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Radiocommunication Sector of ITU

Recommendation ITU-R P.2001-2 (07/2015)

A general purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz

P Series
Radiowave propagation



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RECOMMENDATION ITU-R P.2001-2

A general purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz

(2012-2013-2015)

Scope

This Recommendation contains a general purpose wide-range model for terrestrial propagation which predicts path loss due to both signal enhancements and fading over effectively the range from 0% to 100% of an average year. This makes the model particularly suitable for Monte-Carlo methods, and studies in which it is desirable to use the same propagation model, with no discontinuities in its output, for signals which may be either wanted or potentially interfering. The model covers the frequency range from 30 MHz to 50 GHz, and distances from 3 km to at least 1 000 km.

The ITU Radiocommunication Assembly,

considering

- a) that to support efficient use of the radio spectrum there is a need for sharing studies in which the variability of both wanted and potentially interfering signal levels should be taken into account;
- b) that to plan high-performance radio systems the prediction of signal-level variability must include the small-probability tails of both fading and enhancement distributions;
- c) that Monte-Carlo simulations are useful for spectrum-planning purposes,

noting

- a) that Recommendation ITU-R P.528 provides guidance on the prediction of point-to-area path loss for the aeronautical mobile service for the frequency range 125 MHz to 30 GHz and the distance range up to 1 800 km;
- b) that Recommendation ITU-R P.452 provides guidance on the detailed evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz;
- c) that Recommendation ITU-R P.617 provides guidance on the prediction of point-to-point path loss for trans-horizon radio-relay systems for the frequency range above 30 MHz and for the distance range 100 to 1 000 km;
- d) that Recommendation ITU-R P.1411 provides guidance on prediction for short-range (up to 1 km) outdoor services;
- e) that Recommendation ITU-R P.530 provides guidance on the prediction of point-to-point path loss for terrestrial line-of-sight systems;
- f) that Recommendation ITU-R P.1546 provides guidance on the prediction of point-to-area field strengths in the VHF and UHF bands based principally on statistical analyses of experimental data;
- g) that Recommendation ITU-R P.1812 provides guidance on the prediction of point-to-area field strengths in the VHF and UHF bands based principally on deterministic method;
- h) that Recommendation ITU-R P.844 summarizes modes of long range propagation paths that may also occur at VHF via the ionosphere,

recommends

that the procedure given in the Annex be used for sharing studies over the full range of signal variability, including the small-probability tails for fading and enhancement, and for Monte-Carlo simulations.

Annex

Wide-range propagation model

Description of the calculation method

1 Introduction

This Recommendation describes a radio-wave propagation method for terrestrial paths. It has a wide range of applicability in frequency, distance, and percentage time. In particular, it predicts both fading and enhancements of signal level. It is thus particularly suitable for Monte-Carlo simulations.

Attachment J describes the structure of the model, and in particular how results representing different propagation mechanisms are combined.

1.1 Applicability

The range of applicability is as follows:

Frequency: 30 MHz to 50 GHz.

Distance: The model is believed to be most accurate from about 3 km to 1 000 km. At shorter distances, the effect of clutter (buildings, trees, etc.) will tend to dominate unless the antenna heights are high enough to given an unobstructed path. There is no specific lower limit, although the path length must be greater than zero. A prediction of basic transmission loss less than 20 dB should be considered unreliable. Similarly, there is no specific maximum distance.

Percentage time: The method predicts the basic transmission loss not exceeded for a given percentage of an average year. Any percentage time can be used as an input to the model in the range 0% to 100%. This is limited in a progressive manner within the method such that the time used in the model varies from 0.00001% to 99.99999%. This internal limitation has no significant effect from 0.001% to 99.999% time.

Antenna heights: Antennas heights above ground level must be greater than zero. There is no specific maximum height above ground. The method is believed to be reliable for antenna altitudes up to 8 000 m above sea level.

1.2 Reciprocity, and the designation of terminals

The terms “transmitting antenna” and “receiving antenna”, or more briefly just “transmitter” and “receiver”, are used to distinguish the two terminals. This is convenient for the purposes of description.

The method, however, is symmetrical. Which terminal is designated the “transmitter” makes no difference to the result. By convention the “transmitter” is at the start of the terrain profile.

1.3 Iteration

Some parts of the method require iterative calculations. Explicit iteration procedures are described which have been found to be efficient and stable. However, these are not necessarily optimal. Other iterative methods can be used if they are shown to give very similar results.

1.4 Organization of the Recommendation

The inputs, and the symbols used to denote them, are described in § 2.

Preliminary calculations, including obtaining various radio-climatic parameters, are described in § 3. Climatic parameters, and values derived from the inputs, are listed in approximately alphabetical order of their symbols in Table 3.1. Many of these parameters are used in more than one place in the overall method, and all symbols in Table 3.1 are unique within this Recommendation.

Section 4 describes the four main sub-models into which the method is divided. The following subsections describe the calculation of these sub-models, most of which apply to a group of propagation mechanisms. These descriptions refer extensively to appendices which define various blocks of calculation. The sub-models in the wide-range propagation model (WRPM) are independent of each other and each calculates results over the range 0% to 100%.

Section 5 describes how the final prediction is obtained by combining results from the four main sub-models. The combination method takes account of the statistical correlation properties between the sub-models. Two alternative methods are given. One is appropriate when a direct calculation of the overall basic transmission loss is required for a given value of time percentage. This method involves an approximate treatment of uncorrelated statistics. The second method is appropriate when the WRPM is used within a Monte-Carlo simulator. In this case, the uncorrelated statistics can be modelled more accurately by combining the sub-models within the Monte-Carlo method.

1.5 Style of description

The method is described in a step-by-step manner, that is, expressions are given in the order in which they should be evaluated. Equations are sometimes followed by a “where”, but this is limited to a few lines. Long lists of “where”s are avoided.

Symbols appearing within the Appendices and which do not appear in Table 3.1 should be considered re-usable. They are defined close to where they are used, or cross-referenced if appropriate.

Logarithms are to the base 10 by default. That is, $\log(x) = \log_{10}(x)$. Natural logarithms where used are indicated as $\ln(x) = \log_e(x)$.

2 Inputs

The inputs to the model consist of a terrain profile, described in § 2.1, and other inputs described in § 2.2.

2.1 Terrain profile

A terrain profile giving heights above sea level of the Earth’s surface, whether land or water, at points along the great-circle radio path, must be available. Information is also required on the

distances over sea or a large body of water, and over low-lying coastal land or areas with many lakes, according to the zones defined in Attachment D, § D.1.

In principle, the terrain profile consists of arrays each having the same number of values, n , as follows:

$$d_i: \text{distance from transmitter of } i\text{-th profile point (km)} \quad (2.1a)$$

$$h_i: \text{height of } i\text{-th profile point above sea level (m)} \quad (2.1b)$$

where:

i : 1, 2, 3 ... n = index of the profile point

n : number of profile points.

It is convenient to define an additional array holding zone codes as part of the profile:

$$z_i: \text{zone code at distance } d_i \text{ from transmitter} \quad (2.1c)$$

where the z values are codes representing the zones in Table D.1.

The profile points must be spaced at equal intervals of distance. Thus $d_1 = 0$ km, and $d_n = d$ km where d is the overall length of the path. Similarly, $d_i = (i - 1) d / (n - 1)$ km.

It is immaterial whether an array d_i is populated with distances, or whether d_i is calculated when needed.

There must be at least one intermediate profile point between the transmitter and the receiver. Thus n must satisfy $n \geq 3$. Such a small number of points is appropriate only for short paths, less than of the order of 1 km.

Only general guidance can be given as to the appropriate profile spacing. Typical practice is a spacing in the range 50 to 250 m, depending on the source data and the nature of terrain.

However, it is stressed that equally-spaced points should be included for the complete path, even where it passes over water. Expressions in this method assume that this is so. For instance, it is not acceptable to have zero-height points only at the start and end of a section over sea when the length of the section exceeds the point spacing. Horizon points must be located taking Earth curvature into account, and omitting points in such a manner could result in the misinterpretation of a profile.

2.2 Other inputs

Table 2.2.1 lists the other inputs which must be provided by the user, in addition to the geographic information, including the terrain profile, described in § 2.1 above. The symbols and units given here apply throughout this Recommendation.

TABLE 2.2.1

Other inputs

Symbol	Description
f (GHz)	Frequency
T_{pol}	Code indicating either horizontal or vertical linear polarization
$\phi_{re, rn}$ (degrees)	Longitude, latitude, of receiver
$\phi_{te, tn}$ (degrees)	Longitude, latitude, of transmitter
$h_{tg, rg}$ (m)	Height of electrical centre of transmitting, receiving antenna above ground.
T_{pc} (%)	Percentage of average year for which the predicted basic transmission loss is not exceeded
G_t, G_r (dBi)	Gain of transmitting, receiving, antenna in the azimuthal direction of the path towards the other antenna, and at the elevation angle above the local horizontal of the other antenna in the case of a line-of-sight (LoS) path, otherwise of the antenna's radio horizon, for median effective Earth radius.

Longitudes and latitudes in this method are positive east and north.

2.3 Constants

Table 2.3.1 gives values of constants used in the method.

TABLE 2.3.1

Constants

Symbol	Value	Description
c (m/s)	2.998×10^8	Speed of propagation
R_e (km)	6 371	Average Earth radius
ϵ_{rland}	22.0	Relative permittivity for land
ϵ_{rsea}	80.0	Relative permittivity for sea
σ_{land} (S/m)	0.003	Conductivity for land
σ_{sea} (S/m)	5.0	Conductivity for sea

2.4 Integral digital products

Only the file versions provided with this Recommendation should be used. They are an integral part of the Recommendation. Table 2.4.1 gives details of the digital products used in the method.

TABLE 2.4.1

Digital products

Filename	Ref.	Origin	Latitude (rows)			Longitude (columns)		
			First row (°N)	Spacing (degrees)	Number of rows	First col (°E)	Spacing (degrees)	Number of cols
DN_Median.txt	§ 3.4.1	P.2001	90	1.5	121	0	1.5	241
DN_SupSlope.txt	§ 3.4.1	P.2001	90	1.5	121	0	1.5	241
DN_SubSlope.txt	§ 3.4.1	P.2001	90	1.5	121	0	1.5	241
dndz_01.txt	§ 3.4.2	P.453-10	90	1.5	121	0	1.5	241
Esarain_Pr6_v5.txt	§ C.2	P.837-5	90	1.125	161	0	1.125	321
Esarain_Mt_v5.txt	§ C.2	P.837-5	90	1.125	161	0	1.125	321
Esarain_Beta_v5.txt	§ C.2	P.837-5	90	1.125	161	0	1.125	321
h0.txt	§ C.2	P.839-4	90	1.5	121	0	1.5	241
Surfwv_50_fixed.txt ⁽¹⁾	Appx F	P.836-4 (corrected)	90	1.5	121	0	1.5	241
FoEs50.txt	Appx G	P.2001	90	1.5	121	0	1.5	241
FoEs10.txt	Appx G	P.2001	90	1.5	121	0	1.5	241
FoEs01.txt	Appx G	P.2001	90	1.5	121	0	1.5	241
FoEs0.1.txt	Appx G	P.2001	90	1.5	121	0	1.5	241
TropoClim.txt	§ E.2	P.2001	89.75	0.5	360	-179.75	0.5	720

⁽¹⁾ The file “surfwv_50_fixed.txt” is a corrected version of the file “surfwv_50.txt” associated with Recommendation ITU-R P.836-4. “surfwv_50.txt” has one column less than expected according to the “surfwv_lat.txt” and “surfwv_lon.txt” files provided with the data. It has been assumed that the column corresponding to a longitude of 360° was omitted from the file, and this has been corrected in “surfwv_50_fixed.txt”.

The “First row” value is the latitude of the first row.

The “First col” value is the longitude of the first column. The last column is the same as the first column (360° = 0°) and is provided to simplify interpolation.

“Spacing” gives the latitude/longitude increment between rows/columns.

Except for file “TropoClim.txt”, a parameter value at a particular latitude/longitude should be obtained by bilinear interpolation using the four nearest grid points, as described in Rec. ITU-R P.1144.

TropoClim.txt contains integer zone identifiers rather than continuous meteorological variables. Consequently, the values should not be interpolated to obtain a value at a particular latitude/longitude. Instead the value at the closest grid point should be taken. For this file, note that a) the grid is offset by half a pixel compared to the other files, b) the values in the last column are not a duplicate of the first column. Consequently, the latitudes of the rows range from 89.75°N to 89.75°S, and the longitudes of the columns range from 179.75°W to 179.75°E.

The files are contained in the zip file [R-REC-P.2001-1-201309-I!!ZIP-E](#).



R-REC-P.2001-1-201
309-I!!ZIP-E.zip

3 Preliminary calculations

The following subsections describe the calculation of important parameters derived from the inputs. These parameters are listed in Table 3.1.

TABLE 3.1
Principal parameters

Symbol	Ref.	Description
a_e (km)	§ 3.5	Median effective Earth radius
A_{gsur} $A_{wsur,wsur}$ (dB/km)	§ 3.10	Gaseous attenuation, and the water vapour attenuations with and without rain, for a surface path
a_p (km)	§ 3.5	Effective Earth radius exceeded $p\%$ time, limited not to become infinite
c_p (km ⁻¹)	§ 3.5	Effective Earth curvature. Usually positive, but for small p may be zero or negative
d (km)	§ 3.2	Path length
$d_{lt,lr}$ (km)	§ 3.7	Terminal to horizon distances. For LoS paths set to distances to point with largest knife-edge loss
$d_{tcv,rcv}$ (km)	§ 3.9	Terminal to troposcatter common volume distances
h_{cv} (masl) ⁽¹⁾	§ 3.9	Height of troposcatter common volume
$h_{hi,lo}$ (masl) ⁽¹⁾	§ 3.3	Higher, lower, antenna height
h_m (m)	§ 3.8	Path roughness parameter
h_{mid} (masl) ⁽¹⁾	§ 3.2	Ground height at mid point of path
$h_{tea,rea}$ (m)	§ 3.8	Effective transmitter, receiver, heights above smooth surface for anomalous (ducting/layer-reflection) model
$h_{tep,rep}$ (m)	§ 3.8	Effective transmitter, receiver, heights above smooth surface for diffraction model
$h_{ts,rs}$ (masl) ⁽¹⁾	§ 3.3	Transmitter, receiver, height above mean sea level
$i_{lt,lr}$	§ 3.7	Profile indices of transmitter, receiver, horizons
L_{bfs} (dB)	§ 3.11	Free-space basic transmission loss for the path length and frequency
L_{bm1} (dB)	§ 4.1	Basic transmission loss associated with sub-model 1, diffraction, clear-air and precipitation fading
L_{bm2} (dB)	§ 4.2	Basic transmission loss associated with sub-model 2, anomalous propagation
L_{bm3} (dB)	§ 4.3	Basic transmission loss associated with sub-model 3, troposcatter propagation and precipitation fading
L_{bm4} (dB)	§ 4.4	Basic transmission loss associated with sub-model 4, sporadic-E propagation
L_d (dB)	§ 4.1	Diffraction loss not exceeded $p\%$ time
N_{d1km50} (N-units)	§ 3.4.1	Median value of average refractivity gradient in the lowest 1 km of the atmosphere. Numerically equal to ΔN as defined in ITU-R P.452 but with opposite sign
N_{d1kmp} (N-units)	§ 3.4.1	Average refractivity gradient in the lowest 1 km of the atmosphere exceeded for $p\%$ of an average year. Normally negative but can be zero or positive
N_{d65m1} (N-units)	§ 3.4.2	Refractivity gradient in the lowest 65 m of the atmosphere exceeded for 1% of an average year

TABLE 3.1 (*end*)

Symbol	Ref.	Description
p (%)	§ 3.1	Percentage of average year for which predicted basic transmission loss is not exceeded, limited to range $0.00001\% \leq p \leq 99.99999\%$
q (%)	§ 3.1	Percentage of average year for which predicted basic transmission loss is exceeded, given by $100 - p$
ε_p (mrad)	§ 3.3	Positive value of path inclination
λ (m)	§ 3.6	Wavelength
$\phi_{cve, cvn}$ (degrees)	§ 3.9	Troposcatter common volume longitude, latitude
$\phi_{tcve, tcvn}$ (degrees)	§ 3.9	Longitude, latitude, of mid-point of path segment from transmitter to the troposcatter common volume
$\phi_{rcve, rcvn}$ (degrees)	§ 3.9	Longitude, latitude, of mid-point of path segment from receiver to the troposcatter common volume
$\phi_{me, mn}$ (degrees)	§ 3.2	Path mid-point longitude, latitude
θ_e (rad)	§ 3.5	Angle subtended by d km at centre of spherical Earth
$\theta_{t, r}$ (mrad)	§ 3.7	Horizon elevation angles relative to the local horizontal as viewed from transmitter and receiver
$\theta_{tpos, rpos}$ (mrad)	§ 3.7	Horizon elevation angles relative to the local horizontal limited to be positive (not less than zero)
γ_o (dB/km)	§ 3.10	Sea-level specific attenuation due to oxygen
ω	§ 3.2	Fraction of the path over sea

⁽¹⁾ masl: metres above sea level.

3.1 Limited percentage times

The percentage of an average year for which the predicted loss is not exceed, T_{pc} in Table 2.2.1, is allowed to vary from 0% to 100%. The percentage times used for calculation are limited such that they remain in the range 0.00001% to 99.99999%.

Percentage time basic transmission loss not exceeded:

$$p = T_{pc} + 0.00001 \left(\frac{50 - T_{pc}}{50} \right) \quad \% \quad (3.1.1)$$

Percentage time basic transmission loss is exceeded:

$$q = 100 - p \quad \% \quad (3.1.2)$$

3.2 Path length, intermediate points, and fraction over sea

The path length in km is given by the last distance in the terrain profile, d_n , as described in § 2.1. It is convenient to give this distance an un-subscripted symbol:

$$d = d_n \quad \text{km} \quad (3.2.1)$$

Calculate the longitude and latitude of the mid-point of the path, ϕ_{me} and ϕ_{mn} , from the transmitter and receiver longitudes and latitudes, as given in Table 2.2.1, using the great circle path method of Attachment H by setting $d_{pnt} = 0.5 d$ in equation (H.3.1). Several climatic parameters are required for this location, as described below.

Calculate the ground height in m above sea level at the mid-point of the profile according to whether the number of profile points, n , is odd or even:

$$h_{mid} = h_{0.5(n+1)} \quad n \text{ odd} \quad \text{masl} \quad (3.2.2a)$$

$$h_{mid} = 0.5(h_{0.5n} + h_{0.5n+1}) \quad n \text{ even} \quad \text{masl} \quad (3.2.2b)$$

Set the fraction of the path over sea, ω . This fraction may be obtained from the ITU digitized world map (IDWM). If array z , described in § 2.1, has been coded according to the zones described in Attachment D, Table D.1, where adjacent z values have different codes, the boundary between the two zones should be assumed to occur half-way between the corresponding profile points.

3.3 Antenna altitudes and path inclination

The transmitter and receiver heights above sea level are calculated from the first and last terrain heights from the profile and the input heights above ground given in Table 3.1:

$$h_{ts} = h_1 + h_{tg} \quad \text{masl} \quad (3.3.1a)$$

$$h_{rs} = h_n + h_{rg} \quad \text{masl} \quad (3.3.1b)$$

Assign the higher and lower antenna heights above sea level:

$$h_{hi} = \max(h_{ts}, h_{rs}) \quad \text{masl} \quad (3.3.2a)$$

$$h_{lo} = \min(h_{ts}, h_{rs}) \quad \text{masl} \quad (3.3.2b)$$

The higher and lower antennas heights can be the same if $h_{ts} = h_{rs}$.

Calculate the positive value of path inclination given by:

$$\varepsilon_p = \frac{h_{hi} - h_{lo}}{d} \quad \text{mrad} \quad (3.3.3)$$

3.4 Climatic parameters

Measured values of the following climatic parameters applicable to the region concerned can be used if available. If suitable measurements are not available, the parameters can be obtained for the longitude and latitude of the mid-point of the path from data files as described in the following subsections. The files are organized as arrays of values at a fixed spacing in longitude and latitude. The first row starts at 90°N and contains a full set of latitude values from 0°E to 360°E, even though all of these are at the North Pole. Following lines are at the point spacing further south until the South Pole is reached. The files have different point spacings, but in all cases it is sufficiently accurate to use bilinear interpolation from the four nearest data to the point required. All of these data files have associated longitude and latitude files which define the location of every point.

3.4.1 Refractivity in the lowest 1 km

The parameters N_{d1km50} and N_{d1kmp} give the change in refractivity, in N-units, from the surface to 1 km above the surface of the Earth, not exceeded for 50% and $p\%$ of an average year respectively. These are used to account for ray bending in diffraction calculations via the concept of effective Earth radius or curvature. They can be viewed as the spatially-averaged refractivity gradient in the lowest 1 km of the atmosphere.

N_{d1km50} is numerically equal to ΔN , defined in Recommendations ITU-R P.452 and ITU-R P.1812, but of opposite sign. ΔN is everywhere positive, and thus N_{d1km50} is everywhere negative.

N_{d1kmp} can be negative or positive, depending on location and the value of p . It can fall below -157 N-units, the value at which effective Earth radius becomes infinite.

The change in sign convention adopted here is to align with a conceptually similar parameter, N_{d65m1} , used for clear-air multipath fading and enhancements, obtained as described in § 3.4.2 below.

N_{d1km50} and N_{d1kmp} are available from files “DN_Median.txt”, “DN_SubSlope.txt” and “DN_SupSlope.txt”.

Obtain N_{d1km50} as:

$$N_{d1km50} = -S_{dN} \quad \text{N-units} \quad (3.4.1.1)$$

where S_{dN} is the value interpolated from file “DN_Median.txt” for the path mid-point at ϕ_{me} , ϕ_{mn} .

Obtain N_{d1kmp} as:

$$N_{d1kmp} = N_{d1km50} + S_{\Delta N \text{ sup}} \log(0.02p) \quad \text{N-units} \quad p < 50 \quad (3.4.1.2a)$$

$$N_{d1kmp} = N_{d1km50} - S_{\Delta N \text{ sub}} \log(0.02q) \quad \text{N-units} \quad p \geq 50 \quad (3.4.1.2b)$$

where:

$S_{\Delta N \text{ sup}}$ is the value read from file “DN_SupSlope.txt” for the mid-point of the path

$S_{\Delta N \text{ sub}}$ is the value read from file “DN_SubSlope.txt” for the mid-point of the path.

3.4.2 Refractivity in the lowest 65 m

The parameter N_{d65m1} is the refractivity gradient in the lowest 65 m of the atmosphere not exceeded for 1% of an average year. It is identical to parameter dN_1 in Recommendation ITU-R P.530.

Obtain N_{d65m1} from file “dndz_01.txt” for the mid-point of the path. This file has a point spacing of 1.5 degrees.

3.4.3 Precipitation parameters

Fading due to rain and wet snow need to be calculated for the complete path for sub-model 1 in § 4.1 below, and for the two terminal-to-common-volume path segments in the troposcatter sub-model in § 4.3 below. As a result, rain climatic parameters are required for three different geographic locations from data files, as described in Attachment C, § C.2.

The required locations are given in §§ 4.1 and 4.3 below. The calculations described in § C.2 are preliminary, for each path or path segment. The values calculated each time § C.2 is used should be used for a following iterative procedure for the same path or path segment, as noted at the end of § C.2.

3.5 Effective Earth-radius geometry

Median effective Earth radius:

$$a_e = \frac{157R_e}{157 + N_{d1km50}} \quad \text{km} \quad (3.5.1)$$

Effective Earth curvature:

$$c_p = \frac{157 + N_{d1kmp}}{157 R_e} \quad \text{km}^{-1} \quad (3.5.2)$$

Although c_p is often positive, it can be zero or negative.

Effective Earth radius exceeded for $p\%$ time limited not to become infinite:

$$a_p = \frac{1}{c_p} \text{ km} \quad \text{if } c_p > 10^{-6} \quad (3.5.3a)$$

$$a_p = 10^6 \text{ km} \quad \text{otherwise} \quad (3.5.3b)$$

The path length expressed as the angle subtended by d km at the centre of a sphere of effective Earth radius:

$$\theta_e = \frac{d}{a_e} \quad \text{rad} \quad (3.5.4)$$

3.6 Wavelength

The wavelength is calculated as:

$$\lambda = \frac{10^{-9} c}{f} \quad \text{m} \quad (3.6.1)$$

3.7 Path classification and terminal horizon parameters

The terminal elevation angles and distances are required under median refractivity conditions. The same calculation determines whether the path is line-of-sight (LoS) or non-line-of-sight (NLoS).

Find the highest elevation angle to an intermediate profile point, relative to the horizontal at the transmitter:

$$\theta_{tim} = \max \left(\frac{h_i - h_{ts}}{d_i} - \frac{500 d_i}{a_e} \right) \quad \text{mrad} \quad (3.7.1)$$

where h_i and d_i are given by equations (2.1a) and (2.1b), and the profile index i takes values from 2 to $n - 1$.

Calculate the elevation angle of the receiver as viewed by the transmitter, assuming a LoS path:

$$\theta_{tr} = \frac{h_{rs} - h_{ts}}{d} - \frac{500 d}{a_e} \quad \text{mrad} \quad (3.7.2)$$

Two cases must now be considered.

Case 1. Path is LoS

If $\theta_{tim} < \theta_{tr}$ the path is LoS. Notional terminal distances are taken to the intermediate profile point with the highest diffraction parameter, v , and each horizon elevation angle is taken as that of the other terminal.

Find the intermediate profile point with the highest diffraction parameter:

$$v_{max} = \max \left\{ \left[h_i + \frac{500 d_i (d - d_i)}{a_e} - \frac{h_{ts} (d - d_i) + h_{rs} d_i}{d} \right] \sqrt{\frac{0.002 d}{\lambda d_i (d - d_i)}} \right\} \quad (3.7.3)$$

where the profile index i takes values from 2 to $n - 1$.

The transmitter and receiver horizon distances, and the profile indices of the corresponding horizon points, are now given by:

$$d_{lt} = d_{i_m} \quad \text{km} \quad (3.7.4a)$$

$$d_{lr} = d - d_{i_m} \quad \text{km} \quad (3.7.4b)$$

$$i_{lt} = i_m \quad (3.7.4c)$$

$$i_{lr} = i_m \quad (3.7.4d)$$

where i_m is the profile index which gives v_{max} in equation (3.7.3).

The transmitter and receiver notional horizon elevation angles, relative to their local horizontals, are given by:

$$\theta_t = \theta_{tr} \quad \text{mrad} \quad (3.7.5a)$$

$$\theta_r = -\theta_{tr} - \frac{1000d}{a_e} \quad \text{mrad} \quad (3.7.5b)$$

Case 2. Path is NLoS

If $\theta_{tim} \geq \theta_{tr}$ the path is NLoS. The terminal horizon distances and elevation angles are calculated as follows.

Transmitter horizon distance and profile index of the horizon point are given by:

$$d_{lt} = d_{i_m} \quad \text{km} \quad (3.7.6a)$$

$$i_{lt} = i_m \quad (3.7.6b)$$

where i_m is the profile index which gives θ_{tim} in equation (3.7.1).

Transmitter horizon elevation angle relative to its local horizontal is given by:

$$\theta_t = \theta_{tim} \quad \text{mrad} \quad (3.7.7)$$

Find the highest elevation angle to an intermediate profile point, relative to the horizontal at the receiver:

$$\theta_{rim} = \max \left[\frac{h_i - h_{rs}}{d - d_i} - \frac{500(d - d_i)}{a_e} \right] \quad \text{mrad} \quad (3.7.8)$$

where the profile index i takes values from 2 to $n - 1$.

Receiver horizon distance and profile index of the horizon point are given by:

$$d_{lr} = d - d_{i_m} \quad \text{km} \quad (3.7.9a)$$

$$i_{lr} = i_m \quad (3.7.9b)$$

where i_m is the profile index which gives θ_{rim} in equation (3.7.8).

Receiver horizon elevation angle relative to its local horizontal is given by:

$$\theta_r = \theta_{rim} \quad \text{mrad} \quad (3.7.10)$$

Continue for both cases

Calculate the horizon elevation angles limited such that they are positive.

$$\theta_{tpos} = \max(\theta_t, 0) \quad \text{mrad} \quad (3.7.11a)$$

$$\theta_{rpos} = \max(\theta_r, 0) \quad \text{mrad} \quad (3.7.11b)$$

3.8 Effective heights and path roughness parameter

The effective transmitter and receiver heights above terrain are calculated relative to a smooth surface fitted to the profile.

Calculate the initial provisional values for the heights of the smooth surface at the transmitter and receiver ends of the path, as follows:

$$v_1 = \sum_{i=2}^n (d_i - d_{i-1})(h_i + h_{i-1}) \quad (3.8.1)$$

$$v_2 = \sum_{i=2}^n (d_i - d_{i-1})[h_i(2d_i + d_{i-1}) + h_{i-1}(d_i + 2d_{i-1})] \quad (3.8.2)$$

$$h_{stip} = \left(\frac{2v_1 d - v_2}{d^2} \right) \quad \text{masl} \quad (3.8.3a)$$

$$h_{srip} = \left(\frac{v_2 - v_1 d}{d^2} \right) \quad \text{masl} \quad (3.8.3b)$$

Equations (3.8.4) to (3.8.7) calculate the roughness parameter h_m required by the anomalous propagation (ducting and layer-reflection) model.

Calculate smooth-surface heights limited not to exceed ground level at either transmitter or receiver:

$$h_{stipa} = \min(h_{stip}, h_1) \quad \text{masl} \quad (3.8.4a)$$

$$h_{sripa} = \min(h_{srip}, h_n) \quad \text{masl} \quad (3.8.4b)$$

where h_1 and h_n are ground heights at transmitter and receiver, masl, see equation (2.1.b).

The slope of the least-squares regression fit is given by m_{ses} :

$$m_{ses} = \frac{h_{sripa} - h_{stipa}}{d} \quad \text{m/km} \quad (3.8.5)$$

The effective heights of the transmitter and receiver antennas above the smooth surface are now given by:

$$h_{tea} = h_{ts} - h_{stipa} \quad \text{m} \quad (3.8.6a)$$

$$h_{rea} = h_{rs} - h_{sripa} \quad \text{m} \quad (3.8.6b)$$

Calculate the path roughness parameter given by:

$$h_m = \max[h_i - (h_{stipa} + m_{ses} d_i)] \quad \text{m} \quad (3.8.7)$$

where the profile index i takes all values from i_l to i_r inclusive. The path roughness parameter, h_m , and the effective antenna heights h_{tea} and h_{rea} , are used in Attachment D.

Further calculations involving the smooth surface are now required for the diffraction model. Equations (3.8.8) to (3.8.11) calculate the effective antenna heights required by the spherical-earth and smooth-profile diffraction sub-models described in Attachment A.

Find the highest obstruction height above the straight-line path from transmitter to receiver h_{obs} , and the horizon elevation angles α_{obt} , α_{obr} , all based on flat-Earth geometry, according to:

$$h_{obs} = \max(H_i) \quad \text{m} \quad (3.8.8a)$$

$$\alpha_{obt} = \max\left(\frac{H_i}{d_i}\right) \quad \text{mrad} \quad (3.8.8b)$$

$$\alpha_{obr} = \max\left[\frac{H_i}{(d - d_i)}\right] \quad \text{mrad} \quad (3.8.8c)$$

where:

$$H_i = h_i - \frac{h_{ts}(d - d_i) + h_{rs}d_i}{d} \quad \text{m} \quad (3.8.8d)$$

and the profile index i takes values from 2 to $(n - 1)$.

Calculate provisional values for the heights of the smooth surface at the transmitter and receiver ends of the path:

If h_{obs} is less than or equal to zero, then:

$$h_{st} = h_{stip} \quad \text{masl} \quad (3.8.9a)$$

$$h_{sr} = h_{srp} \quad \text{masl} \quad (3.8.9b)$$

otherwise:

$$h_{st} = h_{stip} - h_{obs}g_t \quad \text{masl} \quad (3.8.9c)$$

$$h_{sr} = h_{srp} - h_{obs}g_r \quad \text{masl} \quad (3.8.9d)$$

where:

$$g_t = \frac{\alpha_{obt}}{(\alpha_{obt} + \alpha_{obr})} \quad (3.8.9e)$$

$$g_r = \frac{\alpha_{obr}}{(\alpha_{obt} + \alpha_{obr})} \quad (3.8.9f)$$

Calculate the final values for the heights of the smooth surface at the transmitter and receiver ends of the path:

If h_{st} is greater than h_1 then:

$$h_{st} = h_1 \quad \text{masl} \quad (3.8.10a)$$

If h_{sr} is greater than h_n then:

$$h_{sr} = h_n \quad \text{masl} \quad (3.8.10b)$$

Calculate the effective antenna heights for the spherical-earth and the smooth-profile version of the Bullington model (described in §§ A.2 and A.5, respectively) given by:

$$h_{tep} = h_{ts} - h_{st} \quad \text{masl} \quad (3.8.11a)$$

$$h_{rep} = h_{rs} - h_{sr} \quad \text{masl} \quad (3.8.11b)$$

3.9 Tropospheric-scatter path segments

For the tropospheric-scatter model described in Attachment E, calculate the horizontal path lengths from transmitter to common volume and common volume to receiver:

$$d_{tcv} = \frac{d \tan (0.001\theta_{rpos} + 0.5\theta_e) - 0.001(h_{ts} - h_{rs})}{\tan (0.001\theta_{tpos} + 0.5\theta_e) + \tan (0.001\theta_{rpos} + 0.5\theta_e)} \quad \text{km} \quad (3.9.1a)$$

Limit d_{tcv} such that $0 \leq d_{tcv} \leq d$:

$$d_{rcv} = d - d_{tcv} \quad \text{km} \quad (3.9.1b)$$

where d , θ_e , θ_{tpos} , and θ_{rpos} all appear in Table 3.1.

Calculate the longitude and latitude of the common volume, ϕ_{cve} and ϕ_{cvn} , from the transmitter and receiver longitudes and latitudes, as given in Table 2.2.1, using the great circle path method of Attachment H by setting $d_{pnt} = d_{tcv}$ in equation (H.3.1).

Calculate the height of the troposcatter common volume given by:

$$h_{cv} = h_{ts} + 1000d_{tcv} \tan(0.001\theta_{tpos}) + \frac{1000d_{tcv}^2}{2a_e} \quad \text{masl} \quad (3.9.2)$$

Calculate the longitude and latitude of the mid-points of the path segments from transmitter to common volume and from receiver to common volume, ϕ_{tcve} , ϕ_{tcvn} , and ϕ_{rcve} , ϕ_{rcvn} . These can be obtained using the great circle path method of Attachment H by setting $d_{pnt} = 0.5 d_{tcv}$ and $d_{pnt} = d - 0.5 d_{rcv}$ in equation (H.3.1), respectively.

3.10 Gaseous absorption on surface paths

Calculate the sea-level specific attenuation due to oxygen, γ_o , dB/km, using equation (F.6.1) of Attachment F, § F.6.

Use the method given in Attachment F, § F.2, to calculate the gaseous attenuations due to oxygen, and for water vapour under both non-rain and rain conditions, for a surface path. This will give values to A_{osur} , A_{wsur} and A_{wrsur} as calculated by equations (F.2.2a) to (F.2.2c).

The total gaseous attenuation under non-rain conditions is given by:

$$A_{gsur} = A_{osur} + A_{wsur} \quad \text{dB} \quad (3.10.1)$$

The values of A_{gsur} , A_{wrsur} and A_{wsur} are used in § 4.

3.11 Free-space basic transmission loss

Free-space basic transmission loss in dB is given as a function of path length D in km by:

$$L_{bfsD}(D) = 92.44 + 20\log(f) + 20\log(D) \quad \text{dB} \quad (3.11.1)$$

Calculate free-space basic transmission loss for path length d using:

$$L_{bfs} = L_{bfsD}(d) \quad \text{dB} \quad (3.11.2)$$

3.12 Knife-edge diffraction loss

Knife-edge diffraction loss in dB is given as a function of the dimensionless parameter v by:

$$J(v) = 6.9 + 20 \log \left[\sqrt{(v - 0.1)^2 + 1} + v - 0.1 \right] \text{ dB} \quad \text{if } v > -0.78 \quad (3.12.1a)$$

$$J(v) = 0 \text{ dB} \quad \text{otherwise} \quad (3.12.1b)$$

Function $J(v)$ is used in Attachments A and G.

4 Obtaining predictions for the principal sub-models

The method consists of four principal sub-models to take account of different sets of propagation mechanisms. The sub-models are combined as described in Attachment J and graphically in Fig. J.2.1. The models are combined in a way that reflects the statistical correlations between the various sub-models.

To avoid over-complicated symbol subscripts, the sub-models are numbered as follows.

Sub-model 1. Propagation close to the surface of the Earth, consisting of diffraction, non-ducting clear-air effects and precipitation fading.

Sub-model 2. Anomalous propagation due to stratified atmosphere, consisting of ducting and layer reflection.

Sub-model 3. Propagation via atmospheric turbulence, consisting of troposcatter and precipitation fading for the troposcatter path.

Sub-model 4. Propagation via sporadic-E reflection.

The results from these sub-models are combined as described in § 5 below.

4.1 Sub-model 1. Normal propagation close to the surface of the Earth

Calculate the diffraction loss not exceeded for $p\%$ time, L_d , as described in Attachment A, where L_d is given by equation (A.1.1).

Use the method given in Attachment B, § B.2 to calculate the notional clear-air zero-fade exceedance percentage time Q_{0ca} that is used within the clear-air method of § B.4.

Parameter A_1 denotes the fade in dB due to combined clear-air and rain/wet-snow. Clear-air enhancements are treated as a fade for which A_1 is negative.

Perform the preliminary rain/wet-snow calculations in § C.2 with the following inputs:

$$\phi_e = \phi_{me} \quad \text{degrees} \quad (4.1.1a)$$

$$\phi_n = \phi_{mn} \quad \text{degrees} \quad (4.1.1b)$$

$$h_{rainlo} = h_{lo} \quad \text{masl} \quad (4.1.1c)$$

$$h_{rainhi} = h_{hi} \quad \text{masl} \quad (4.1.1d)$$

$$d_{rain} = d \quad \text{km} \quad (4.1.1e)$$

Calculate A_1 using:

$$A_1 = A_{iter}(q) \quad \text{dB} \quad (4.1.2)$$

where $A_{iter}(q)$ is the iterative function described in Attachment I.