RECOMMENDATION ITU-R P.620-5

Propagation data required for the evaluation of coordination distances in the frequency range 100 MHz to 105 GHz

(Question ITU-R 208/3)

(1986-1992-1995-1997-1999-2003)

The ITU Radiocommunication Assembly,

considering

a) 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;

b) that the determination of the coordination area should be based on the best propagation data available and should be adequately conservative;

c) that the World Radiocommunication Conference (Istanbul, 2000) (WRC-2000) approved a revision of Appendix 7 of the Radio Regulations based on material in Recommendation ITU-R-SM.1448 which in turn is based on material in Recommendation ITU-R P.620 covering the frequency range 100 MHz to 105 GHz;

d) that Resolution 74 (WRC-2000) describes a process to keep the technical bases of Appendix 7 current,

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 with distance until either the required transmission loss is achieved or a limiting distance is reached.

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.

The iteration method can always use a uniform step size, 1 km being recommended. In the case of mode (1) the functions defining propagation loss are monotonic with distance and, if preferred, a more efficient iteration procedure may be used.

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 790 MHz the model is based on an empirical fit to measured data;

– from 790 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 1 GHz and above 40.5 GHz interference produced by hydrometeor scatter can be ignored. Below 1 GHz the level of the scattered signal is very low and above 40.5 GHz, although significant scattering occurs, the scattered signal is then highly attenuated on the path from the scatter volume to the terrestrial station.

For mode (1) the distance is incremented from a specified minimum which varies according to propagation factors relevant to each frequency range. For mode (2) distance is decremented from a maximum given in Table 2. For auxiliary mode (2), distance is decremented from the main mode (2) coordination distance for the same azimuth.

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:

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

where ζ is earth station latitude (degrees).

β_p is then determined using:

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

For frequencies between 790 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:

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

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_{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.

4.3 Use of radio-climatic information from other Recommendations

In certain sections for both mode (1) and mode (2) calculations, reference is made to radio-climatic information obtained from other ITU-R Recommendations. These are:

a) Recommendation ITU-R P.836-3 for water vapour density;

b) Recommendation ITU-R P.837-3 for rain rate;

c) Recommendation ITU-R P.839-3 for rain height.

These Recommendations are referenced where necessary to obtain a radio-climatic parameter for a particular location defined by longitude and latitude. In other parts of the mode (1) and mode (2) calculations constant values of some radio-climatic parameters are used. In these cases no reference is needed to the other Recommendations.

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 minimum distance applies to both mode (1) and mode (2) and is always the shortest coordination distance under any circumstances.

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:

$$d_{max1} = \begin{cases} 1200 & \text{km} \quad \text{for} \quad f \le 60\ \text{GHz} & \text{(6a)} \\ 80 - 10\log\left(\dfrac{p_1}{50}\right) & \text{km} \quad \text{for} \quad f > 60\ \text{GHz} & \text{(6b)} \end{cases}$$

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

5.3 Use of distance limits for iterative calculations

For mode (1) calculations, distance is incremented from the minimum distance limit and never continues beyond the maximum distance limit. For mode (2) calculations, distance is decremented from the maximum distance limit (or from the main contour in the case of auxiliary mode (2)), and never continues to distances less than the minimum.

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:

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

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 790 MHz the method described in § 2 of Appendix 2;

– for frequencies between 790 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 1 GHz to 40.5 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).

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.

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	§ 4.2 of Annex 1	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	§ 4.2 of Annex 1	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 (83)	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 (57)	Input
h_R	km	The effective rain height above the ground	Appendix 3	Input
$L_b(p_1)$	dB	The minimum permissible basic transmission loss required for p_1% of the time for propagation mode (1)	§ 1	Input
$L_b(p_2)$	dB	The minimum permissible basic transmission loss required for p_2% of the time for propagation mode (2)	§ 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 790 MHz 0.001% to 50% for f between 790 MHz and 105 GHz	Equation (8)	Input or derived
p_{w1}	%	The worst-month time percentage for propagation mode (1)	§ 6.1	Input

TABLE 1 (*end*)

Parameter	Units	Definition	Where defined	Status
p_2	%	The average annual time percentage for propagation mode (2) 0.001% to 10%	Equation (9)	Input or derived
p_{w2}	%	The worst-month time percentage for propagation mode (2)	§ 7.2	Input
r_E	km	The effective radius of the Earth (= 8 500 km)	Appendix 3	Input
$R(_{p2})$	mm/h	The surface rainfall rate exceeded on average for p_2% of a year, used in the propagation mode (2) calculations	Appendix 3	Input
s	km	The distance increment used in the iterative calculation of the coordination distance (the recommended value is 1 km)	§ 1	Input
ε	degrees	The earth station antenna main beam elevation angle	§ 3 of Appendix 3	Input
φ	degrees	An angular offset from the axis of the antenna main beam used in the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input
γ_P	dB/km	The specific attenuation due to rain	Appendix 3	Input
λ	m	The wavelength used in determining the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input
θ_h	degrees	The earth station horizon elevation angle	§ 1 of Appendix 2	Input
θ_{bw}	degrees	The antenna 3 dB beamwidth used in the antenna reference radiation pattern (Appendix 4)	Equations (95) and (96)	Input
ρ	g/m^3	Atmospheric water vapour density exceeded for 50% of time	Equations (21) and (56)	Input
ρ_0	g/m^3	Atmospheric water vapour density exceeded for 50% of time at the earth station	Equation (22b)	Input
ρ_{dmin}	g/m^3	Atmospheric water vapour density exceeded for 50% of time at d_{min} on the relevant azimuth	Equation (22b)	Input
ρ_i	g/m^3	Atmospheric water vapour density exceeded for 50% of time for each step of the mode (1) iteration	Equation (32)	Input
ω	degrees	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 Appendix 3	Input
ζ	degrees	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:

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

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:

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

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

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

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 790 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.:

$$d_i = d_{min} + i \cdot s \qquad (15)$$

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:

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

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

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

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

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

3 Frequencies between 790 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 $i = 0, 1, 2 \ldots$ 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:

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

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

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:

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

Obtain from Recommendation ITU-R P.836 the median water vapour densities ρ_0 at the earth station and ρ_{dmin} at distance d_{min} along the relevant azimuth.

Calculate the attenuation due to water vapour for the part of the path which lies within the minimum distance, using:

$$A_w = d_{min} \cdot \gamma_w\left(\frac{\rho_0 + \rho_{dmin}}{2}\right) \tag{22b}$$

where ρ_0 and ρ_{dmin} are defined in Appendix 1 to Annex 1.

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):

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

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:

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

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):

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

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):

$$L_4(p_1) = L_b(p_1) - A_2 \tag{30}$$

Iterative calculations

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

$$d_i = d_{min} + i \cdot s \tag{31}$$

For the position on the Earth's surface at distance d_i on the relevant azimuth obtain from Recommendation ITU-R P.836 the water vapour density exceeded for 50% time, ρ_i (g/m^3). Then, calculate the distance-dependent attenuation due to gaseous absorption using:

$$A_g = (\gamma_o + \gamma_d) \cdot d_i + \sum_{n=0}^{i} \gamma_w(\rho_n) \cdot s \tag{32}$$

where $\gamma_w(\rho_n)$ is given by equation (21).

Calculate the following zone-dependent parameters:

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

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

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

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

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

$$\sigma = -0.6 - \varepsilon_L \times 10^{-9} \, d_i^{3.1} \, \tau \tag{35}$$

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

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

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

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

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

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

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

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

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

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:

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

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)

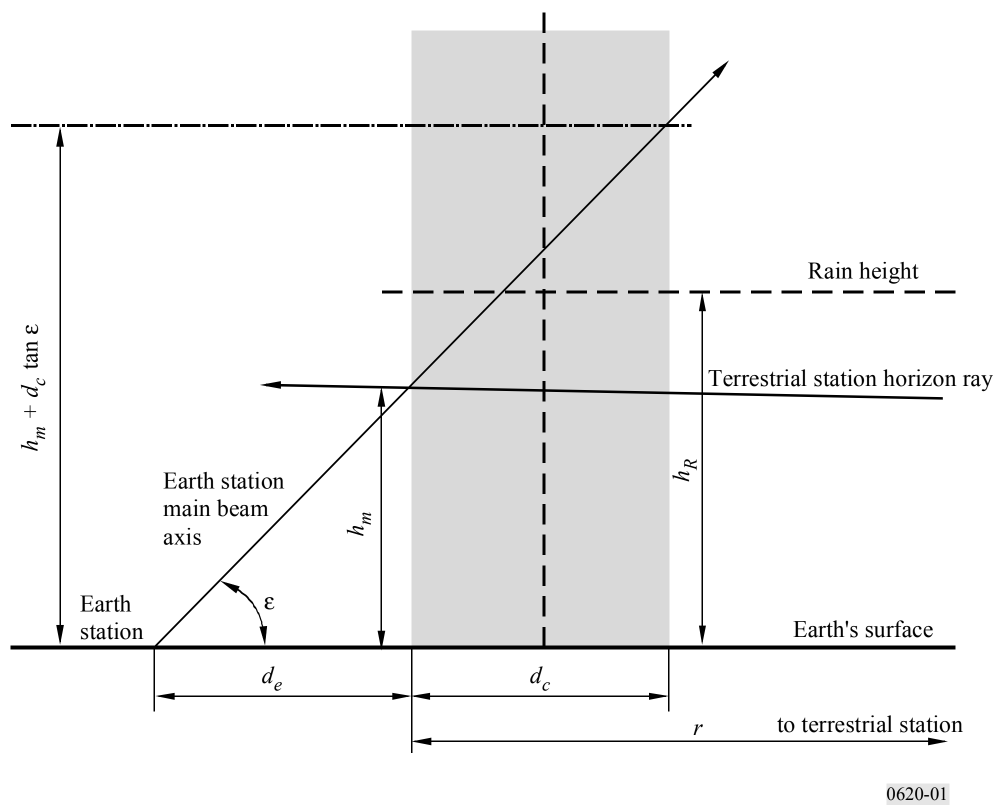
1 Overview

The methodology to determine the coordination distance for propagation mode (2) rain scatter interference is based on the bistatic radar equation, with the so-called "narrow-beam" approximation for the earth station antenna, in which the spreading loss from the scattering volume to the earth station antenna is cancelled by the antenna gain. The method thus depends primarily on the pathlength from the terrestrial station to the scattering volume, i.e. the rain cell.

The algorithm given below allows transmission loss, $L_r(p_2)$ (dB), to be obtained as a function of rainfall rate, $R(p_2)$ (mm/h), and with the separation distance between the edge of the rain cell and the possible location of the terrestrial station, r_i (km), as a parameter. The geometry of the rain scatter process is illustrated in Fig. 1.

FIGURE 1

Geometry of the rain scatter process



The procedure to determine the hydrometeor scatter contour is as follows:

The value of $R(p_2)$, should be found from Recommendation ITU-R P.837-3 for the required average annual time percentage, p_2 (0.001% to 10%), and the latitude and longitude appropriate to the earth station location.

Values of $L_r(p_2)$ are then calculated for decrementing values of r_i, starting at the maximum calculation distance d_{max2} for propagation mode (2), given in Table 2. The recommended distance decrement, s (km), is 1 km. The value of r_i is decremented until the corresponding value of $L_r(p_2)$ is just less than the required transmission loss $L_b(p_2)$. Thus, decrement r_i until either of the following conditions are true:

$$L_r(p_2) < L_b(p_2) \qquad (50a)$$

or

$$r_i < d_{min} \qquad (50b)$$

where this latter condition represents the minimum calculation distance.

The calculation distance, d_r, is then given by the immediately preceding value of r_i:

$$d_r = r_{i-1} = d_{max2} - s \cdot (i-1) \qquad (51)$$

The resulting calculation distance, d_r, is the propagation pathlength between the terrestrial station and the edge of the rain cell that will provide the required transmission path loss. Assuming that scattering from the rain cell is isotropic in azimuth, the coordination contour is defined as a circle, centred at the edge of the rain cell, with radius d_r.

The coordination contour is then drawn as a circle of radius d_r centred at a distance d_e from the earth station along the earth-station azimuthal direction, where d_e is the distance from the earth station to the edge of the rain cell, as indicated in Fig. 1; determination of the distance d_e is defined in the following procedure.

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 determination of the calculation distance, from which the iterative calculations begin. 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 the rainfall rate exceeded for p_2% of time, $R(p_2)$, from Recommendation ITU-R P.837-3, for the latitude and longitude of the earth station. Note that p_2% is the average annual percentage time applicable to propagation mode (2).

Note also that the rainfall rate and rain height will not vary significantly between the location of the earth station and the location of the rain cell along the azimuthal direction of the earth station, since the distance between these two points will typically be less than ~30 km, for earth-station elevation angles down to 10°.

Determine the specific attenuation, γ_R (dB/km), due to rain using Recommendation ITU-R P.838, assuming vertical polarization.

Set the diameter of the rain cell, d_c (km):

$$d_c = 3.3 R(p_2)^{-0.08} \tag{52}$$

Determine the mean rain height above ground, h_R (km), from Recommendation ITU-R P.839 for the latitude and longitude of the earth station.

Calculate an intermediate parameter, η:

$$\eta = (R(p_2) + 1)^{0.19} \tag{53}$$

Calculate the scaling distance, r_m (km) for the attenuation outside the common scattering volume:

$$r_m = 600 R(p_2)^{-0.5} \times 10^{-\eta} \tag{54}$$

The specific attenuation due to dry air (dB/km) is evaluated from the following expression:

$$\gamma_o = \left[7.19 \times 10^{-3} + \frac{6.09}{f^2 + 0.227} + \frac{4.81}{(f - 57)^2 + 1.5} \right] f^2 \times 10^{-3} \tag{55}$$

From Recommendation ITU-R P.836, determine the surface water-vapour density, ρ (g/m^3), exceeded for 50% of time at the latitude and longitude corresponding to the earth station. Note that, for simplicity in determining propagation mode (2) contours, the water-vapour density is assumed constant over the path. The water-vapour specific attenuation is then given in dB/km by:

$$\gamma_{wv} = \left[0.050 + 0.0021\rho + \frac{3.6}{(f - 22.2)^2 + 8.5} \right] f^2 \rho \times 10^{-4} \tag{56}$$

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

$$G_T = 42 \tag{57}$$

Iterative calculations

Beginning with the maximum calculation distance, obtained from Table 2, evaluate equations (58) to (77) inclusive, for decreasing values of r_i, where r_i is the current separation distance (km) between the rain cell and the possible location of a terrestrial station and $i = 0, 1, 2, \ldots$ etc.:

$$r_i = d_{max2} - i \cdot s \tag{58}$$

Continue this process until the condition given in inequality (50) is true. At this point, the rain-scatter calculation distance, d_r, has the preceding value of r_i, i.e.:

$$d_r = d_{max2} - (i - 1) \cdot s \tag{59}$$

If an iteration results in $d_r < d_{min}$, then $d_r = d_{min}$ and the iteration terminates.

Determine the height above ground of the point of intersection between the antenna beams from the terrestrial station and the earth station:

$$h_m = r_E \left(\frac{1}{\cos \delta} - 1 \right) \tag{60}$$

where:

δ is the angular separation between the rain cell and the point on the Earth's surface at the current distance, r_i:

$$\delta = \frac{r_i}{r_E} \qquad \text{rad} \tag{61}$$

r_E: effective radius of the Earth, $r_E = 8\,500$ km.

Determine the pathlength from the terrestrial station to the beam intersection point:

$$r_t = h_m \sqrt{1 + 2\frac{r_E}{h_m}} \tag{62}$$

Determine the pathlength from the beam intersection to the earth station:

$$r_r = \sqrt{r_E^2 \sin^2 \varepsilon + h_m^2 + 2 h_m r_E} - r_E \sin \varepsilon \tag{63}$$

where:

ε: elevation angle of the earth station antenna.

Determine the horizontal distance from the earth station to the edge of the rain cell:

$$d_e = r_E \arcsin\left(\frac{r_r}{h_m + r_E} \cos \varepsilon \right) \tag{64}$$

Calculate the parameter h_c which depends on the region within the rain cell where the beam intersection occurs:

$$h_c = \begin{cases} h_m & \text{for } h_R \le h_m \\ h_R & \text{for } h_m < h_R < h_m + d_c \tan \varepsilon \\ h_m + d_c \tan \varepsilon & \text{for } h_R \ge h_m + d_c \tan \varepsilon \end{cases} \tag{65}$$

Calculate the attenuation from the point at the current distance to the beam intersection:

$$\Gamma_2 = \gamma_R r_m \left[1 - \exp\left(-\frac{r_t}{r_m} \right) \right] \tag{66}$$

and the attenuation from the beam intersection to the earth station:

$$\Gamma_1 = \begin{cases} \gamma_R r_m \left[1 - \exp\left(-\frac{d_e}{r_m} \right) \right] & \text{for } h_m \le h_R \\ \gamma_R r_m \left[\exp\left(-\frac{(h_m - h_R) \cot \varepsilon}{r_m} \right) - \exp\left(-\frac{d_e}{r_m} \right) \right] & \text{for } h_m > h_R \end{cases} \tag{67}$$

From these, evaluate the total path attenuation for scattering by rain below the rain height:

$$\Gamma_b = \exp\left[-0.23\left(\frac{\Gamma_1}{\cos\varepsilon} + \Gamma_2\right)\right] \tag{68}$$

and the total path attenuation for scattering from the melting layer and ice above the rain height:

$$\Gamma_a = \exp\left[-0.23\left(\frac{\Gamma_1}{\cos\varepsilon} + \gamma_R \frac{h_c - h_m}{\sin\varepsilon}\right)\right] \tag{69}$$

Calculate the effective scatter transfer function for scattering by rain below the rain height:

$$C_b = \frac{4.34}{\gamma_R(1+\cos\varepsilon)}\left[1 - \exp\left\{-0.23\,\gamma_R(h_c - h_m)\frac{\sin\varepsilon}{1-\cos\varepsilon}\right\}\right] \tag{70}$$

and for scattering by ice above the rain height:

$$C_a = \frac{0.67}{\sin\varepsilon_s}\left[\exp\{-1.5(h_c - h_R)\} - \exp\{-1.5(h_m - h_R + d_c\tan\varepsilon)\}\right] \tag{71}$$

The total effective scatter transfer function is then given by:

$$C = \Gamma_b\, C_b + \Gamma_a\, C_a \tag{72}$$

Determine the deviation from Rayleigh scattering for frequencies above 10 GHz:

$$10\log S = \begin{cases} 0.005(f-10)^{1.7}\,R(p_2)^{0.4} & \text{for } 10 \le f \le 40 \\ 0 & \text{for } f < 10 \text{ or when } C_b = 0 \end{cases} \tag{73}$$

Note that this deviation from Rayleigh scattering applies only to scattering from rain, below the rain height.

The attenuation by atmospheric gases is now evaluated from the following expressions. First, determine the equivalent path lengths, to take account of the decrease in gaseous specific attenuation with height. For the path from the terrestrial station to the rain cell:

$$d_{to} = \begin{cases} 0.9r_t & \text{for } r_t < 270 \text{ km} \\ 243 + 0.4(r_t - 270) & \text{for } r_t \ge 270 \text{ km} \end{cases} \tag{74a}$$

$$d_{tv} = \begin{cases} 0.85r_t & \text{for } r_t < 220 \text{ km} \\ 187 + 0.4(r_t - 220) & \text{for } r_t \ge 220 \text{ km} \end{cases} \tag{74b}$$

and for the path from the rain cell to the earth station:

$$d_{ro} = 0.8r_r \tag{75a}$$

$$d_{rv} = 0.5r_r \tag{75b}$$

The gaseous attenuation is then determined from:

$$A_g = \gamma_o(d_{to} + d_{ro}) + \gamma_{wv}(d_{tv} + d_{rv}) \tag{76}$$

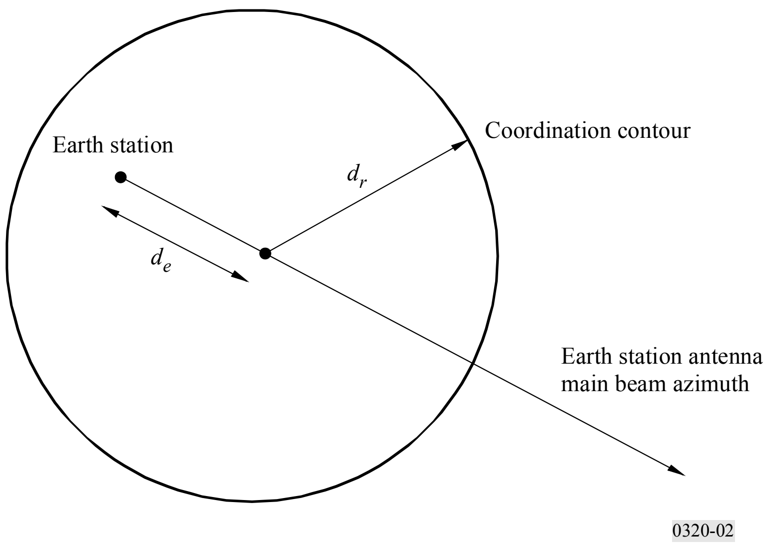
Finally, the transmission loss is determined from:

$$L_r(p_2) = 173 + 20 \log r_i - 20 \log f - 14 \log R(p_2) - 10 \log C + 10 \log S - G_T + A_g \tag{77}$$

The distance d_r which results from this iteration is the distance from the terrestrial station to the edge of the rain cell, and the coordination contour then given by a circle of radius d_r, centred at a distance d_e from the earth station, along its azimuthal direction, as indicated in Fig. 2.

FIGURE 2

Location of coordination contour



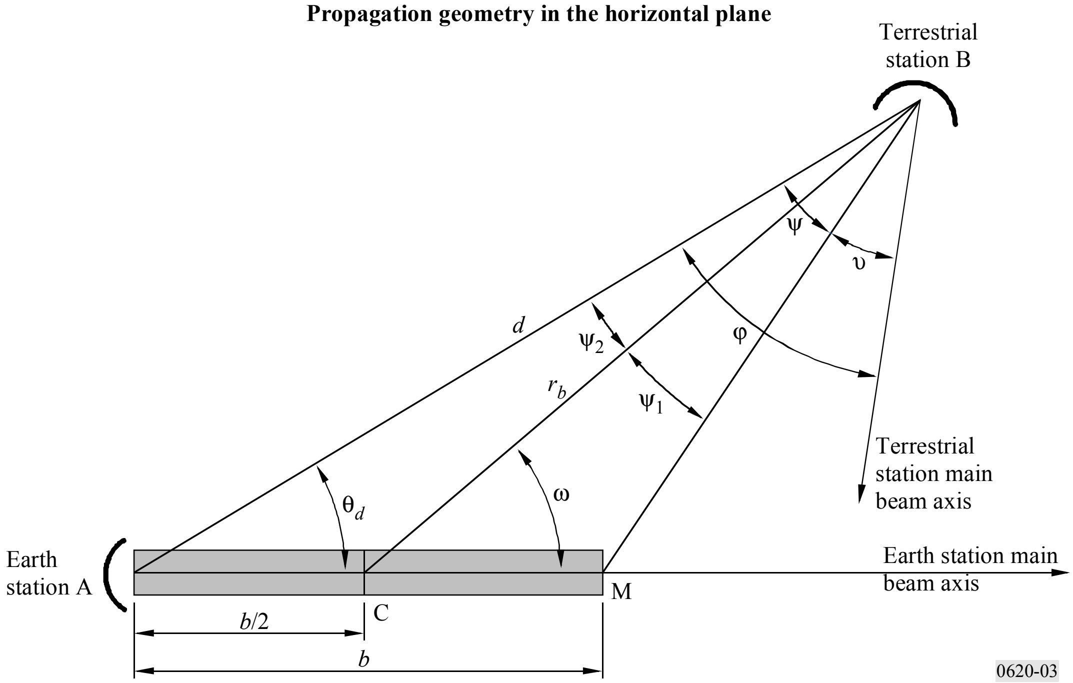
4 Determination of auxiliary contours for propagation mode (2)

Propagation mode (2) auxiliary contours allow the azimuthal offset of a terrestrial station antenna beam from the coordinating earth station's location to be taken into consideration. Figure 3 shows the hydrometeor scatter region projected on to the horizontal plane. In this Figure, the earth station and the terrestrial station are located at the points A and B, respectively, where the terrestrial station is on a radial defined by the angle ω from the point C at the centre of the propagation mode (2) main, or supplementary, contour. Point C is also the centre of the auxiliary contour.

The shaded area in Fig. 3 represents the critical region, along the earth station's main beam axis, between the earth station and the rain height. Within this critical region a common volume can be formed between the earth station beam and the beam of any terrestrial stations within the propagation mode (2) main, or supplementary, contour. This critical region's length is b and its maximum horizontal extent is at point M. Intersection of this critical region by the terrestrial station main beam axis, would result in significant hydrometeor scatter interference via main lobe-to-main lobe coupling.

FIGURE 3

Propagation geometry in the horizontal plane



For a given point within the propagation mode (2) main, or supplementary, contour, the angle subtended by the critical region is termed the critical angle, ψ. The protection angle, υ, represents the angle of the terrestrial station main beam axis away from the critical region. The beam avoidance angle between the terrestrial station's main beam axis and the earth station's location is φ. It is the sum of the two angles ψ and υ and it is this quantity that has a fixed value for a specific auxiliary contour. Each auxiliary contour is generated by varying the angle, ω, and deriving the distance, r_b, from point C to the auxiliary contour. As the angle ω increases from 0° to 360°, the angles ψ and υ change, but their sum remains the same.

The algorithm in § 4.1 of this Appendix can be used to calculate the auxiliary propagation mode (2) contour for a given value of beam avoidance angle φ.

The method is based on iteratively decrementing the distance, r_b, between terrestrial station and the earth station, starting at the main contour distance, d_r, given by equation (59) above, until either the shortest value of r_b is found for which the required minimum loss is achieved, or the minimum coordination distance is reached. For each value of r_b, the critical angle ψ is determined and then the protection angle υ is calculated. The terrestrial station antenna gain corresponding to υ and the current distance r_b are then used in equation (77) to obtain the propagation mode (2) path loss.

The above process is repeated for each angle ω, to generate a complete auxiliary contour for a given value of beam avoidance angle φ. For some combinations of beam avoidance angle and angle ω, an auxiliary contour may coincide with the main, or supplementary, propagation mode (2) contour.

4.1 The step-by-step algorithm

Auxiliary propagation mode (2) contours are constructed by calculating distances along radials from the centre of the circular mode (2) main, or supplementary, contour, which is the point C, at the distance $b/2$ from the earth station along the azimuth of its main beam axis. The distance $b/2$ is equal to d_e, where d_e is given by equation (64).

For the selected value of beam avoidance angle, φ, generate the auxiliary contour for values of angle, ω, ranging from 0° to 180° in steps of 1°, as follows:

a) Set r_b to the main, or supplementary, mode (2) contour distance d_r calculated as described in equation (59).

b) Compute ψ from:

$$\psi_1 = \arctan\left(\frac{b \sin \omega}{2r_b - b \cos \omega}\right) \tag{78}$$

$$\psi_2 = \arctan\left(\frac{b \sin \omega}{2r_b + b \cos \omega}\right) \tag{79}$$

$$\psi = \psi_1 + \psi_2 \tag{80}$$

c) If $\psi > \varphi$ then the auxiliary mode (2) contour coincides with the main or supplementary mode (2) contour for the current value of ω, and the calculation for that value of ω is completed, and go to step j). Otherwise proceed through the following steps d) to i) until one of the terminating conditions described in step f) and step i) is satisfied.

d) Decrement r_b by subtracting 0.2 km from its value.

e) Recalculate the critical angle ψ using equations (78), (79) and (80).

f) If $(0.5\ b \sin \omega / \sin \psi_2) < d_{min}$, the auxiliary mode (2) contour coincides with the minimum coordination distance d_{min} and the calculation for the current value of ω is completed – go to step j). Otherwise, proceed to step g).

g) Compute the protection angle $\upsilon = \varphi - \psi$.

h) Calculate $G(\upsilon)$, the terrestrial station antenna gain at the angle υ relative to the beam axis, using the reference antenna pattern given in Appendix 4.

i) In equation (77), use the gain calculated in step h) in place of G_T and the new value of r_b, and calculate the corresponding propagation mode (2) path loss L_r. If $L_r < L_b(p_2)$, then increment r_b by adding 0.2 km to its value and take this as the distance for the current radial. Otherwise, repeat from step d).

j) Once the new value of r_b has been found for the current value of angle ω, calculate the angle θ_d from the location of the earth station, and if appropriate the distance, d, to that contour point using:

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

$$\theta_d = \omega - \psi_2 \tag{82}$$

An auxiliary propagation mode (2) contour is symmetrical about the earth station main beam axis. Thus, values of d and θ_d corresponding to the values of ω from 181° to 359° can be found by noting that results for a given value of ω are the same as for $(-\omega)$ or $(360° - \omega)$.

The step size for incrementing r_b used above, 0.2 km, is suitable for most situations. It controls the granularity of the result when viewed as a set of r_b values. For low values of earth station beam elevation, the granularity becomes more noticeable in the values of d and θ_d, and a smaller step size may be used.

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

(based on Recommendation ITU-R F.699)

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:

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \qquad \text{for} \qquad 0 < \varphi < \varphi_m \tag{83}$$

$$G(\varphi) = G_1 \qquad \text{for} \qquad \varphi_m \leq \varphi < \varphi_r \tag{84}$$

$$G(\varphi) = 32 - 25 \log \varphi \qquad \text{for} \qquad \varphi_r \leq \varphi < 48° \tag{85}$$

$$G(\varphi) = -10 \qquad \text{for} \qquad 48° \leq \varphi \leq 180° \tag{86}$$

$$G_1 = 2 + 15 \log \left(\frac{D}{\lambda} \right) \tag{87}$$

$$\varphi_m = \frac{20\lambda}{D} \sqrt{G_{max} - G_1} \tag{88}$$

$$\varphi_r = 15.85 \left(\frac{D}{\lambda} \right)^{-0.6} \tag{89}$$

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):

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \varphi \right)^2 \qquad \text{for} \qquad 0 < \varphi < \varphi_m \tag{90}$$

$$G(\varphi) = G_1 \qquad \text{for} \qquad \varphi_m \leq \varphi < 100 \frac{\lambda}{D} \tag{91}$$

$$G(\varphi) = 52 - 10 \log \frac{D}{\lambda} - 25 \log \varphi \qquad \text{for} \qquad 100 \frac{\lambda}{D} \leq \varphi < 48° \tag{92}$$

$$G(\varphi) = 10 - 10 \log \frac{D}{\lambda} \qquad \text{for} \qquad 48° \leq \varphi \leq 180° \tag{93}$$

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

$$20 \log \frac{D}{\lambda} \approx G_{max} - 7.7 \tag{94}$$

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:

$$D/\lambda \approx 69.3 / \theta_{bw} \tag{95}$$

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

G_{max} may then be estimated approximately by:

$$G_{max} \text{ (dBi)} \approx 44.5 - 20 \log \theta_{bw} \tag{96}$$

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 3. 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 3), the coordination distance for propagation mode (1) d_1 (km) (calculated) etc.

TABLE 3

Definition of terms

Parameter	Units	Definition	Where defined	Status
A_1	dB	The non-distant-dependent part of the ducting loss	Equation (25)	Derived
A_2	dB	The non-distant-dependent part of the troposcatter loss	Equation (29)	Derived
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_g	dB	The attenuation due to atmospheric gases in propagation mode (1) and propagation mode (2) calculations	Equations (32) and (76)	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
A_w	dB	Attenuation due to water vapour over the part of the path within the minimum distance for mode (1)	Equation (22b)	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)	§ 4.1 of Appendix 3	Derived
C	–	Effective scatter transfer function used in propagation mode (2)	Equation (72)	Derived
C_a, C_b	–	Effective scatter transfer functions for scattering above and below the rain height	Equations (71) and (70)	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 of Appendix 3	Derived

TABLE 3 (*continued*)

Parameter	Units	Definition	Where defined	Status
d_1	km	The coordination distance for propagation mode (1)	§ 2, 3 and 4 of Appendix 2	Derived
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_c	km	The diameter of the rain cell, used in propagation mode (2) calculations	Equation (52)	Derived
d_e	km	The horizontal distance from the earth station to the edge of the rain cell	Equation (64)	Derived
d_h	km	The distance of the radio horizon, as viewed from the centre of the earth station antenna	§ 1 of Appendix 2	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	The longest continuous inland distance, Zone A2, within the distance d_i, used in the iterative calculation of the propagation mode (1) coordination distance	§ 4.2 of Annex 1	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_{to}, d_{tv} d_{ro}, d_{rv}	km	Distances used in determining gaseous attenuation for mode (2) calculations	Equations (74a), (74b) (75a) and (75b)	Derived
d_r	km	The distance from the rain cell at which the loss equals or exceeds the required transmission loss for mode (2) propagation	§ 1 of Appendix 3	Derived
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	§ 4.2 of Annex 1	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	Not applicable	Input
$G(\varphi)$	dB	The antenna gain at an off-axis angle of φ determined from the antenna reference radiation pattern (Appendix 4)	Equations (83) to (86), (90) to (93)	Derived
G_L		A term used in the conversion from worst-month time percentage to annual time percentage	Equations (7a) and (7b)	Derived

TABLE 3 (*continued*)

Parameter	Units	Definition	Where defined	Status
G_1	dB	The gain of the antenna first side lobe determined from the antenna reference radiation pattern (Appendix 4)	Equation (87)	Derived
G_{max}	dB	The antenna on-axis gain used in the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input
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 (57)	Input
h_c	km	A parameter used in propagation mode (2) calculations, depending on the region within the rain cell	Equation (65)	Derived
h_m	km	The height above ground of the beam intersection in propagation mode (2) calculations	Equation (60)	Derived
h_R	km	The effective rain height above ground	Not applicable	Input
$L(p_1)$	dB	The minimum permissible basic transmission loss required for p_1% (mode (1)) of the time	§ 1	Input
$L_b(p_2)$	dB	The minimum permissible basic transmission loss required for p_2% (mode (2)) of the time	§ 1	Input
$L_{bl}(p_1)$	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
$L_r(p_2)$	dB	The transmission loss, obtained as a monotonic function of rainfall rate R, used in determining the propagation mode (2) coordination distance	Equation (77)	Derived
N_0	–	The path centre sea level surface refractivity	Equation (3)	Derived

TABLE 3 (*continued*)

Parameter	Units	Definition	Where defined	Status
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 790 MHz 0.001% to 50% for f between 790 MHz and 105 GHz	Equation (8) § 6.1	Input
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
$R(p_2)$	mm/h	The surface rainfall rate exceeded on average for p_2% of a year, used in the propagation mode (2) calculations		Input
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 (78), (79) § 4.1 of Appendix 3	Derived
r_E	km	The effective radius of the Earth (= 8 500 km)	§ 3 of Appendix 3	Input
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	Equation (51)	Derived
r_m	km	Scaling distance for attenuation outside the common scattering volume in the mode (2) calculation	Equation (54)	Derived
r_r	km	The pathlength from the beam intersection to the earth station in propagation mode (2) calculations	Equation (63)	Derived
r_t	km	The pathlength from the beam intersection to the terrestrial station in propagation mode (2) calculations	Equation (62)	Derived
s	km	The distance increment used in the iterative calculation of the coordination distance (the recommended value is 1 km)	§ 1	Input
S	–	The deviation from Rayleigh scattering, in the propagation mode (2) calculation	Equation (73)	Derived
β	–	A parameter used in the calculation of the propagation mode (1) coordination distance	Equation (38)	Derived
β_p	%	The relative incidence of clear-air anomalous propagation	Equations (2a) and (2b)	Derived
δ	radians	The angular separation at the Earth's centre between the earth station and the current distance in propagation mode (2) calculations	Equation (61)	Derived
ε_L	–	An allowance for additional distance-dependent and other losses, including those associated with terrain height	Equation (27)	Derived

TABLE 3 (*continued*)

Parameter	Units	Definition	Where defined	Status
ε	degrees	The earth station antenna main beam elevation angle	§ 3 of Appendix 3	Input
φ	degrees	An angular offset from the axis of the antenna main beam used in the antenna reference radiation pattern (Appendix 4)	Appendix 4	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 (89)	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 (88)	Derived
Γ		A term used in the iterative calculation of the propagation mode (1) coordination distance	Equation (39)	Derived
Γ_1	dB	A term used in the calculation of the propagation mode (2) coordination distance	Equation (67)	Derived
Γ_2	dB	A term used in the calculation of the propagation mode (2) coordination distance	Equation (66)	Derived
Γ_a	dB	A term used in the calculation of the propagation mode (2) coordination distance	Equation (69)	Derived
Γ_b	dB	A term used in the calculation of the propagation mode (2) coordination distance	Equation (68)	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_{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	Equations (20) and (55)	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	Appendix 3	Input
γ_w	dB/km	The specific attenuation due to water vapour	Equation (21)	Derived
γ_{wv}	dB/km	The specific attenuation due to water vapour absorption used in the hydrometeor scatter model	Equation (56)	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	Equation (44)	Derived
η	–	An intermediate parameter in the propagation mode (2) calculation	Equation (53)	Derived
λ	m	The wavelength used in determining the antenna reference radiation pattern (Appendix 4)	Appendix 4	Input

TABLE 3 (*end*)

Parameter	Units	Definition	Where defined	Status
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)	Equation (82) § 4.1 of Appendix 3	Derived
θ_h	degrees	The earth station horizon elevation angle	§ 1 of Appendix 2	Input
θ_{bw}	degrees	The antenna 3 dB beamwidth used in the antenna reference radiation pattern (Appendix 4)	Equations (95) and (96)	Input
ρ	g/m^3	Atmospheric water vapour density exceeded for 50% of time	Equations (21) and (56)	Input
ρ_0	g/m^3	Atmospheric water vapour density exceeded for 50% of time at the earth station	Equation (22b)	Input
ρ_{dmin}	g/m^3	Atmospheric water vapour density exceeded for 50% of time at d_{min} on the relevant azimuth	Equation (22b)	Input
ρ_i	g/m^3	Atmospheric water vapour density exceeded for 50% of time for each step of the mode (1) iteration	Equation (32)	Input
σ	–	A parameter used in the iterative calculation of the propagation mode (1) coordination distance	Equation (36)	Derived
τ	–	A parameter used in the iterative calculation of the propagation mode (1) coordination distance	Equation (33)	Derived
υ	degrees	The protection angle, used in determining auxiliary contours for propagation mode (2)	Step g), § 4.1 of Appendix 3	Derived
ω	degrees	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 of Appendix 3	Input
ψ	degrees	The angle subtended by the critical region within which a common volume may occur between the earth station and the beam of any terrestrial station, in propagation mode (2)	Equation (80) § 4.1 of Appendix 3	Derived
ζ	degrees	The earth station latitude (North positive, South negative)	Equations (1a) and (1b)	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