RECOMMENDATION ITU-R P.1812

A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands

(Question ITU-R 203/3)

(2007)

Scope

This Recommendation describes a propagation prediction method suitable for terrestrial point-to-area services in the frequency range 30 MHz to 3 GHz for the detailed evaluation of signal levels exceeded for a given percentage of time, p%, in the range $1\% \leq p \leq 50\%$ and a given percentage of locations, p_L, in the range $1\% \leq p_L \leq 99\%$. The method provides detailed analysis based on the terrain profile.

The method is suitable for predictions for radiocommunication systems utilizing terrestrial circuits having path lengths from 0.25 km up to about 3 000 km distance, with both terminals within approximately 3 km height above ground. It is not suitable for propagation predictions on either air-ground or space-Earth radio circuits.

This Recommendation complements Recommendation ITU-R P.1546.

The ITU Radiocommunication Assembly,

considering

a) that there is a need to give guidance to engineers in the planning of terrestrial radiocommunication services in the VHF and UHF bands;

b) that, for stations working in the same or adjacent frequency channels, the determination of the minimum geographical distance of separation required to avoid unacceptable interference due to long-distance terrestrial propagation is a matter of great importance,

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 (P-P) 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 P-P 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,

recommends

1 that the procedure given in Annex 1 should be used for the detailed evaluation of point-to-area signal levels in connection with these services.

Annex 1

1 Introduction

The propagation prediction method described in this Annex is recommended for the detailed evaluation of signal levels suitable for use in connection with terrestrial point-to-area services in the VHF and UHF bands. It predicts the signal level (i.e. electric field strength) exceeded for a given percentage, p%, of an average year in the range $1\% \leq p \leq 50\%$ and p_L% locations in the range $1\% \leq p_L \leq 99\%$. Therefore, this method may be used to predict both the service area and availability for a desired signal level (coverage), and the reductions in this service area and availability due to undesired, co- and/or adjacent-channel signals (interference).

The propagation model of this method is symmetric in the sense that it treats both radio terminals in the same manner. From the model's perspective, it does not matter which terminal is the transmitter and which is the receiver. However, for convenience in the model's description, the terms "transmitter" and "receiver" are used to denote the terminals at the start and end of the radio path, respectively.

The method is first described in terms of calculating basic transmission loss (dB) not exceeded for p% time for the median value of locations. The location variability and building entry loss elements are then characterized statistically with respect to receiver locations. A procedure is then given for converting to electric field strength (dB(μV/m)) for an effective radiated power of 1 kW.

This method is intended primarily for use with systems using low-gain antennas. However, the change in accuracy when high-gain antennas are used only affects the troposcatter element of the overall method, and the change in the predictions is small. For example, even with 40 dBi antennas at both ends of the link the over-estimation of troposcatter signals will amount to only about 1 dB.

The method is suitable for predictions for radiocommunication systems utilizing terrestrial circuits having path lengths from 0.25 km up to about 3 000 km distance, with both terminals within approximately 3 km height above ground. It is not suitable for propagation predictions on either air-ground or space-Earth radio circuits.

The propagation prediction method in this Annex is path-specific. Point-to-area predictions using this method consist of series of many P-P (i.e. transmitter-point-to-receiver-multipoint) predictions, uniformly distributed over notional service areas. The number of points should be large enough to ensure that the predicted values of basic transmission losses or field strengths thus obtained are reasonable estimates of the median values, with respect to locations, of the corresponding quantities for the elemental areas that they represent.

In consequence, it is assumed that users of this Recommendation are able to specify detailed terrain profiles (i.e. elevations above mean sea level) as functions of distance along the great circle paths (i.e. geodesic curves) between the terminals, for many different terminal locations (receiver-points). For most practical applications of this method to point-to-area coverage and interference predictions, this assumption implies the availability of a digital terrain elevation database, referenced to latitude and longitude with respect to a consistent geodetic datum, from which the terrain profiles may be extracted by automated means. If these detailed terrain profiles are not available, then Recommendation ITU-R P.1546 should instead be used for predictions.

In view of the foregoing, the location variability and building entry loss model elements of this Recommendation are characterized via the statistics of lognormal distributions with respect to receiver locations. Although this statistical characterization of the point-to-area propagation problem would appear to make the overall model unsymmetrical (i.e. non-reciprocal), users of this Recommendation should note that the location variability could, in principle, be applied at either end of the path (i.e. either terminal), or even both (i.e. the transmitter and the receiver). However, the location variability correction is only meaningful in situations when exact location of a given terminal is unknown and a statistical representation over that terminal's potential locations is required. There are unlikely to be many situations where this could meaningfully be applied to the transmitter location. If the locations of both terminals are known exactly and this procedure is being used in P-P mode, then this Recommendation is only applicable with p_L = 50%.

A similar point is true regarding building entry losses. The argument is slightly more complicated than for location variability owing to the fact that the median entry loss correction is non-zero. At the transmitter end, users should also add the building entry loss to the basic transmission loss if the transmitter is inside a building, but users must also be aware that the median loss values in Table 6 may be misleading if the transmitter is not in a "median" location.

2 Model elements of the propagation prediction method

This propagation prediction method takes account of the following model elements:

– *line-of-sight*
– *diffraction* (embracing smooth-Earth, irregular terrain and sub-path cases)
– *tropospheric scatter*
– *anomalous propagation* (ducting and layer reflection/refraction)
– *height-gain variation in clutter*
– *location variability*
– *building entry losses.*

3 Input parameters

3.1 Basic input data

Table 1 describes the basic input data, which defines the radio terminals, the frequency, and the percentage time and locations for which a prediction is required.

The latitude and longitude of the two stations are stated as basic inputs on the basis that they are needed to obtain the path profile. Radio-meteorological parameters must be obtained for a single location associated with the radio path, and for a long path the path-centre should be selected. It is appropriate to obtain the radio-meteorological parameters for the transmitter location when predicting its coverage area.

TABLE 1

Basic input data

Parameter	Units	Minimum	Maximum	Description
f	GHz	0.03	3.0	Frequency (GHz)
p	%	1.0	50.0	Percentage of average year for which the calculated signal level is exceeded
p_L	%	1	99	Percentage of locations for which the calculated signal level is exceeded
φ_t, φ_r	degrees	−80	+80	Latitude of transmitter, receiver
ψ_t, ψ_r	degrees	−180.0	180.0	Longitude of transmitter, receiver (positive = East of Greenwich)
h_{tg}, h_{rg}	m	1	3 000	Antenna centre height above ground level

3.2 Terrain profile

A terrain profile for the radio path is required for the application of the propagation prediction method. In principle, this consists of three arrays each having the same number of values, n, as follows:

d_i: distance from transmitter of i-th profilepoint (km) (1a)

h_i: height of i-th profilepoint above sealevel (m) (1b)

$g_i = h_i$ + representative clutter height of i-th profilepoint (m) (1c)

where:

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

n: number of profile points.

Note that the first profile point is at the transmitter. Thus d_1 is zero and h_1 is the terrain height at the transmitter in metres above sea level. Similarly, the n-th profile point is at the receiver. Thus d_n is the path length in km, and h_n the terrain height at the receiver in metres above sea level. If no representative clutter height information is available for a path profile, then $g_i = h_i$.

As there is no standardized set of clutter categories, this Recommendation does not define the clutter types or heights to be used. It should be noted that, if used, the heights of clutter should be "representative" clutter heights that improve the accuracy of the model, not the physical heights of the clutter represented. For guidance the clutter types given in Table 2 may be useful. In this Recommendation, setting the clutter height to zero is equivalent to removing the clutter loss.

TABLE 2

Representative clutter types

Clutter type	Representative clutter height (m)	Terminal clutter loss model
Open/rural/water	10	Equation (54b)
Suburban	10	Equation (54a)
Urban/trees/forest	15	Equation (54a)
Dense urban	20	Equation (54a)

3.3 Radio-climatic zones

Information is also needed on what lengths of the path are in the radio-climatic zones described in Table 3.

TABLE 3

Radio-climatic zones

Zone type	Code	Definition
Coastal land	A1	Coastal land and shore areas, i.e. land adjacent to the sea up to an altitude of 100 m relative to mean sea or water level, but limited to a distance of 50 km from the nearest sea area. Where precise 100 m data are not available an approximate value may be used
Inland	A2	All land, other than coastal and shore areas defined as "coastal land" above
Sea	B	Seas, oceans and other large bodies of water (i.e. covering a circle of at least 100 km in diameter)

For maximum consistency of results between administrations it is strongly recommended that the calculations of this procedure be based on the ITU Digitized World Map (IDWM) which is available from the BR for mainframe or personal computer environments. If all points on the path are at least 50 km from the sea or other large bodies of water, then only the inland category applies.

3.4 Terminal distances from the coast

If the path is over zone B two further parameters are required, d_{ct}, d_{cr}, giving the distance of the transmitter and the receiver from the coast (km), respectively, in the direction of the other terminal. For a terminal on a ship or sea platform the distance is zero.

3.5 Basic radio-meteorological parameters

The prediction procedure requires two radio-meteorological parameters to describe the variability of atmospheric refractivity.

– ΔN (N-units/km), the average radio-refractive index lapse-rate through the lowest 1 km of the atmosphere, provides the data upon which the appropriate effective Earth radius can be calculated for path profile and diffraction obstacle analysis. Note that ΔN is a positive quantity in this procedure.
– N_0 (N-units), the sea-level surface refractivity, is used only by the troposcatter model as a measure of variability of the troposcatter mechanism.

Appendix 1 gives global maps of ΔN and N_0, and data files containing the digitized maps are available from the Bureau.

3.6 Incidence of ducting

The degree to which signal levels will be enhanced due to anomalous propagation, particularly ducting, is quantified by a parameter β_0 (%), the time percentage for which refractive index lapse-rates exceeding 100 N-units/km can be expected in the first 100 m of the lower atmosphere. The value of β_0 is calculated as follows.

Calculate the parameter μ_1, which depends on the degree to which the path is over land (inland and/or coastal) and water:

$$\mu_1 = \left(10^{\frac{-d_{tm}}{16-6.6\tau}} + 10^{-5 \cdot (0.496 + 0.354\tau)} \right)^{0.2} \tag{2}$$

where the value of μ_1 shall be limited to $\mu_1 \leq 1$,

and:

$$\tau = 1 - e^{-\left(4.12 \times 10^{-4} \times d_{lm}^{2.41}\right)} \tag{3}$$

d_{tm}: longest continuous land (inland + coastal) section of the great-circle path (km)

d_{lm}: longest continuous inland section of the great-circle path (km).

The radio-climatic zones to be used for the derivation of d_{tm} and d_{lm} are defined in Table 3. If all points on the path are at least 50 km from the sea or other large bodies of water, then only the inland category applies and d_{tm} and d_{lm} are equal to the path length, d.

Calculate the parameter μ_4, which depends on μ_1 and the latitude of the path centre in degrees:

$$\mu_4 = \mu_1^{(-0.935 + 0.0176|\varphi|)} \qquad \text{for } |\varphi| \leq 70° \tag{4}$$

$$\mu_4 = \mu_1^{0.3} \qquad \text{for } |\varphi| > 70°$$

where:

φ: path centre latitude (degrees).

Calculate β_0:

$$\beta_0 = \begin{cases} 10^{-0.015|\varphi| + 1.67} \mu_1 \mu_4 & \% \qquad \text{for } |\varphi| \leq 70° \\ 4.17 \mu_1 \mu_4 & \% \qquad \text{for } |\varphi| > 70° \end{cases} \tag{5}$$

3.7 Effective Earth radius

The median effective Earth radius factor k_{50} for the path is given by:

$$k_{50} = \frac{157}{157 - \Delta N} \tag{6}$$

The value of the average radio-refractivity lapse-rate, ΔN, may be obtained from Fig. 1, using the latitude and longitude of the path centre as representative for the entire path.

The median value of effective Earth radius a_e is given by:

$$a_e = 6371 \cdot k_{50} \qquad \text{km} \tag{7a}$$

The effective Earth radius exceeded for β_0 time, a_β, is given by:

$$a_\beta = 6371 \cdot k_\beta \qquad \text{km} \tag{7b}$$

where $k_\beta = 3.0$ is an estimate of the effective Earth-radius factor exceeded for β_0 time.

3.8 Parameters derived from the path profile analysis

Values for a number of path-related parameters necessary for the calculations, as indicated in Table 4, must be derived via an initial analysis of the path profile based on the value of a_e given by equation (7a). Information on the derivation, construction and analysis of the path profile is given in Appendix 7 of this Annex.

TABLE 4

Parameter values to be derived from the path profile analysis

Parameter	Description
d	Great-circle path distance (km)
d_{lt}, d_{lr}	Distance from the transmit and receive antennas to their respective horizons (km)
θ_t, θ_r	Transmit and receive horizon elevation angles respectively (mrad)
θ	Path angular distance (mrad)
h_{ts}, h_{rs}	Antenna centre height above mean sea level (m)
h_{tc}, h_{rc}	max(h_{ts}, g_1) and max(h_{rs}, g_n) respectively
h_{te}, h_{re}	Effective heights of antennas above the terrain (m)
d_b	Aggregate length of the path sections over water (km)
ω	Fraction of the total path over water: $$\omega = d_b / d$$ where d is the great-circle distance (km) calculated using equation (63). For totally overland paths: $\omega = 0$

4 The prediction procedure

4.1 General

The overall prediction procedure is described in this section. First, the basic transmission loss, L_b (dB), not exceeded for the required annual percentage time, p%, and 50% locations is evaluated as described in § 4.2-4.6 (i.e. the basic transmission losses due to line-of-sight propagation, propagation by diffraction, propagation by tropospheric scatter, propagation by ducting/layer reflection and the combination of these propagation mechanisms to predict the basic transmission loss, respectively). In § 4.7-4.10, methods to account for the inclusion of terminal clutter effects, the effects of location variability and building entry loss are described. Finally, § 4.11 gives expressions that relate the basic transmission loss to the field strength (dB μV/m) for 1 kW effective radiated power.

4.2 Line-of-sight propagation (including short-term effects)

The following should all be evaluated for both line-of-sight and trans-horizon paths.

The basic transmission loss due to free-space propagation is given by:

$$L_{bfs} = 92.44 + 20\log f + 20\log d \qquad \text{dB} \qquad (8)$$

Corrections for multipath and focusing effects at p and β_0 percentage times, respectively, are given by:

$$E_{sp} = 2.6\left(1 - e^{-\frac{d_{lt}+d_{lr}}{10}}\right)\log\left(\frac{p}{50}\right) \quad \text{dB} \tag{9a}$$

$$E_{s\beta} = 2.6\left(1 - e^{-\frac{d_{lt}+d_{lr}}{10}}\right)\log\left(\frac{\beta_0}{50}\right) \quad \text{dB} \tag{9b}$$

Calculate the basic transmission loss not exceeded for time percentage, p%, due to line-of-sight propagation (regardless of whether or not the path is actually line-of-sight), as given by:

$$L_{b0p} = L_{bfs} + E_{sp} \quad \text{dB} \tag{10}$$

Calculate the basic transmission loss not exceeded for time percentage, β_0%, due to line-of-sight propagation (regardless of whether or not the path is actually line-of-sight), as given by:

$$L_{b0\beta} = L_{bfs} + E_{s\beta} \quad \text{dB} \tag{11}$$

4.3 Propagation by diffraction

NOTE – 1 This method, which has been taken over from Recommendation ITU-R P.452, has been found to have limitations[1] and as a consequence work is ongoing to propose an improved method. Notably other diffraction methods are under consideration now that will lead to an update of this section.

Diffraction loss is calculated by a method based on the Deygout construction for a maximum of three edges. The principal edge always exists, identified as the profile point having the highest value of diffraction parameter, ν. Secondary edges may also exist on the transmitter and receiver sides of the principal edge. The knife-edge losses for the edges which exist are then combined with an empirical correction. This method provides an estimate of diffraction loss for all types of path, including over-sea or over-inland or coastal land, and irrespective of whether the path is smooth or rough.

The above method is always used for median effective Earth radius, as described in § 4.3.1. If an overall prediction is required for p = 50%, no further diffraction calculation is necessary.

In the general case where p < 50%, the calculation must be performed a second time for an effective Earth-radius factor equal to 3, as described in § 4.3.2. This second calculation gives an estimate of diffraction loss not exceeded for β_0% time, where β_0 is given by equation (5).

The diffraction loss not exceeded for p% time, for $0.001\% \le p \le 50\%$, is then calculated using a limiting or interpolation procedure described in § 4.3.3.

The method uses an approximation to the single knife-edge diffraction loss as a function of the dimensionless parameter, ν, given by:

$$J(\nu) = 6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right) \tag{12}$$

Note that $J(-0.78) \approx 0$, and this defines the lower limit at which this approximation should be used. $J(\nu)$ is set to zero for $\nu \le -0.78$.

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[1] Especially, measurements in Switzerland have found inconsistent results with a standard deviation of 15 dB.

4.3.1 Median diffraction loss

The median diffraction loss, L_{d50} (dB), is calculated using the median value of the effective Earth radius, a_e, given by equation (7a).

Median diffraction loss for the principal edge

Calculate a correction, ζ_m, for overall path slope given by:

$$\zeta_m = \cos\left(\tan^{-1}\left(10^{-3} \cdot \frac{h_{rc} - h_{tc}}{d}\right)\right) \tag{13}$$

Find the main (i.e. principal) edge, and calculate its diffraction parameter, ν_{m50}, given by:

$$\nu_{m50} = \max_{i=2}^{n-1}\left(\zeta_m H_i \sqrt{\frac{2 \times 10^{-3} d}{\lambda d_i (d - d_i)}}\right) \tag{14}$$

where the vertical clearance, H_i, is:

$$H_i = g_i + 10^3 \frac{d_i (d - d_i)}{2 a_e} - \frac{h_{tc}(d - d_i) + h_{rc} \cdot d_i}{d} \tag{14a}$$

and:

- λ: wavelength (m) = $0.3/f$
- f: frequency (GHz)
- d: path length (km)
- d_i: distance of the i-th profile point from transmitter (km) (see § 3.2)
- $h_{tc,rc}$: $\max(h_{ts,rs}, g_{1,n})$, respectively.

Set i_{m50} to the index of the profile point with the maximum value, ν_{m50}.

Calculate the median knife-edge diffraction loss for the main edge, L_{m50}, given by:

$$\begin{aligned} L_{m50} &= J(\nu_{m50}) && \text{if } \nu_{m50} \geq -0.78 \\ &= 0 && \text{otherwise} \end{aligned} \tag{15}$$

If $L_{m50} = 0$, the median diffraction loss, L_{d50}, and the diffraction loss not exceeded for β_0% time, $L_{d\beta}$, are both zero and no further diffraction calculations are necessary.

Otherwise possible additional losses due to secondary edges on the transmitter and receiver sides of the principal edge should be investigated, as follows.

Median diffraction loss for transmitter-side secondary edge

If $i_{m50} = 2$, there is no transmitter-side secondary edge, and the associated diffraction loss, L_{t50}, should be set to zero. Otherwise, the calculation proceeds as follows. Calculate a correction, ζ_t, for the slope of the path from the transmitter to the principal edge:

$$\zeta_t = \cos\left(\tan^{-1}\left(10^{-3} \cdot \frac{g_{i_{m50}} - h_{tc}}{d_{i_{m50}}}\right)\right) \tag{16}$$

Find the transmitter-side secondary edge and calculate its diffraction parameter, ν_{t50}, given by:

$$\nu_{t50} = \max_{i=2}^{i_{m50}-1}\left(\zeta_t H_i \sqrt{\frac{2\times10^{-3} d_{i_{m50}}}{\lambda d_i \cdot \left(d_{i_{m50}} - d_i\right)}}\right) \tag{17}$$

where:

$$H_i = g_i + 10^3 \frac{d_i\left(d_{i_{m50}} - d_i\right)}{2a_e} - \frac{h_{tc}\left(d_{i_{m50}} - d_i\right) + g_{i_{m50}} \cdot d_i}{d_{i_{m50}}} \tag{17a}$$

Set i_{t50} to the index of the profile point for the transmitter-side secondary edge (i.e. the index of the terrain height array element corresponding to the value ν_{t50}).

Calculate the median knife-edge diffraction loss for the transmitter-side secondary edge, L_{t50}, given by:

$$\begin{aligned} L_{t50} &= J(\nu_{t50}) && \text{if } \nu_{t50} \geq -0.78 \text{ and } i_{m50} > 2 \\ &= 0 && \text{otherwise} \end{aligned} \tag{18}$$

Median diffraction loss for the receiver-side secondary edge

If $i_{m50} = n - 1$, there is no receiver-side secondary edge, and the associated diffraction loss, L_{r50}, should be set to zero. Otherwise the calculation proceeds as follows. Calculate a correction, ζ_r, for the slope of the path from the principal edge to the receiver:

$$\zeta_r = \cos\left(\tan^{-1}\left(10^{-3} \cdot \frac{h_{rc} - g_{i_{m50}}}{d - d_{i_{m50}}}\right)\right) \tag{19}$$

Find the receiver-side secondary edge and calculate its diffraction parameter, ν_{r50}, given by:

$$\nu_{r50} = \max_{i=i_{m50}+1}^{n-1}\left(\zeta_r H_i \sqrt{\frac{2\times10^{-3}\left(d - d_{i_{m50}}\right)}{\lambda\left(d_i - d_{i_{m50}}\right)\left(d - d_i\right)}}\right) \tag{20}$$

where:

$$H_i = g_i + 10^3 \frac{\left(d_i - d_{i_{m50}}\right)\left(d - d_i\right)}{2a_e} - \frac{g_{i_{m50}}\left(d - d_i\right) + h_{rc}\left(d_i - d_{i_{m50}}\right)}{d - d_{i_{m50}}} \tag{20a}$$

Set i_{r50} to the index of the profile point for the receiver-side secondary edge (i.e. the index of the terrain height array element corresponding to the value ν_{r50}).

Calculate the median knife-edge diffraction loss for the receiver-side secondary edge, L_{r50}, given by:

$$\begin{aligned} L_{r50} &= J(\nu_{r50}) && \text{if } \nu_{r50} \geq -0.78 \text{ and } i_{m50} < n - 1 \\ &= 0 && \text{otherwise} \end{aligned} \tag{21}$$

Combination of the edge losses for median Earth curvature

Calculate the median diffraction loss, L_{d50}, given by:

$$L_{d50} = L_{m50} + \left(1 - e^{-\frac{L_{m50}}{6}}\right)\left(L_{t50} + L_{r50} + 10 + 0.04d\right) \quad \text{if } \nu_{m50} > -0.78$$
$$= 0 \quad \text{otherwise} \tag{22}$$

In equation (22) L_{t50} will be zero if the transmitter-side secondary edge does not exist and, similarly, L_{r50} will be zero if the receiver-side secondary edge does not exist.

If $L_{d50} = 0$, then the diffraction loss not exceeded for β_0% time will also be zero.

If the prediction is required only for $p = 50\%$, no further diffraction calculations will be necessary (see § 4.3.3). Otherwise, the diffraction loss not exceeded for β_0% time must be calculated, as follows.

4.3.2 The diffraction loss not exceeded for β_0% of the time

The diffraction loss not exceeded for β_0% time is calculated using the effective Earth radius exceeded for β_0% time, a_β, given by equation (7b). For this second diffraction calculation, the same edges as those found for the median case should be used for the Deygout construction. The calculation of this diffraction loss then proceeds as follows.

Principal edge diffraction loss not exceeded for β_0% time

Find the main (i.e. principal) edge diffraction parameter, $\nu_{m\beta}$, given by:

$$\nu_{m\beta} = \zeta_m H_{im\beta} \sqrt{\frac{2 \times 10^{-3} d}{\lambda d_{im50}\left(d - d_{im50}\right)}} \tag{23}$$

where:

$$H_{im\beta} = g_{im50} + 10^3 \frac{d_{im50}\left(d - d_{im50}\right)}{2a_\beta} - \frac{h_{tc}\left(d - d_{im50}\right) + h_{rc} \cdot d_{im50}}{d} \tag{23a}$$

Calculate the knife-edge diffraction loss for the main edge, $L_{m\beta}$, given by:

$$L_{m\beta} = J\left(\nu_{m\beta}\right) \quad \text{if } \nu_{m\beta} \geq -0.78$$
$$= 0 \quad \text{otherwise} \tag{24}$$

Transmitter-side secondary edge diffraction loss not exceeded for β_0% time

If $L_{t50} = 0$, then $L_{t\beta}$ will be zero. Otherwise calculate the transmitter-side secondary edge diffraction parameter, $\nu_{t\beta}$, given by:

$$\nu_{t\beta} = \zeta_t H_{it\beta} \sqrt{\frac{2 \times 10^{-3} d_{im50}}{\lambda d_{it50}\left(d_{im50} - d_{it50}\right)}} \tag{25}$$

where:

$$H_{it\beta} = g_{it50} + 10^3 \frac{d_{it50}(d_{im50} - d_{it50})}{2a_\beta} - \frac{h_{tc}(d_{im50} - d_{it50}) + g_{im50} \cdot d_{it50}}{d_{im50}} \tag{25a}$$

Calculate the knife-edge diffraction loss for the transmitter-side secondary edge, $L_{t\beta}$, given by:

$$\begin{aligned} L_{t\beta} &= J(\nu_{t\beta}) && \text{if } \nu_{t\beta} \geq -0.78 \\ &= 0 && \text{otherwise} \end{aligned} \tag{26}$$

Receiver-side secondary edge diffraction loss not exceeded for β_0% *time*

If $L_{r50} = 0$, then $L_{r\beta}$ will be zero. Otherwise, calculate the receiver-side secondary edge diffraction parameter, $\nu_{r\beta}$, given by:

$$\nu_{r\beta} = \zeta_r H_{ir\beta} \sqrt{\frac{2 \times 10^{-3}(d - d_{im50})}{\lambda(d_{ir50} - d_{im50})(d - d_{ir50})}} \tag{27}$$

where:

$$H_{ir\beta} = g_{ir50} + 10^3 \frac{(d_{ir50} - d_{im50}) \cdot (d - d_{ir50})}{2a_\beta} - \frac{g_{im50} \cdot (d - d_{ir50}) + h_{rc} \cdot (d_{ir50} - d_{im50})}{d - d_{im50}} \tag{27a}$$

Calculate the knife-edge diffraction loss for the receiver-side secondary edge, $L_{r\beta}$, given by:

$$\begin{aligned} L_{r\beta} &= J(\nu_{r\beta}) && \text{if } \nu_{r\beta} \geq -0.78 \\ &= 0 && \text{otherwise} \end{aligned} \tag{28}$$

Combination of the edge losses not exceeded for β_0% *time*

Calculate the diffraction loss not exceeded for β_0% of the time, $L_{d\beta}$, given by:

$$\begin{aligned} L_{d\beta} &= L_{m\beta} + \left(1 - e^{-\frac{L_{m\beta}}{6}}\right)(L_{t\beta} + L_{r\beta} + 10 + 0.04d) && \text{if } \nu_{m\beta} > -0.78 \\ &= 0 && \text{otherwise} \end{aligned} \tag{29}$$

4.3.3 The diffraction loss not exceeded for *p*% of the time

The application of the two possible values of effective Earth radius factor is controlled by an interpolation factor, F_i, based on a log-normal distribution of diffraction loss over the range $\beta_0\% < p \leq 50\%$, given by:

$$F_i = 0 \qquad \text{if } p = 50\% \tag{30a}$$

$$= \frac{I\left(\frac{p}{100}\right)}{I\left(\frac{\beta_0}{100}\right)} \qquad \text{if } 50\% > p > \beta_0\% \tag{30b}$$

$$= 1 \qquad \text{if } \beta_0\% \geq p \tag{30c}$$

where $I(x)$ is the inverse complementary cumulative normal distribution as a function of the probability x. An approximation for $I(x)$ which may be used with confidence for $x \leq 0.5$ is given in Appendix 3 to this Annex.

The diffraction loss, L_{dp}, not exceeded for p% time, is now given by:

$$L_{dp} = L_{d50} + (L_{d\beta} - L_{d50})\ F_i \qquad \text{dB} \tag{31}$$

where L_{d50} and $L_{d\beta}$ are defined by equations (22) and (29), respectively, and F_i is defined by equations (30a-c), depending on the values of p and β_0.

The median basic transmission loss associated with diffraction, L_{bd50}, is given by:

$$L_{bd50} = L_{bfs} + L_{d50} \qquad \text{dB} \tag{32}$$

where L_{bfs} is given by equation (8).

The basic transmission loss associated with diffraction not exceeded for p% time is given by:

$$L_{db} = L_{b0p} + L_{dp} \qquad \text{dB} \tag{33}$$

where L_{b0p} is given by equation (10).

4.4 Propagation by tropospheric scatter

NOTE 1 – At time percentages much below 50%, it is difficult to separate the true tropospheric scatter mode from other secondary propagation phenomena which give rise to similar propagation effects. The "tropospheric scatter" model adopted in this Recommendation is therefore an empirical generalization of the concept of tropospheric scatter which also embraces these secondary propagation effects. This allows a continuous consistent prediction of basic transmission loss over the range of time percentages p from 0.001% to 50%, thus linking the ducting and layer reflection model at the small time percentages with the true "scatter mode" appropriate to the weak residual field exceeded for the largest time percentage.

NOTE 2 – This troposcatter prediction model has been derived for interference prediction purposes and is not appropriate for the calculation of propagation conditions above 50% of time affecting the performance aspects of trans-horizon radio-relay systems.

The basic transmission loss due to troposcatter, L_{bs} (dB), not exceeded for any time percentage, p, below 50%, is given by:

$$L_{bs} = 190.1 + L_f + 20\log d + 0.573\theta - 0.15\,N_0 - 10.125\left(\log\left(\frac{50}{p}\right)\right)^{0.7} \qquad \text{dB} \tag{34}$$

where:

L_f: frequency dependent loss:

$$L_f = 25\log(f) - 2.5\left[\log\left(\frac{f}{2}\right)\right]^2 \qquad \text{dB} \tag{35}$$

N_0: path centre sea-level surface refractivity, which may be derived from Fig. 2.

4.5 Propagation by ducting/layer reflection

The basic transmission loss associated with ducting/layer-reflection not exceeded for p% time, L_{ba} (dB), is given by:

$$L_{ba} = A_f + A_d(p) \quad \text{dB} \tag{36}$$

where:

A_f : total of fixed coupling losses (except for local clutter losses) between the antennas and the anomalous propagation structure within the atmosphere:

$$A_f = 102.45 + 20\log f + 20\log(d_{lt} + d_{lr}) + A_{st} + A_{sr} + A_{ct} + A_{cr} \quad \text{dB} \tag{37}$$

A_{st}, A_{sr}: site-shielding diffraction losses for the transmitting and receiving stations respectively:

$$A_{st,sr} = \begin{cases} 20\log\left(1 + 0.361\,\theta''_{t,r}\,(f \cdot d_{lt,lr})^{1/2}\right) + 0.264\,\theta''_{t,r}\,f^{1/3} & \text{dB} \quad \text{for } \theta''_{t,r} > 0 \text{ mrad} \\ 0 & \text{dB} \quad \text{for } \theta''_{t,r} \le 0 \text{ mrad} \end{cases} \tag{38}$$

where:

$$\theta''_{t,r} = \theta_{t,r} - 0.1\,d_{lt,lr} \quad \text{mrad} \tag{38a}$$

A_{ct}, A_{cr}: over-sea surface duct coupling corrections for the transmitting and receiving stations respectively:

$$A_{ct,cr} = -3e^{-0.25 d^2_{ct,cr}}\left(1 + \tanh(0.07(50 - h_{ts,rs}))\right) \quad \text{dB} \quad \text{for} \quad \omega \ge 0.75,\ d_{ct,cr} \le d_{lt,lr},\ d_{ct,cr} \le 5 \text{ km} \tag{39}$$

$$A_{ct,cr} = 0 \quad \text{dB} \quad \text{for all other conditions} \tag{39a}$$

It is useful to note the limited set of conditions under which equation (39) is needed.

$A_d(p)$: time percentage and angular-distance dependent losses within the anomalous propagation mechanism:

$$A_d(p) = \gamma_d \cdot \theta' + A(p) \quad \text{dB} \tag{40}$$

where:

γ_d : specific attenuation:

$$\gamma_d = 5 \times 10^{-5}\, a_e f^{1/3} \quad \text{dB/mrad} \tag{41}$$

θ': angular distance (corrected where appropriate (via equation (38a)) to allow for the application of the site shielding model in equation (36)):

$$\theta' = \frac{10^3 d}{a_e} + \theta'_t + \theta'_r \quad \text{mrad} \tag{42}$$

$$\theta'_{t,r} = \begin{cases} \theta_{t,r} & \text{for } \theta_{t,r} \le 0.1\,d_{lt,lr} \quad \text{mrad} \\ 0.1\,d_{lt,lr} & \text{for } \theta_{t,r} > 0.1\,d_{lt,lr} \quad \text{mrad} \end{cases} \tag{42a}$$

$A(p)$: time percentage variability (cumulative distribution):

$$A(p) = -12 + (1.2 + 3.7 \times 10^{-3} d) \log\left(\frac{p}{\beta}\right) + 12\left(\frac{p}{\beta}\right)^{\Gamma} \quad \text{dB} \tag{43}$$

$$\Gamma = \frac{1.076}{(2.0058 - \log \beta)^{1.012}} \times e^{-\left(9.51 - 4.8 \log \beta + 0.198 (\log \beta)^2\right) \times 10^{-6} \cdot d^{1.13}} \tag{43a}$$

$$\beta = \beta_0 \cdot \mu_2 \cdot \mu_3 \quad \% \tag{44}$$

μ_2: correction for path geometry:

$$\mu_2 = \left(\frac{500}{a_e} \frac{d^2}{\left(\sqrt{h_{te}} + \sqrt{h_{re}}\right)^2}\right)^{\alpha} \tag{45}$$

The value of μ_2 shall not exceed 1.

$$\alpha = -0.6 - \varepsilon \cdot 10^{-9} \cdot d^{3.1} \cdot \tau \tag{45a}$$

where:

ε: 3.5

τ: is defined in equation (3), and the value of α shall not be allowed to reduce below −3.4

μ_3: correction for terrain roughness:

$$\mu_3 = \begin{cases} 1 & \text{for } h_m \le 10 \text{ m} \\ e^{-4.6 \times 10^{-5} (h_m - 10)(43 + 6 d_I)} & \text{for } h_m > 10 \text{ m} \end{cases} \tag{46}$$

and:

$$d_I = \min(d - d_{lt} - d_{lr}, 40) \quad \text{km} \tag{46a}$$

The remaining terms have been defined in Tables 1 and 2 and Appendix 2 to this Annex.

4.6 Basic transmission loss not exceeded for *p*% time and 50% locations ignoring the effects of terminal clutter

The following procedure should be applied to the results of the foregoing calculations for all paths, in order to compute the basic transmission loss not exceeded for *p*% time and 50% locations. In order to avoid physically unreasonable discontinuities in the predicted notional basic transmission losses, the foregoing propagation models must be blended together to get modified values of basic transmission losses in order to achieve an overall prediction for *p*% time and 50% locations.

Calculate an interpolation factor, F_j, to take account of the path angular distance:

$$F_j = 1.0 - 0.5\left(1.0 + \tanh\left(3.0\,\xi \cdot \frac{(\theta - \Theta)}{\Theta}\right)\right) \tag{47}$$

where:

Θ: fixed parameter determining the angular range of the associated blending; set to 0.3

ξ: fixed parameter determining the blending slope at the end of the range; set to 0.8

θ: path angular distance (mrad) defined in Table 7.

Calculate an interpolation factor, F_k, to take account of the path great-circle distance:

$$F_k = 1.0 - 0.5\left(1.0 + \tanh\left(3.0\,\kappa \cdot \frac{(d - d_{sw})}{d_{sw}}\right)\right) \tag{48}$$

where:

d: great circle path length defined in Table 3 (km)

d_{sw}: fixed parameter determining the distance range of the associated blending; set to 20

κ: fixed parameter determining the blending slope at the ends of the range; set to 0.5.

Calculate a notional minimum basic transmission loss, L_{minb0p} (dB), associated with line-of-sight propagation and over-sea sub-path diffraction:

$$L_{\min b0p} = \begin{cases} L_{b0p} + (1-\omega)L_{dp} & \text{for } p < \beta_0 \quad \text{dB} \\ L_{bd50} + (L_{b0\beta} + (1-\omega)L_{dp} - L_{bd50}) \cdot F & \text{for } p \geq \beta_0 \quad \text{dB} \end{cases} \tag{49}$$

where:

L_{b0p}: notional line-of-sight basic transmission loss not exceeded for p% time, given by equation (10)

$L_{b0\beta}$: notional line-of-sight basic transmission loss not exceeded for β_0% time, given by equation (11)

L_{dp}: diffraction loss not exceeded for p% time, equation (31), calculated using the method as described in § 4.3

L_{bd50}: median basic transmission loss associated with diffraction, equation (32), calculated using the method as described in § 4.3

F_i: two effective Earth radii diffraction interpolation factor, given by equation (30).

Calculate a notional minimum basic transmission loss, L_{minbap} (dB), associated with line-of-sight and trans-horizon signal enhancements:

$$L_{minbap} = \eta \cdot \ln\left(e^{\left(\frac{L_{ba}}{\eta}\right)} + e^{\left(\frac{L_{b0p}}{\eta}\right)}\right) \quad \text{dB} \tag{50}$$

where:

L_{ba}: ducting/layer reflection basic transmission loss not exceeded for p% time, given by equation (36)

L_{b0p}: notional line-of-sight basic transmission loss not exceeded for p% time, given by equation (10)

η = 2.5.

Calculate a notional basic transmission loss, L_{bda} (dB), associated with diffraction and line-of-sight or ducting/layer-reflection enhancements:

$$L_{bda} = \begin{cases} L_{bd} & \text{for } L_{minbap} > L_{bd} \\ L_{minbap} + (L_{bd} - L_{minbap}) \cdot F_k & \text{for } L_{minbap} \le L_{bd} \end{cases} \qquad \text{dB} \qquad (51)$$

where:

L_{bd}: basic transmission loss for diffraction not exceeded for p% time from equation (33)

L_{minbap}: notional minimum basic transmission loss associated with line-of-sight propagation and trans-horizon signal enhancements from equation (50)

F_k: interpolation factor given by equation (48), according to the value of the path great-circle distance, d.

Calculate a modified basic transmission loss, L_{bam} (dB), which takes diffraction and line-of-sight or ducting/layer-reflection enhancements into account:

$$L_{bam} = L_{bda} + (L_{minb0p} - L_{bda}) \cdot F_j \qquad \text{dB} \qquad (52)$$

where:

L_{bda}: notional basic transmission loss associated with diffraction and line-of-sight or ducting/layer-reflection enhancements, given by equation (51)

L_{minb0p}: notional minimum basic transmission loss associated with line-of-sight propagation and over-sea sub-path diffraction, given by equation (49)

F_j: interpolation factor given by equation (47), according to the value of the path angular distance, θ.

Calculate the basic transmission loss not exceeded for p% time and 50% locations ignoring the effects of terminal clutter, L_{bu} (dB), as given by:

$$L_{bu} = -5 \log\left(10^{-0.2 L_{bs}} + 10^{-0.2 L_{bam}}\right) \qquad \text{dB} \qquad (53)$$

where:

L_{bs}: basic transmission loss due to troposcatter not exceeded for p% time, given by equation (34)

L_{bam}: modified basic transmission loss taking diffraction and line-of-sight ducting/layer-reflection enhancements into account, given by equation (52).

4.7 Terminal clutter losses

When the transmitter or receiver antenna is located below the height R_t or R_r representative of ground cover surrounding the transmitter or receiver, the transmitter and receiver clutter losses, A_{ht}, A_{hr}, are calculated as follows. The method for transmitter and receiver is identical, and in the following, $A_h = A_{ht}$ or A_{hr}, $h = h_{tg}$ or h_{rg} and $R = R_t$ or R_r as appropriate.

If $h \ge R$ then $A_h = 0$

If $h < R$, then A_h can take one of two forms, depending on clutter type (see Table 2):

$$A_h = J(\nu) - 6.03 \qquad \text{dB} \qquad (54a)$$

or:

$$A_h = -K_{h2} \log(h/R) \qquad \text{dB} \qquad (54b)$$

$J(\nu)$ is calculated using equation (12).

The terms ν and K_{h2} are given by:

$$\nu = K_{nu} \sqrt{h_{dif}\, \theta_{clut}} \qquad (54c)$$

$$h_{dif} = R - h \qquad \text{m} \qquad (54d)$$

$$\theta_{clut} = \tan^{-1}(h_{dif}/27) \qquad \text{degrees} \qquad (54e)$$

$$K_{h2} = 21.8 + 6.2 \log(f) \qquad (54f)$$

$$K_{nu} = 0.342 \sqrt{f} \qquad (54g)$$

where:

f: frequency (GHz).

The form of equation (54a) represents Fresnel diffraction loss over an obstacle and would be applied to clutter categories such as buildings. In particular urban clutter would be of this type.

Equation (54b) is used to represent the height gain function below the first interference maximum caused by two-ray interference from the ground. This is not really a clutter issue, but this simple approach allows it to be treated within the same framework as clutter. If required, it would be used by specifying a "non-cluttered" clutter type with a "clutter height", R, that represents the height of the first interference lobe.

The basic transmission loss not exceeded for p% time and 50% locations, including the effects of terminal clutter losses, L_{bc} (dB), is given by:

$$L_{bc} = L_{bu} + A_{ht} + A_{hr} \qquad \text{dB} \qquad (55)$$

where:

L_{bu}: the basic transmission loss not exceeded for p% time and 50% locations at (or above, as appropriate) the height of representative clutter, given by equation (53)

$A_{ht,hr}$: the additional losses to account for clutter shielding the transmitter and receiver, equations (54a and 54b) as appropriate. These should be set to zero if there is no such shielding.

4.8 Location variability of losses

In this Recommendation, and generally, location variability refers to the spatial statistics of local ground cover variations. This is a useful result over scales substantially larger than the ground cover variations, and over which path variations are insignificant. As location variability is defined to exclude multipath variations, it is independent of system bandwidth.

In the planning of radio systems, it will also be necessary to take multipath effects into account. The impact of these effects will vary with systems, being dependent on bandwidths, modulations and coding schemes. Guidance on the modelling of these effects is given in Recommendation ITU-R P.1406.

Extensive data analysis suggests that the distribution of median field strength due to ground cover variations over such an area in urban and suburban environments is approximately lognormal with zero mean.

Values of the standard deviation are dependent on frequency and environment, and empirical studies have shown a considerable spread. Representative values for areas of 500 × 500 m are given by the following expression:

$$\sigma_L = K + 1.3 \log(f) \qquad \text{dB} \tag{56}$$

where:

K = 5.1, for receivers with antennas below clutter height in urban or suburban environments for mobile systems with omnidirectional antennas at car-roof height

K = 4.9 for receivers with rooftop antennas near the clutter height

K = 4.4 for receivers in rural areas

f: required frequency (GHz).

If the area over which the variability is to apply is greater than 500 × 500 m, or if the variability is to relate to all areas at a given range, rather than the variation across individual areas, the value of σ_L will be greater. Empirical studies have suggested that location variability is increased (with respect to the small area values) by up to 4 dB for a 2 km radius and up to 8 dB for a 50 km radius.

The percentage locations, p_L, can vary between 1% and 99%. This model is not valid for percentage locations less than 1% or greater than 99%.

It should be noted that, for some planning purposes (e.g. multilateral allotment plans) it will generally be necessary to use a definition of "location variability" that includes a degree of multipath fading. This will allow for the case of a mobile receiver, stationary in a multipath null, or for a rooftop antenna where a number of frequencies are to be received and the antenna cannot be optimally positioned for all. Additionally, such planning may also need to consider variability over a greater area than that assumed in this Recommendation.

In this context, the values given in Table 5 have been found appropriate for the planning of a number of radio services.

TABLE 5

Values of location variability standard deviations used in certain planning situations

	Standard deviation		
	100 MHz	**600 MHz**	**2 000 MHz**
Broadcasting, analogue (dB)	8.3	9.5	–
Broadcasting, digital (dB)	5.5	5.5	5.5

The location variability correction should not be applied when the receiver/mobile is adjacent to the sea.

When the receiver/mobile is located on land and outdoors but its height above ground is greater than or equal to the height of representative clutter, it is reasonable to expect that the location variability will decrease monotonically with increasing height until, at some point, it vanishes. In this Recommendation, the location variability height variation, $u(h)$, is given by:

$$u(h) = 1 \quad \text{for} \quad 0 \le h < R$$
$$u(h) = 1 - \frac{(h - R)}{10} \quad \text{for} \quad R \le h < R + 10 \tag{57}$$
$$u(h) = 0 \quad \text{for} \quad R + 10 \le h$$

where R (m) is the height of representative clutter at the receiver/mobile location. Therefore, for a receiver/mobile located outdoors, the standard deviation of the location variability, σ_L, as given by either equation (56) or Table 5, should be multiplied by the height variation function, $u(h)$, given in equation (57), when computing values of the basic transmission loss for values of p_L% different from 50%.

4.9 Building entry loss

Building entry loss is defined as the difference (dB) between the mean field strength (with respect to locations) outside a building at a given height above ground level and the mean field strength inside the same building (with respect to locations) at the same height above ground level.

For *indoor reception* two important parameters must also be taken into account. The first is the building entry loss and the second is the variation of the building entry loss due to different building materials. The standard deviations, given below, take into account the large spread of building entry losses but do not include the location variability within different buildings. It should be noted that there is limited reliable information and measurement results about building entry loss. Provisionally, building entry loss values that may be used are given in Table 6.

TABLE 6

Building entry loss[(1)], L_{be}, σ_{be}

F	Median value, L_{be} (dB)	Standard deviation, σ_{be} (dB)
0.2 GHz	9	3
0.6 GHz	11	6
1.5 GHz	11	6

(1) These values may have to be updated when more experimental data become available.

For frequencies below 0.2 GHz, L_{be} = 9 dB, σ_{be} = 3 dB; for frequencies above 1.5 GHz, L_{be} = 11 dB, σ_{be} = 6 dB. Between 0.2 GHz and 0.6 GHz (and between 0.6 GHz and 1.5 GHz), appropriate values for L_{be} and σ_{be} can be obtained by linear interpolation between the values for L_{be} and σ_{be} given in the Table for 0.2 GHz and 0.6 GHz (0.6 GHz and 1.5 GHz).

The field-strength variation for indoor reception is the combined result of the outdoor variation (σ_L) and the variation due to building attenuation (σ_{be}). These variations are likely to be uncorrelated. The standard deviation for indoor reception (σ_i) can therefore be calculated by taking the square root of the sum of the squares of the individual standard deviations.

$$\sigma_i = \sqrt{\sigma_L^2 + \sigma_{be}^2} \tag{58}$$

where σ_L is the standard deviation of location variability, as given by equation (56) or Table 5.

For example, for digital emissions with bandwidth greater than 1 MHz, at VHF, where the signal standard deviations are 5.5 dB and 3 dB respectively, the combined value is 6.3 dB. In Band IV/V, where the signal standard deviations are 5.5 dB and 6 dB, the combined value is 8.1 dB.

4.10 Basic transmission loss not exceeded for *p*% time and p_L% locations

In order to compute the desired percentage locations, the median loss, L_{loc}, and the standard deviation, σ_{loc}, are given by:

$$L_{loc} = 0 \quad \text{(outdoors)} \tag{59a}$$

$$L_{loc} = L_{be} \quad \text{(indoors)} \tag{59b}$$

and:

$$\sigma_{loc} = u(h) \cdot \sigma_L \quad \text{(outdoors)} \tag{60a}$$

$$\sigma_{loc} = \sigma_i \quad \text{(indoors)} \tag{60b}$$

where the median building entry loss, L_{be}, is given in Table 6, the height function, $u(h)$, is given by equation (57) and the standard deviations, σ_L and σ_i, are given by equation (56) (or Table 5) and equation (58), respectively.

The basic transmission loss not exceeded for *p*% time and p_L% locations, L_b (dB), is given by:

$$L_b = \max\left\{ L_{b0p}, L_{bc} + L_{loc} - I\left(\frac{p_L}{100}\right) \cdot \sigma_{loc} \right\} \quad \text{dB} \tag{61}$$

where:

- L_{b0p}: basic transmission loss not exceeded for *p*% time and 50% locations associated with line-of-sight with short term enhancements, given by equation (10)
- L_{bc}: basic transmission loss not exceeded for *p*% of time and 50% locations, including the effects of terminal clutter losses, given by equation (55)
- L_{loc}: median value of the location loss, as given by equations (59a) and (59b)
- $I(x)$: inverse complementary cumulative normal distribution as a function of probability, *x*. An approximation for $I(x)$ which may be used for $0.000001 \le x \le 0.999999$ is given in Appendix 3 to this Annex
- σ_{loc}: combined standard deviation (i.e. building entry loss and location variability), given by equations (60a) and (60b).

The percentage locations, p_L, can vary between 1% and 99%. This model is not valid for percentage locations less than 1% or greater than 99%.

4.11 The field strength exceeded for *p*% time and p_L% locations

The field strength normalized to 1 kW effective radiated power exceeded for *p*% time and 50% locations, E_p dB(μV/m), may be calculated using:

$$E_p = 199.36 + 20\log(f) - L_b \quad \text{dB(μV/m)} \tag{62}$$

where:

- L_b: basic transmission loss not exceeded for *p*% time and p_L% locations calculated by equation (61)
- f: required frequency (GHz).

Appendix 1
to Annex 1

Radio-meteorological data required for the prediction procedure

Figure 1 gives average annual values of ΔN as positive values in N-units/km.

FIGURE 1

Average annual values of ΔN, N-units/km

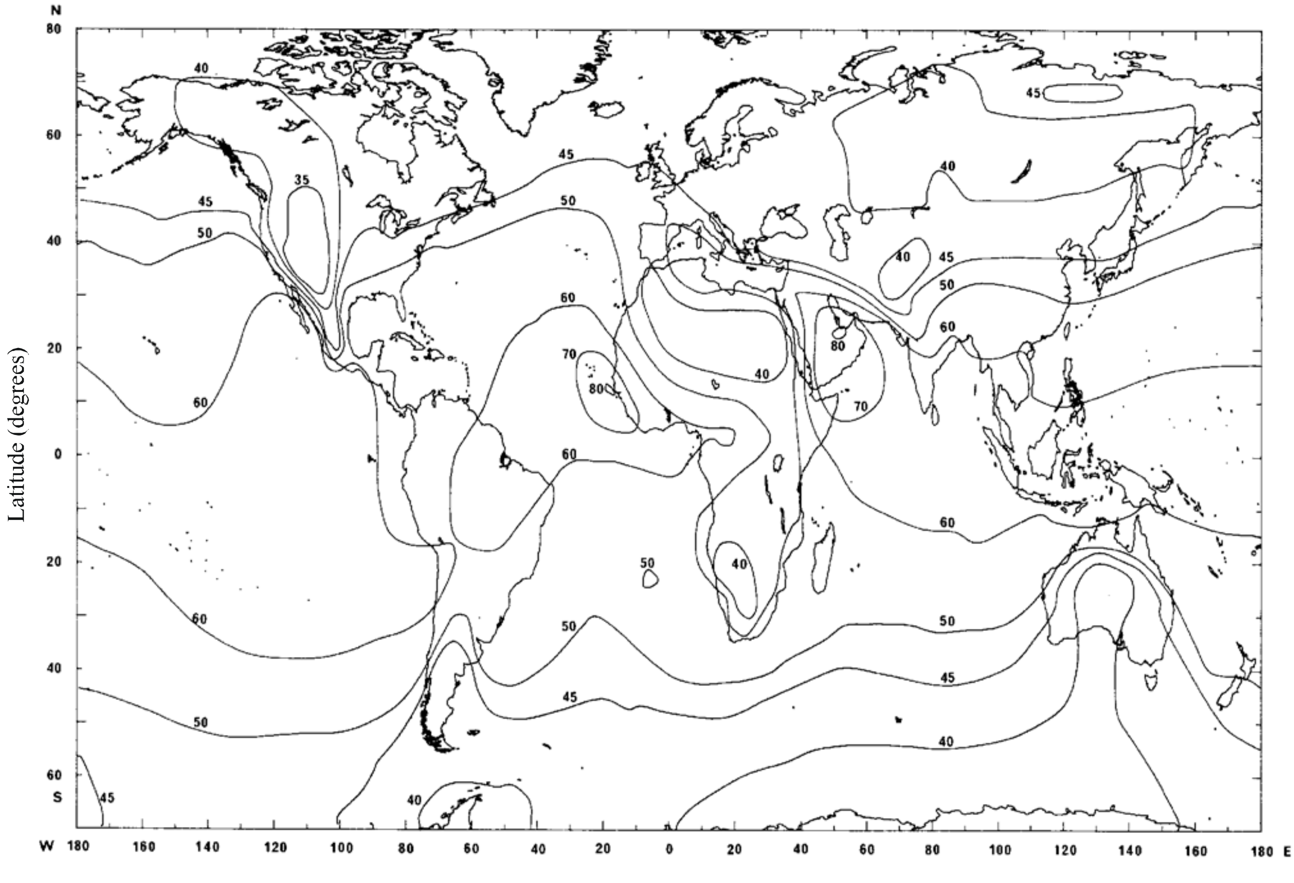
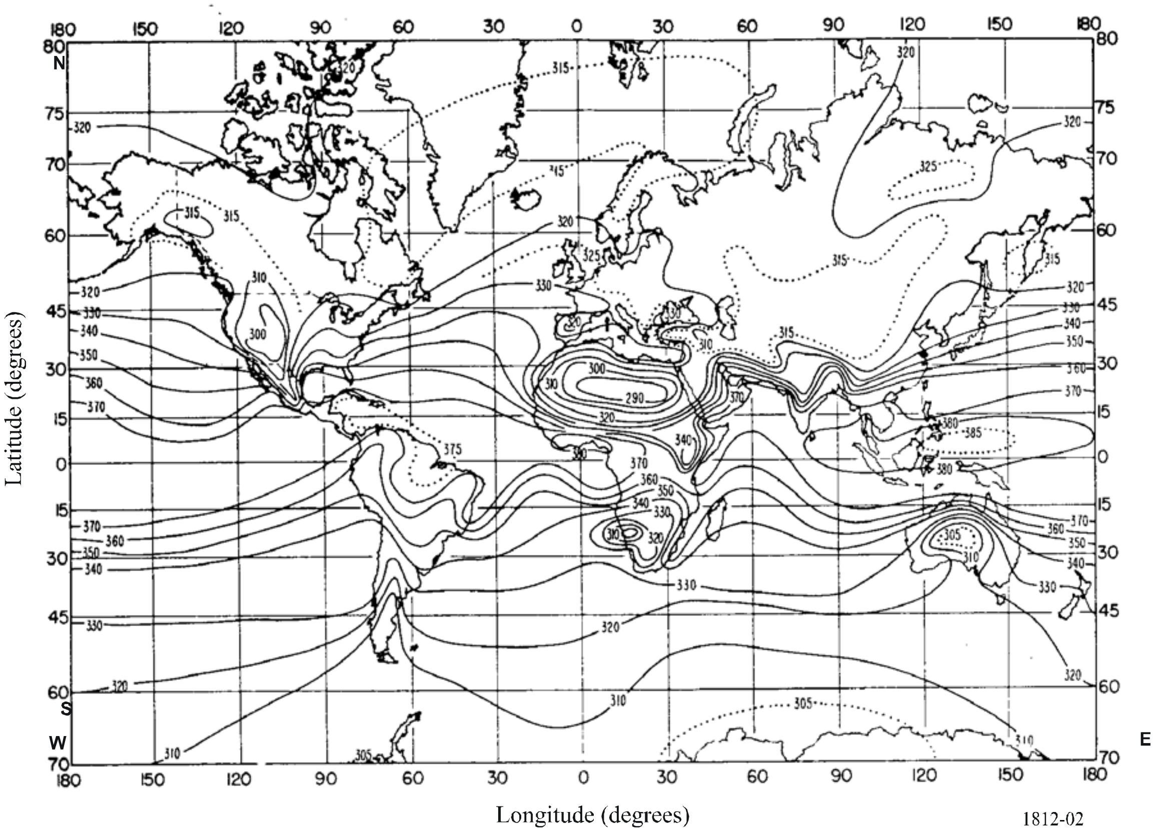


Figure 2 gives average annual values of sea-level surface refractivity, N_0, in N-units. Parameter N_0 is used only in the tropospheric-scatter part of the overall method.

FIGURE 2

Sea-level surface refractivity, N-units



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Appendix 2
to Annex 1

Path profile analysis

1 Introduction

For path profile analysis, a path profile of terrain heights above mean sea level is required. The parameters that need to be derived from the path profile analysis for the purposes of the propagation models are given in Table 7.

2 Construction of path profile

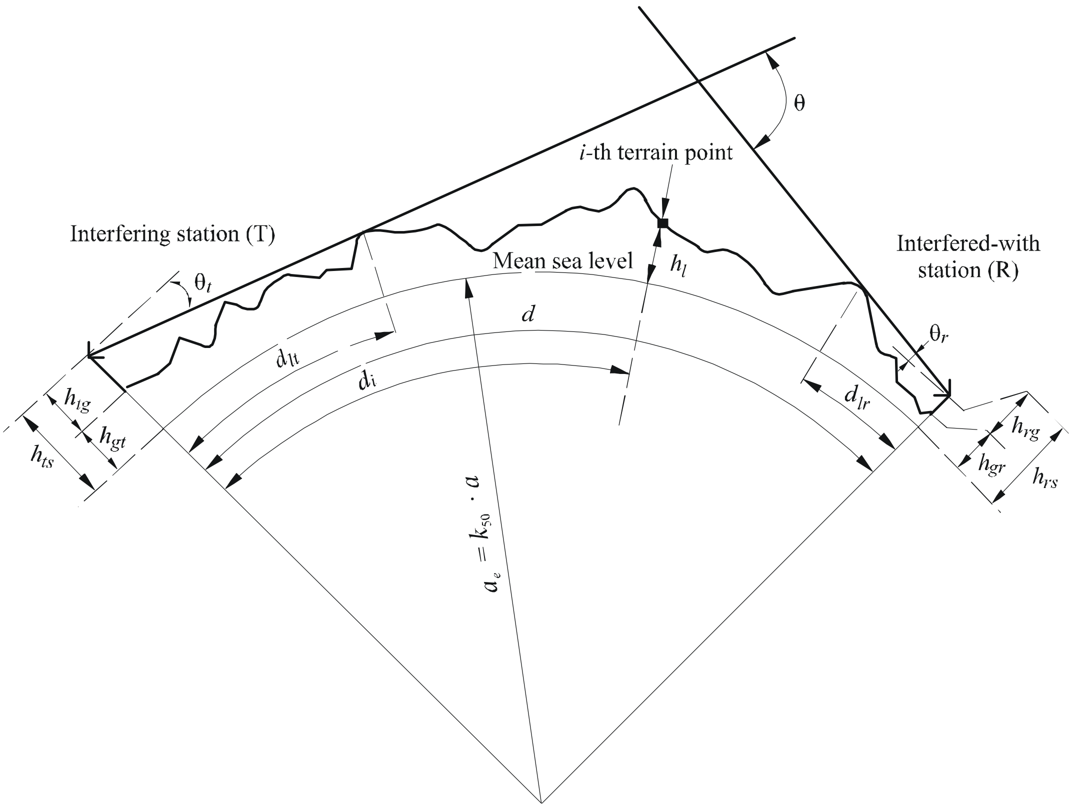
Based on the geographical coordinates of the transmitting (φ_t, ψ_t) and receiving (φ_r, ψ_r) stations, terrain heights (above mean sea level) along the great-circle path should be derived from a topographical database or from appropriate large-scale contour maps. The distance resolution of the profile should be as far as is practicable to capture significant features of the terrain. Typically, a distance increment of 30 m to 1 km is appropriate. In general, it is appropriate to use longer distance increments for longer paths. The profile should include the ground heights at the transmitting and receiving station locations as the start and end points. The equations of this section take Earth curvature into account where necessary, based on the value of a_e found in equation (7a).

Although equally spaced profile points are considered preferable, it is possible to use the method with non-equally spaced profile points. This may be useful when the profile is obtained from a digital map of terrain height contours. However, it should be noted that the Recommendation has been developed from testing using equally spaced profile points; information is not available on the effect of non-equally spaced points on accuracy.

For the purposes of this Recommendation the point of the path profile at the transmitting station is considered as point 1, and the point at the receiving station is considered as point n. The path profile therefore consists of n points. Figure 3 gives an example of a path profile of terrain heights above mean sea level, showing the various parameters related to the actual terrain.

FIGURE 3

Example of a (trans-horizon) path profile



Note 1 – The value of θ_t as drawn will be negative.

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Table 7 defines parameters used or derived during the path profile analysis.

TABLE 7

Path profile parameter definitions

Parameter	Description
a_e	Effective Earth's radius (km)
d	Great-circle path distance (km)
d_{ii}	Incremental distance for regular (i.e. equally spaced) path profile data (km)
f	Frequency (GHz)
λ	Wavelength (m)
h_{ts}	Transmitter antenna height (m) above mean sea level (amsl)
h_{rs}	Receiver antenna height (m) (amsl)
θ_t	For a trans-horizon path, horizon elevation angle above local horizontal (mrad), measured from the transmitting antenna. For a line-of-sight path this should be the elevation angle of the receiving antenna
θ_r	For a trans-horizon path, horizon elevation angle above local horizontal (mrad), measured from the receiving antenna. For a line-of-sight path this should be the elevation angle of the transmitting antenna
θ	Path angular distance (mrad)
h_{st}	Height of the smooth-Earth surface (amsl) at the transmitting station location (m)
h_{sr}	Height of the smooth-Earth surface (amsl) at the receiving station location (m)
h_i	Height of the *i*-th terrain point amsl (m) h_1: ground height of the transmitter h_n: ground height of receiver
h_m	Terrain roughness (m)
h_{te}	Effective height of transmitting antenna (m)
h_{re}	Effective height of receiving antenna (m)

3 Path length

The path length can be obtained using great-circle geometry from the geographical coordinates of the transmitting (φ_t, ψ_t) and receiving (φ_r, ψ_r) stations. Alternatively the path length can be found from the path profile. The path length, d (km), can be found from the path profile data:

$$d = d_n \qquad \text{km} \tag{63}$$

For regularly spaced path profile data it is also true that:

$$d_i = (i-1) \cdot d_{ii} \qquad \text{km} \tag{64}$$

for $i = 1, \ldots, n$, where d_{ii} is the incremental path distance (km).

4 Path classification

The path profile must be used to determine whether the path is line-of-sight or trans-horizon based on the median effective Earth's radius of a_e, as given by equation (7a).

A path is trans-horizon if the physical horizon elevation angle as seen by the transmitting antenna (relative to the local horizontal) is greater than the angle (again relative to the transmitter's local horizontal) subtended by the receiving antenna.

The test for the trans-horizon path condition is thus:

$$\theta_{max} > \theta_{td} \qquad \text{mrad} \tag{65}$$

where:

$$\theta_{max} = \max_{i=2}^{n-1} (\theta_i) \qquad \text{mrad} \tag{66}$$

θ_i: elevation angle to the i-th terrain point

$$\theta_i = \frac{h_i - h_{ts}}{d_i} - \frac{10^3 \, d_i}{2 \, a_e} \qquad \text{mrad} \tag{67}$$

where:

h_i: height of the i-th terrain point amsl (m)

h_{ts}: transmitter antenna height amsl (m)

d_i: distance from transmitter to the i-th terrain element (km)

$$\theta_{td} = \frac{h_{rs} - h_{ts}}{d} - \frac{10^3 \, d}{2 \, a_e} \qquad \text{mrad} \tag{68}$$

where:

h_{rs}: receiving antenna height amsl (m)

d: total great-circle path distance (km)

a_e: median effective Earth's radius appropriate to the path (see equation (7a)).

5 Derivation of parameters from the path profile

5.1 All paths

The parameters to be derived from the path profile are those contained in Table 7.

5.1.1 Transmitting antenna horizon elevation angle, θ_t

The transmitting antenna's horizon elevation angle is the maximum antenna horizon elevation angle when equation (66) is applied to the $n - 2$ terrain profile heights.

$$\theta_t = \max(\theta_{max}, \theta_{td}) \qquad \text{mrad} \tag{69}$$

with θ_{max} as determined in equation (66).

5.1.2 Transmitting antenna horizon distance, d_{lt}

The horizon distance is the minimum distance from the transmitter at which the maximum antenna horizon elevation angle is calculated from equation (66).

$$d_{lt} = d_i \qquad \text{km} \qquad \text{for } \max(\theta_i) \tag{70}$$

If no horizon is detected, then set $d_{lt} = d_{im50}$ (see § 4.3.1).

5.1.3 Receiving antenna horizon elevation angle, θ_r

If no horizon is detected ($\theta_t = \theta_{td}$), then set:

$$\theta_r = \frac{h_{ts} - h_{rs}}{d} - 10^3 \frac{d}{2a_e} \qquad \text{mrad} \qquad (71)$$

However, if a transmitter horizon is detected, then the receive antenna horizon elevation angle is the maximum antenna horizon elevation angle when equation (66) is applied to the $n - 2$ terrain profile heights.

$$\theta_r = \max_{j=2}^{n-1} (\theta_j) \qquad \text{mrad} \qquad (72)$$

$$\theta_j = \frac{h_j - h_{rs}}{d - d_j} - \frac{10^3 (d - d_j)}{2 a_e} \qquad \text{mrad} \qquad (72a)$$

5.1.4 Receiving antenna horizon distance, d_{lr}

The horizon distance is the minimum distance from the receiver at which the maximum antenna horizon elevation angle is calculated from equation (64).

$$d_{lr} = d - d_j \qquad \text{km} \qquad \text{for max } (\theta_j) \qquad (73)$$

If no horizon is detected, then set $d_{lr} = d - d_{im50}$ (see § 4.3.1).

5.1.5 Angular distance θ (mrad)

$$\theta = \frac{10^3 d}{a_e} + \theta_t + \theta_r \qquad \text{mrad} \qquad (74)$$

5.1.6 "Smooth-Earth" model and effective antenna heights

5.1.6.1 General

To determine the effective antenna heights, and to allow an appropriate assessment of the path roughness to be made, it is necessary to derive an effective "smooth-Earth" surface as a reference plane over which the irregular terrain of the path is deemed to exist. Once this is derived the values of the terrain roughness parameter (§ 5.1.6.4) and effective antenna heights for the transmitting and receiving stations can be obtained.

5.1.6.2 Exceptions

For straightforward "sea" paths, i.e. $\omega \geq 0.9$, and where both antenna horizons fall on the sea surface, the derivation of the smooth-Earth surface calculation can be omitted if required. In such case the reference plane can be taken to be a mean sea (or water) level over the whole path, the terrain roughness may be assumed to be 0 m, and the effective antenna heights are equal to the real heights above the sea surface.

For all other paths it is necessary to apply the smooth-Earth terrain approximation procedure detailed in § 5.1 and to derive the effective antenna heights and the terrain roughness as in § 5.1.6.4.

5.1.6.3 Deriving the smooth-Earth surface

Derive a straight line approximation to the terrain heights amsl of the form:

$$h_{si} = h_{st} + m \cdot d_i \qquad \text{m} \qquad (75)$$

where:

h_{si}: height amsl (m), of the least-squares fit surface at distance d_i (km) from the interference source

h_{st}: height amsl (m), of the smooth-Earth surface at the path origin, i.e. at the transmitting station

m: slope of the least-squares surface relative to sea level (m/km).

Alternative methods are available for the next two steps in the calculation. Equations (76a) and (77a) may be used if the profile points are equally spaced. Equations (76b) and (77b), which are more complicated, must be used if the profile points are not equally spaced, and may be used in either case.

For equally spaced profiles:

$$m = \frac{\sum_{i=1}^{n}(h_i - h_a)\left(d_i - \frac{d}{2}\right)}{\sum_{i=1}^{n}\left(d_i - \frac{d}{2}\right)^2} \quad \text{m/km} \tag{76a}$$

For any profile:

$$m = \left(\frac{1}{d^3}\right)\sum_{i=2}^{n} 3(d_i - d_{i-1})(d_i + d_{i-1} - d)(h_i + h_{i-1} - 2h_a) + (d_i - d_{i-1})^2 (h_i - h_{i-1}) \quad \text{m/km} \tag{76b}$$

where:

h_i: real height of the i-th terrain point amsl (m)

h_a: mean of the real path heights amsl from h_0 to h_n inclusive (m) given by:

For equally spaced profiles:

$$h_a = \frac{1}{n}\sum_{i=1}^{n} h_i \quad \text{m} \tag{77a}$$

For any profile a weighted mean is calculated:

$$h_a = \left(\frac{1}{2d}\right)\sum_{i=2}^{n}(d_i - d_{i-1})(h_i + h_{i-1}) \quad \text{m} \tag{77b}$$

The height of the smooth-Earth surface at the transmitting station, h_{st}, is then given by:

$$h_{st} = h_a - m\frac{d}{2} \quad \text{m} \tag{78}$$

and hence the height of the smooth-Earth surface at the receiving station, h_{sr}, is given by:

$$h_{sr} = h_{st} + m \cdot d \quad \text{m} \tag{79}$$

Correction must then be made if the smooth-Earth heights fall above the true ground height, i.e.:

$$h_{st} = \min\ (h_{st}, h_1) \quad \text{m} \tag{80a}$$

$$h_{sr} = \min\ (h_{sr}, h_n) \quad \text{m} \tag{80b}$$

If either or both of h_{st} or h_{sr} were modified by equations (80a) or (80b) then the slope, m, of the smooth-Earth surface must also be corrected:

$$m = \frac{h_{sr} - h_{st}}{d} \quad \text{m/km} \tag{81}$$

The terminal effective heights, h_{te} and h_{re}, are given by:

$$\begin{aligned} h_{te} &= h_{tg} + h_1 - h_{st} \quad \text{m} \\ h_{re} &= h_{rg} + h_n - h_{sr} \quad \text{m} \end{aligned} \tag{82}$$

5.1.6.4 Terrain roughness, h_m

The terrain roughness parameter, h_m (m) is the maximum height of the terrain above the smooth-Earth surface in the section of the path between, and including, the horizon points:

$$h_m = \max_{i=i_{lt}}^{i_{lr}} \left[h_i - (h_{st} + m \cdot d_i) \right] \quad \text{m} \tag{83}$$

where:

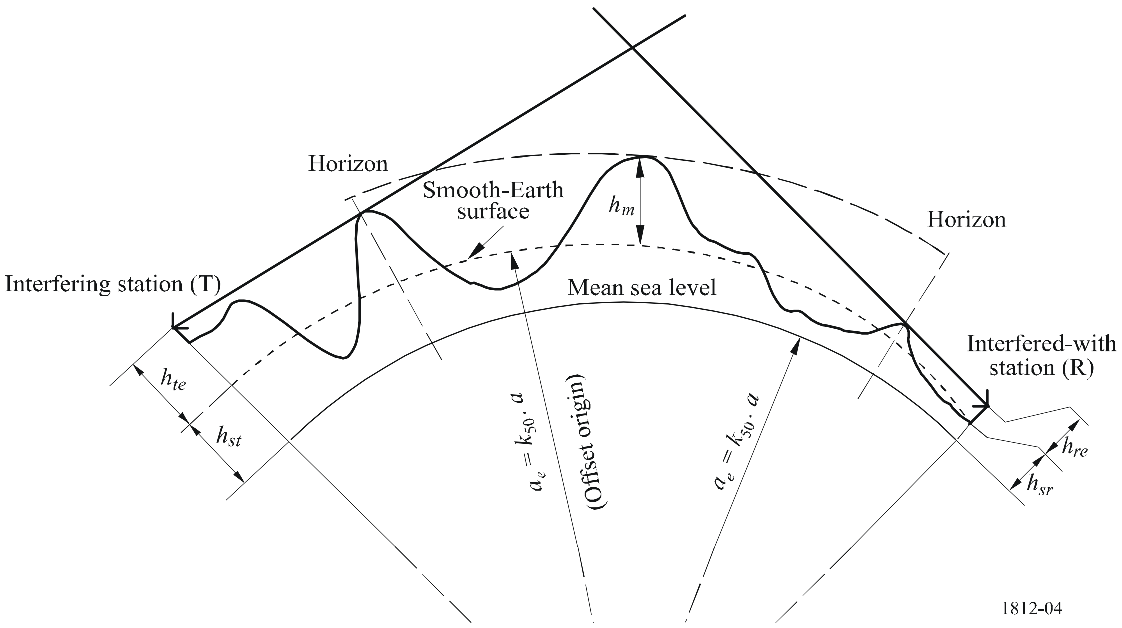
i_{lt}: index of the profile point at distance d_{lt} from the transmitter

i_{lr}: index of the profile point at distance d_{lr} from the receiver.

The smooth-Earth surface and the terrain roughness parameter h_m are illustrated in Fig. 4.

FIGURE 4

An example of the smooth-Earth surface and terrain roughness parameter



Appendix 3
to Annex 1

An approximation to the inverse complementary cumulative normal distribution function

The following approximation to the inverse complementary cumulative normal distribution function is valid for $0.000001 \leq x \leq 0.999999$ and is in error by a maximum of 0.00054. If $x < 0.000001$, which implies $\beta_0 < 0.0001\%$, x should be set to 0.000001. Similar considerations hold for $x > 0.999999$. This approximation may be used with confidence for the interpolation function in equations (30b) and (49) and in equation (61). For the latter equation, however, the value of x must be limited: $0.01 \leq x \leq 0.99$.

The function $I(x)$ is given by:

$$I(x) = T(x) - \xi(x) \qquad \text{for } 0.000001 \leq x \leq 0.5 \tag{84a}$$

and, by symmetry:

$$I(x) = \xi(1-x) - T(1-x) \qquad \text{for } 0.5 < x \leq 0.999999 \tag{84b}$$

where:

$$T(x) = \sqrt{[-2\ln(x)]} \tag{85a}$$

$$\xi(x) = \frac{[(C_2 \cdot T(x) + C_1) \cdot T(x)] + C_0}{[(D_3 \cdot T(x) + D_2) T(x) + D_1] T(x) + 1} \tag{85b}$$

$$C_0 = 2.515516698 \tag{85c}$$

$$C_1 = 0.802853 \tag{85d}$$

$$C_2 = 0.010328 \tag{85e}$$

$$D_1 = 1.432788 \tag{85f}$$

$$D_2 = 0.189269 \tag{85g}$$

$$D_3 = 0.001308 \tag{85h}$$