Figure. At the other extreme, when ω = 90° (position X), the look angle reaches its maximum, the protection angle will be at its minimum and r_b will have its largest value $r_{b\,max}$ for the contour.

4.2 The step-by-step algorithm

The following algorithm can be used to calculate the auxiliary propagation mode (2) coordination contour for a given value of the avoidance angle Φ.

– The limits of the minimum protection angle, δ_0, are:

$\delta_{0\,min} = 1.0°$

$\delta_{0\,max} = 48.0°$

– Determine the horizontal distance, b (km), between the earth station and the most distant common volume possible:

$$b = h_R \cot \varepsilon_s \tag{73}$$

where ε_s is the earth station antenna main beam elevation angle.

– Calculate the value of δ_0 that corresponds to the chosen Φ, as follows:

a) Set $\delta_0 = \delta_{0\,min}$.

b) Calculate the transmitter side lobe gain at this angle δ_0 off boresight using the reference antenna pattern given in Appendix 4.

c) Use the resulting gain in place of the parameter G_T in equation (71) to compute the maximum distance for the auxiliary contour, $r_{b\,max}$, for the required transmission loss threshold.

d) Calculate ψ_0 using:

$$\psi_0 = 2 \arc \tan \left(\frac{b/2}{r_{b\,max}} \right) \tag{74}$$

e) Calculate the avoidance angle, Φ′, for the selected δ_0 using:

$$\Phi' = \psi_0 + \delta_0 \tag{75}$$

f) If $|\Phi' - \Phi| > 0.01\ \Phi$ then use the standard bisection technique to determine a new estimate for δ_0 and repeat from step b) until convergence is achieved as defined by $|\Phi' - \Phi| \leq 0.01\ \Phi$.

g) Use the final value of δ_0 and $r_{b\,max}$ hereafter.

– Derive $r_{b\,min}$ by:

a) calculating the antenna side lobe gain for the above value of Φ using the reference antenna pattern given in Appendix 4;

b) using this side lobe gain in place of the parameter G_T in equation (71) to compute the distance for the auxiliary contour, for the required transmission loss threshold. This distance is $r_{b\,min}$.

– Generate the contour for values of ω from 0° to 180° in steps of 1° as follows:

a) Set $r_b = 0.5\ (r_{b\,min} + r_{b\,max})$.

b) Compute ψ from:

$$\psi_1 = \arc \tan \left(\frac{b \sin \omega}{2 r_b - b \cos \omega} \right) \tag{76}$$

$$\psi_2 = \arc \tan \left(\frac{b \sin \omega}{2 r_b - b \cos \omega} \right) \tag{77}$$

$$\psi = \psi_1 + \psi_2 \tag{78}$$

c) Compute $\delta = \Phi - \psi$.

d) Compute $G(\delta)$ using the reference antenna pattern given in Appendix 4.

e) Using the resulting side lobe gain, $G(\delta)$, in place of the parameter G_T in equation (71), compute the distance r'_b for the required transmission loss threshold.

f) If $|r'_b - r_b| < 0.5$ km, then the desired value has been found.

If not, a new value is given to r_b:

$$r_b = 0.5\,(r_b + r_{b\,max}) \qquad \text{for} \qquad r'_b > r_b \tag{79}$$

$$r_b = 0.5\,(r_b + r_{b\,min}) \qquad \text{for} \qquad r'_b \le r_b \tag{80}$$

and steps b) to f) are repeated.

– Once the value of r_b has been found, calculate the distance, d, and the azimuth, θ_d, from the location of the earth station to that contour point using:

$$d = 0.5\,b \sin\omega / \sin\psi_2 \tag{81}$$

$$\theta_d = \arcsin(r_b \sin\psi_2 / 0.5\,b) \qquad \text{for} \qquad (d^2 - r_b^2 + 0.25\,b^2)/(b\,d) > 0 \tag{82}$$

$$\theta_d = \pi - \arcsin(r_b \sin\psi_2 / 0.5\,b) \qquad \text{for} \qquad (d^2 - r_b^2 + 0.25\,b^2)/(b\,d) \le 0 \tag{83}$$

– The values of r_b for ω from 181° to 359° can be found by using the symmetry relationship:

$$r_b(\omega) = r_b(-\omega) = r_b(360° - \omega) \tag{84}$$

APPENDIX 4

TO ANNEX 1

Reference radiation patterns for line-of-sight radio-relay system antennas for use in coordination studies and interference assessment in the frequency range from 1 to about 40 GHz

This Appendix gives a reference radiation pattern for line-of-sight radio-relay system antennas for use in the propagation mode (2) coordination calculations when the actual antenna pattern is not available.

It is essential that every effort be made to utilize the actual antenna pattern in coordination studies and interference assessment, however, if this is not available the following reference radiation pattern should be adopted for frequencies in the range of 1 to 40 GHz:

a) In cases where the ratio between the antenna diameter and the wavelength is greater than 100, the following equation should be used:

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda}\varphi\right)^2 \qquad \text{for} \qquad 0 < \varphi < \varphi_m \tag{85}$$

$$G(\varphi) = G_1 \qquad \text{for} \qquad \varphi_m \le \varphi < \varphi_r \tag{86}$$

$$G(\varphi) = 32 - 25 \log \varphi \qquad \text{for} \qquad \varphi_r \le \varphi < 48° \tag{87}$$

$$G(\varphi) = -10 \qquad \text{for} \qquad 48° \le \varphi \le 180° \tag{88}$$

$$G_1 = 2 + 15 \log \left(\frac{D}{\lambda} \right) \tag{89}$$

$$\varphi_m = \frac{20\lambda}{D} \sqrt{G_{max} - G_1} \tag{90}$$

$$\varphi_r = 15.85 \left(\frac{D}{\lambda} \right)^{-0.6} \tag{91}$$

b) In cases where the ratio between the antenna diameter and the wavelength is less than or equal to 100, the following equation should be used (see Notes 6 and 7):

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \quad \text{for} \quad 0 < \varphi < \varphi_m \tag{92}$$

$$G(\varphi) = G_1 \quad \text{for} \quad \varphi_m \leq \varphi < 100 \frac{\lambda}{D} \tag{93}$$

$$G(\varphi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \varphi \quad \text{for} \quad 100 \frac{\lambda}{D} \leq \varphi < 48° \tag{94}$$

$$G(\varphi) = 10 - 10 \log \frac{D}{\lambda} \quad \text{for} \quad 48° \leq \varphi \leq 180° \tag{95}$$

c) In cases where only the maximum antenna gain is known, D/λ may be estimated from the following expression:

$$20 \log \frac{D}{\lambda} \approx G_{max} - 7.7 \tag{96}$$

where G_{max} is the main lobe antenna gain (dBi).

d) In cases where only the beamwidths of the antenna are known:

D/λ (expressed in the same unit) may be estimated from the following expression:

$$D/\lambda \approx 69.3 / \theta_{bw} \tag{97}$$

where θ_{bw} is the beamwidth (3 dB down) (degrees);

G_{max} may then be estimated approximately by:

$$G_{max} \text{ (dBi)} \approx 44.5 - 20 \log \theta_{bw} \tag{98}$$

NOTE 1 – It is essential that every effort be made to utilize the actual antenna pattern in coordination studies and interference assessment.

NOTE 2 – It should be noted that the radiation pattern of an actual antenna may be worse than the reference radiation pattern over a certain range of angles (see Note 3). Therefore, the reference radiation pattern in this Appendix should not be interpreted as establishing the maximum limit for radiation patterns of existing or planned radio-relay system antennas.

NOTE 3 – The reference radiation pattern should be used with caution over the range of angles for which the particular feed system may give rise to relatively high levels of spill-over.

NOTE 4 – The reference patterns in a) and b) are only applicable for one polarization (horizontal or vertical). Reference patterns for two polarizations (horizontal and vertical) are under study.

NOTE 5 – The reference radiation pattern included in this Appendix is only for antennas which are rotationally symmetrical. The reference radiation pattern for antennas with asymmetrical apertures requires further study. For such antennas, the above reference patterns may be considered to be provisionally valid.

NOTE 6 – For further information, a mathematical model of average radiation patterns for use in certain coordination studies and interference assessment is given in Recommendation ITU-R F.1245.

NOTE 7 – Further study is required to ensure that reference radiation patterns continue to develop to take account of advances in antenna design.

NOTE 8 – While generally applicable, the reference patterns in a) and b) do not suitably model some practical fixed service antennas and should be treated with caution over a range of angles from 5° to 70° (see also Notes 2 and 3).

APPENDIX 5

TO ANNEX 1

Input and derived parameters

In some cases a parameter may be either an input parameter or may be derived within this Recommendation. The status of the parameters (input or derived) is listed in Table 5. The status is defined as:

– *Input:* An input parameter, the value of which is not given or cannot be obtained from within this Recommendation e.g. frequency, earth station latitude, etc.

– *Derived:* A parameter, the value of which is derived, defined (e.g. a constant) or calculated within this Recommendation, e.g. surface rainfall rate $R(p)$ (mm/h) (obtained from maps and graphs), d_{max2} (obtained from Table 5), the coordination distance for propagation mode (1) d_1 (km) (calculated) etc.

The definition and location for parameters marked * are given in Table 1.

TABLE 5

Definition of terms

Parameter	Units	Definition	Where defined	Status
A_c	dB	A correction for direct coupling into over-sea ducts	Equation (24)	Derived
A_d	dB	The correction for horizon distance along each azimuth from an earth station	Equation (10)	Derived
A_h	dB	The total loss due to terrain shielding along each azimuth from an earth station	Equations (11a) to (11c) § 1 of Appendix 2	Derived
b	km	The horizontal distance between the earth station and the most distant common volume possible, used in calculating the auxiliary contours for propagation mode (2)	Equation (73)	Derived
C	–	Effective scatter transform used in propagation mode (2)	Equation (60)	Derived
d	km	The distance from the earth station to a point on the auxiliary contour, used in calculating the auxiliary contours for propagation mode (2)	Equation (81) § 4.1 and 4.2 of Appendix 3	Derived
d_1	km	The coordination distance for propagation mode (1)	§ 2, 3 and 4 of Appendix 2	Derived

TABLE 5 (*continued*)

Parameter	Units	Definition	Where defined	Status
d_c	km	*	*	Input
d_h	km	*	*	Input
d_i	km	The current distance from the earth station used in the iterative calculation of the mode (1) coordination distance	Equations (15), (31) and (48)	Derived
d_{lm}	km	*	*	Input
d_{max1}	km	The maximum calculation distance for propagation mode (1)	§ 5.2	Derived
d_{max2}	km	The maximum calculation distance for propagation mode (2)	Table 2	Derived
d_{min}	km	The minimum coordination distance for both propagation mode (1) and propagation mode (2)	Equations (5a) to (5f)	Derived
d'_{min}	km	The minimum coordination distance for low frequencies	Equation (4)	Derived
d_0, d_v	km	Distances used in determining the mode (2) coordination distance	Equations (69a), (69b) (70a) and (70b)	Derived
d_r	km	The distance from the earth station at which the loss equals or exceeds the required transmission loss for mode (2) propagation	§ 1 of Appendix 3	Derived
d_s	km	The slant path length within the rain cell	Equation (59)	Derived
d_t	km	*	*	Input
d_{tm}	km	*	*	Input
D	m	*	*	Input
E	dB	The loss for heights above the melting layer, applicable to scatter coupling	Equations (67a) and (67b)	Derived
f	GHz	*	*	Input
$G(\varphi)$	dB	The antenna gain at an off-axis angle of φ determined from the antenna reference radiation pattern (Appendix 4)	Equations (85) to (88), (92) to (95)	Derived
G_L		A term used in the conversion from worst-month time percentage to annual time percentage	Equations (7a) and (7b)	Derived
G_1	dB	The gain of the antenna first side lobe determined from the antenna reference radiation pattern (Appendix 4)	Equation (89)	Derived
G_{max}	dB	*	*	Input
G_T	dB	*	*	Input
h_R	km	The effective rain height above ground	Equations (62) and (63a) to (63e)	Derived
$L_b(p_1)$	dB	*	*	Input
$L_b(p_2)$	dB	*	*	Input

TABLE 5 (*continued*)

Parameter	Units	Definition	Where defined	Status
$L_{bl}(p_1)$	dB	A loss applicable to a path which is assumed to be wholly land (Zone A1 or A2), used in the iterative calculation of the propagation mode (1) coordination distance	Equation (16)	Derived
$L_{bs}(p_1)$	dB	A loss applicable to a path which is assumed to be wholly cold sea (Zone B) or warm sea (Zone C), used in the iterative calculation of the propagation mode (1) coordination distance	Equations (17a) and (17b)	Derived
$L_1(p_1)$ $L_2(p_1)$ $L_3(p_1)$ $L_4(p_1)$ $L_5(p_1)$ $L_6(p_1)$ $L_7(p_1)$ $L_8(p_1)$ $L_9(p_1)$	dB dB dB dB dB dB dB dB dB	Losses used in the iterative calculation of the propagation mode (1) coordination distance	Equations (14), (18), (26), (30), (40), (41), (46), (47) and (49)	Derived
L_f	dB	A frequency dependent loss used in the calculation of the propagation mode (1) coordination distance	Equation (28)	Derived
L_r	dB	The transmission loss, obtained as a monotonic function of rainfall rate (R), used in determining the propagation mode (2) coordination distance	Equation (71)	Derived
N_0	–	The path centre sea level surface refractivity	Equation (3)	Derived
p_c	%	The percentage time at which the rainfall rate $R(p)$ can be assumed to approach zero	Equation (56) Table 3	Derived
p_1	%	*	*	Input
p_{w1}	%	*	*	Input
p_2	%	*	*	Input
p_{w2}	%	*	*	Input
$R(p_2)$	mm/h	The surface rainfall rate exceeded on average for p_2% of a year, used in the propagation mode (2) calculations	Equations (51) to (56)	Derived
r_b	km	The distance from the centre of the common volume to the auxiliary contour, used in calculating the auxiliary contours for propagation mode (2)	Equations (79), (80) and (84) § 4.1 and 4.2 of Appendix 3	Derived
$r_{b\,max}$	km	The maximum value of r_b which occurs for $\omega = 90°$	§ 4.1 of Appendix 3	Derived
$r_{b\,min}$	km	The minimum value of r_b which occurs for $\omega = 0°$	§ 4.1 of Appendix 3	Derived
r_i	km	The current distance between the region of maximum scattering and the possible location of a terrestrial station, used in the iterative calculation of the propagation mode (2) coordination distance	Equations (66) and (67)	Derived
s	km	*	*	Input

TABLE 5 (*continued*)

Parameter	Units	Definition	Where defined	Status
α	–	The index used in the relation $\gamma_R = k\,R^{\alpha}$ for the specific attenuation due to rain	Table 4	Derived
β_p	%	The relative incidence of clear-air anomalous propagation	Equations (2a) and (2b)	Derived
Δd	km	The distance of a point along the earth station beam azimuth to be used as the centre of the (circular) propagation mode (2) coordination contour	Equation (72)	Derived
δ	degrees	The required minimum protection angle, used in calculating the auxiliary contours for propagation mode (2) (see § 4.2 of Appendix 3)	§ 4.1 and 4.2 of Appendix 3	Derived
ε	–	ε is an allowance for additional distance-dependent and other losses, including those associated with terrain height	Equation (27)	Derived
ε_s	degrees	*	*	Input
φ	degrees	*	*	Input
φ_r	degrees	An angular offset from the axis of the antenna main beam used in the antenna reference radiation pattern (Appendix 4)	Equation (91)	Derived
φ_m	degrees	An angular offset from the axis of the antenna main beam used in the antenna reference radiation pattern (Appendix 4)	Equation (90)	Derived
Γ_1	–	A term used in the iterative calculation of the propagation mode (1) coordination distance	Equation (39)	Derived
Γ_2	dB	A term used in the calculation of the propagation mode (2) coordination distance	Equation (61)	Derived
γ_d	dB/km	A specific attenuation term, used in the iterative calculation of the propagation mode (1) coordination distance	Equation (23)	Derived
γ_g	dB/km	The specific attenuation due to gaseous absorption	Equation (32)	Derived
γ_{gm}	dB/km	The specific attenuation due to gaseous absorption used in the frequency range 60 GHz to 105 GHz	Equation (45)	Derived
γ_o	dB/km	The specific attenuation due to dry air	Equation (20)	Derived
γ_{om}	dB/km	The specific attenuation due to dry air used in the frequency range 60 GHz to 105 GHz	Equations (43a) and (43b)	Derived
γ_R	dB/km	The specific attenuation due to rain	Equation (58)	Derived
γ_w	dB/km	The specific attenuation due to water vapour	Equation (21)	Derived
γ_{wdl}	dB/km	The specific attenuation due to water vapour absorption used in the ducting propagation model for paths over land, Zone A1 and Zone A2 (a water vapour density of 7.5 g/m^3 is used)	Equation (22b)	Derived
γ_{wds}	dB/km	The specific attenuation due to water vapour absorption used in the ducting propagation model for paths over sea, Zone B and Zone C (a water vapour density of 10.0 g/m^3 is used)	Equation (22c)	Derived

TABLE 5 (*end*)

Parameter	Units	Definition	Where defined	Status
γ_{wr}	dB/km	The specific attenuation due to water vapour absorption used in the hydrometeor scatter model (a water vapour density of 7.5 g/m^3 is used)	Equation (64)	Derived
γ_{wt}	dB/km	The specific attenuation due to water vapour absorption used in the troposcatter propagation model (a water vapour density of 3 g/m^3 is used)	Equation (22a)	Derived
γ_{wm}	dB/km	The specific attenuation due to water vapour absorption used in the frequency range 60 GHz to 105 GHz (a water vapour density of 3 g/m^3 is used)	Equation (44)	Derived
Φ	degrees	*	*	Input
k	dB/km	The coefficient used in the relation $\gamma_R = k\,R^{\alpha}$ for the specific attenuation due to rain	Table 4	Derived
λ	m	*	*	Input
μ_1	–	A parameter, which depends on the degree to which the path is over land (inland and/or coastal) and water, used in the iterative calculation of the propagation mode (1) coordination distance	Equation (34)	Derived
μ_2	–	A parameter used in the iterative calculation of the propagation mode (1) coordination distance	Equation (36)	Derived
μ_4	–	A parameter used in the iterative calculation of the propagation mode (1) coordination distance	Equations (37a) and (37b)	Derived
θ_d	degrees	The azimuth relative to the main beam direction from the earth station to a point on the auxiliary contour, used in calculating the auxiliary contours for propagation mode (2)	Equations (82) and (83) § 4.1 and 4.2 of Appendix 3	Derived
θ_h	degrees	*	*	Input
θ_{bw}	degrees	*	*	Input
ρ	g/m^3	*	*	Input
τ	–	A parameter used in the iterative calculation of the propagation mode (1) coordination distance	Equation (33)	Derived
ω	degrees	*	*	Input
ψ	degrees	*	*	Input
ζ	degrees	*	*	Input
ζ_r	degrees	A latitude, related to the earth station latitude, used in determining an appropriate value for the relative incidence of clear-air anomalous propagation, β_p	Equations (1a) and (1b)	Derived