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Recommendation ITU-R P.528-5
(09/2021)

A propagation prediction method for aeronautical mobile and radionavigation services using the VHF, UHF and SHF bands

P Series

Radiowave propagation

International Telecommunication Union

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Note: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R P.528-5*, **

A propagation prediction method for aeronautical mobile and radionavigation services using the VHF, UHF and SHF bands

(Question ITU-R 203/3)

(1978-1982-1986-2012-2019-2021)

Scope

This Recommendation contains a method for predicting basic transmission loss in the frequency range 100 MHz to 30 GHz for aeronautical services. It provides a step-by-step method to compute the basic transmission loss. The only data needed for this method are the distance between antennas, the heights of the antennas above mean sea level, the frequency, the polarization, and the time percentage.

This Recommendation also gives the calculations for the expected protection ratio or wanted-to-unwanted signal ratio exceeded at the receiver for at least 95% of the time, $R(95)$. This calculation requires the following additional data for both the wanted and unwanted signals: the transmitted power, the gain of transmitting antenna, and the gain of receiving antenna.

The ITU Radiocommunication Assembly,

considering

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

b) that the propagation model given in Annex 2 is based on a considerable amount of experimental data (see Annex 1);

c) that the aeronautical service often provides a safety of life function and therefore requires a higher standard of availability than many other services;

d) that a time availability of 95% should be used to obtain more reliable service,

recommends

1 that the integral software in this Recommendation should be used to generate basic transmission loss values and curves for terminal heights, frequencies, and time percentages likely to be encountered in the aeronautical services;

2 that the following Notes should be regarded as part of this Recommendation.

NOTE 1 – It should be emphasized that the generated values are based on data obtained mainly for a continental temperate climate.

NOTE 2 – The method gives basic transmission loss, that is, the loss between ideal loss-free isotropic antennas. Where surface reflection multipath at the ground station or the facility has been mitigated using counterpoises or a directional vertical radiation pattern suitable antenna radiation patterns should be included within the analysis.

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* This Recommendation is brought to the attention of Study Group 5.

** Radiocommunication Study Group 3 made editorial amendments to this Recommendation in the year 2022 in accordance with Resolution ITU-R 1.

Annex 1

Development and application of the model

Transmission loss prediction methods have been developed that determine the basic transmission losses for time percentages from 1% to 99% of the time for antenna heights applicable to the aeronautical services. These methods are based on a considerable amount of experimental data, and extensive comparisons of predictions with data have been made. In performing these calculations, a smooth (terrain parameter $\Delta h = 0$) Earth with a mean annual global reference atmosphere was used. The atmospheric model relies on an exponential horizontal stratification of the atmosphere through which ray tracing is performed to account for ray bending due to changes in refractivity. Constants for average ground, isotropic antennas, and long-term power fading statistics for a continental temperate climate were also used. Although these parameters may be considered either reasonable or worst-case for many applications, the computed values should be used with caution if conditions differ drastically from those assumed.

With the exception of a region 'near' the radio horizon, values of median basic transmission loss for 'within-the-horizon' paths were obtained by adding the attenuation due to atmospheric absorption (in decibels) to the transmission loss corresponding to free-space conditions. Within the region 'near' the radio horizon, values of the transmission loss were calculated using geometric optics, to account for interference between the direct ray and a ray reflected from the surface of the Earth.

The two-ray interference model was not used exclusively for within-the-horizon calculations, because the lobing structure obtained from it for short paths is highly dependent on surface characteristics (roughness as well as electrical constants), atmospheric conditions (the effective earth radius is variable in time), and antenna characteristics (polarization, orientation and gain pattern). Such curves would often be more misleading than useful, because the detailed structure of the lobing is highly dependent on parameters that are difficult to determine with sufficient precision. However, the lobing structure is given statistical consideration in the calculation of variability.

For time availabilities other than 50%, the basic transmission loss, L_b, user-generated values do not always increase monotonically with distance. This occurs because variability changes with distance can sometimes overcome the median level changes. Variability includes contributions from both hourly-median or long-term power fading and within-the-hour or short-term phase interference fading. Both surface reflection and tropospheric multipath are included in the short-term fading. Long-term power fading statistics are based on a large amount of empirical data collected over extended periods of times at a diversity of locations and link geometries.

The basic transmission loss, $L_b(5)$ values may be used to estimate L_b values for an unwanted interfering signal that is exceeded during 95% (100% – 5%) of the time. Median (50%) propagation conditions may be estimated with the $L_b(50)$ values. The $L_b(95)$ values may be used to estimate the service range for a wanted signal at which service would be available for 95% of the time in the absence of interference.

The expected protection ratio or wanted-to-unwanted signal ratio exceeded at the receiver for at least 95% of the time, $R(95)$, can be estimated as follows:

$$R(95) = R(50) + Y_R(95) \qquad (1)$$

$$R(50) = [P_t + G_t + G_r - L_b(50)]_{Wanted} - [P_t + G_t + G_r - L_b(50)]_{Unwanted} \qquad (2)$$

and

$$Y_R = -\sqrt{[L_b(95) - L_b(50)]^2_{Wanted} + [L_b(5) - L_b(50)]^2_{Unwanted}} \qquad (3)$$

In equation (2), P_t is the transmitted power, and G_t and G_r are the isotropic gains of the transmitting and receiving antennas expressed in dB.

Additional variabilities could easily be included in equation (3) for such things as antenna gain when variabilities for them can be determined. Continuous (100%) or simultaneous channel utilization is implicit in the $R(95)$ formulation provided above so that the impact of intermittent transmitter operation should be considered separately.

The integral software to generate basic transmission loss values and curves is made available in the supplement file R-REC-P.528-5-202109-I!!ZIP-E.zip, with documentation. In addition, there are select tabulated basic transmission loss values also available in the supplement file.

Annex 2

Step by step method

This Annex uses the convention that variables describing the low terminal will be represented by the subscript '1' (i.e. the low terminal height h_{r1}) while variables for the high terminal will be represented by the subscript '2' (i.e. the high terminal height h_{r2}). In addition, the base letters of certain variables signify their reference:

– d, a great-circle distance measured along the surface of the Earth;

– r, a length as travelled by the ray between two points in space;

– h, a height measured above mean sea level;

– z, a radial measured from the centre of the Earth.

For the purposes of this Recommendation, the average Earth radius and mean sea level refer to the same reference surface.

1   Introduction

This Annex describes a step-by-step method for calculating the basic transmission loss for user-specified path, defined by:

–   terminal heights, h_{r1} and h_{r2}, in km above mean sea level, with $0.0015 \leq h_{r1,2} \leq 20$ (1.5 metres to 20 000 metres)

–   frequency, f, in MHz, with $100 \leq f \leq 30\,000$ MHz

–   time percentage, p, with $1 \leq p \leq 99$

–   great-circle distance, d, between the two terminals, in km

–   parameter indicating either horizontal or vertical linear polarization, T_{pol}.

For some aeronautical scenarios, link geometries are defined by the elevation angle of the low terminal to the high terminal (instead of by the great-circle distance between the terminals). It is
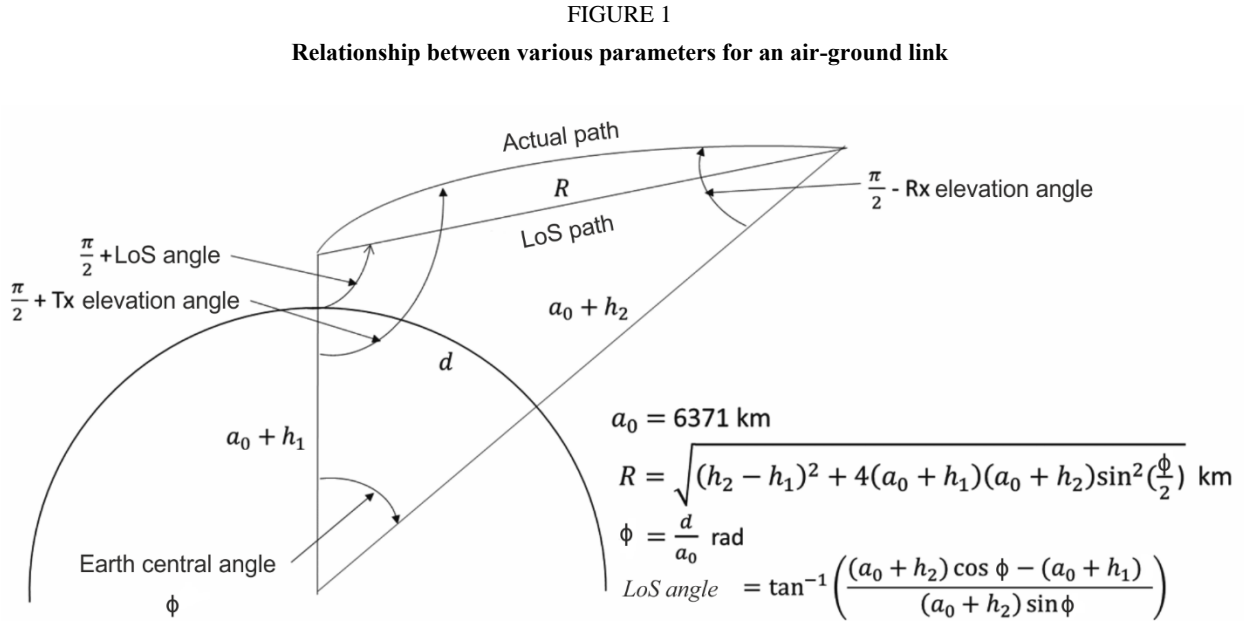
therefore useful to provide the following set of equations to convert from free space elevation angle, θ_{elev}, to great-circle distance, d, to facilitate the use of this Recommendation.

$$\phi = \arcsin\left(\frac{6371+h_{r1}}{6371+h_{r2}}\cos\theta_{elev}\right) \quad \text{(rad)} \tag{4}$$

$$\theta_{ca} = \frac{\pi}{2} - \theta_{elev} - \phi \quad \text{(rad)} \tag{5}$$

$$d = 6371\theta_{ca} \quad \text{(km)} \tag{6}$$

Figure 1 demonstrates the relationship between various parameters used in this Recommendation.

FIGURE 1

Relationship between various parameters for an air-ground link

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Note that ray bending effects on the actual path are exaggerated for effect.

2   Assumptions and definitions

Recommendation ITU-R P.528 assumes the following values:

a_0 :   average radius of the Earth. Set to 6 371 km

a_e :   effective radius of the Earth. Set to 9 257 km

ε_r :   relative dielectric constant. Set to 15 (corresponding to average ground)

σ :   conductivity. Set to 0.005 S/m (corresponding to average ground).

3   Step-by-step method

Step 3-1: Compute the parameters associated with each terminal. This requires using the steps presented in § 4 for both the low terminal and the high terminal. Once completed, proceed to Step 3-2. Use § 4 as follows:

given:

$h_{r1,2}$:   height of terminal above mean sea level, in km;

f: frequency, in MHz;

find:

$d_{r1,2}$:   great-circle distance to the terminal's smooth Earth horizon, in km;

$\theta_{r1,2}$:   incident angle of the grazing ray from the terminal's smooth Earth horizon, in rad;

$h_{e1,2}$:   effective height of the terminal, in km;

$\Delta h_{1,2}$:   terminal height correction term, in km;

$A_{a1,2}$:   median atmospheric absorption loss for the ray from the terminal to its smooth Earth horizon, in dB;

$r_{1,2}$:   length of the ray path from the terminal to its smooth Earth horizon, in km.

Step 3-2: Determine the maximum line-of-sight distance, d_{ML}, between the two terminals.

$$d_{ML} = d_{r1} + d_{r2} \quad \text{(km)} \tag{7}$$

Step 3-3: Smooth Earth diffraction is modelled linearly in this Recommendation. This is done by selecting two distances well beyond d_{ML}, computing the smooth Earth diffraction loss at these distances, and constructing a smooth Earth diffraction line that passes through both of these points.

Step 3-3.1: Compute two distances, d_3 and d_4, that are well beyond the maximum line-of-sight distance d_{ML} from equation (7).

$$d_3 = d_{ML} + 0.5(a_e^2/f)^{1/3} \quad \text{(km)} \tag{8}$$

$$d_4 = d_{ML} + 1.5(a_e^2/f)^{1/3} \quad \text{(km)} \tag{9}$$

Step 3-3.2: Compute the diffraction losses A_{d3} and A_{d4} at the corresponding distances d_3 and d_4. This will require using § 10 twice, once for each distance, $d_{3,4}$. Once completed, proceed to Step 3-3.3. Use the method in § 10 as follows:

given:

$d_{3,4}$:   the distance of interest, d_0, as required for § 10, in km;

$d_{r1,2}$:   great-circle distance to the smooth Earth horizon of the terminals, h_1 and h_2, in km, as determined in Step 3-1 above;

f :   frequency, in MHz;

T_{pol} :   parameter indicating either horizontal or vertical linear polarization;

find:

$A_{d3,4}$:   smooth Earth diffraction loss, A_d, in dB, corresponding to the distance $d_{3,4}$.

Step 3-3.3: Create the smooth Earth diffraction line from the two distances, d_3 and d_4, and their respective losses, A_{d3} and A_{d4}, by computing the slope M_d and intercept A_{d0}.

$$M_d = (A_{d4} - A_{d3})/(d_4 - d_3) \quad \text{(dB/km)} \tag{10}$$

$$A_{d0} = A_{d4} - M_d d_4 \quad \text{(dB)} \tag{11}$$

Step 3-3.4: Compute the diffraction loss at the distance d_{ML}.

$$A_{dML} = M_d d_{ML} + A_{d0} \quad \text{(dB/km)} \tag{12}$$

Step 3-3.5: Compute the distance, d_d, at which the diffraction model predicts 0 dB of loss.

$$d_d = -(A_{d0}/M_d) \quad \text{(km)} \tag{13}$$

Step 3-4: Determine if the propagation path is in the line-of-sight region or transhorizon for the desired distance d. If $d < d_{ML}$ the path is line-of-sight and go to Step 3-5. Else, the path is transhorizon and go to Steps 3-6 to 3-12.

Step 3-5: Refer to § 6 for the line-of-sight region calculations.

Step 3-6: In the transhorizon region ($d \geq d_{ML}$), as distance increases, the propagation path will begin with smooth Earth diffraction and transition into troposcatter. Physically, the models for smooth Earth diffraction and troposcatter need to be consistent at the transition point. Physical consistency implies there is no discontinuity at the transition point. Since the troposcatter model is non-linear, the following iterative process ensures that the transition between the two models occurs without discontinuity.

Step 3-6.1: Let d' and d'' be the iterative test distances and be initialized to:

$$d' = d_{ML} + 3 \quad \text{(km)} \tag{14}$$

$$d'' = d_{ML} + 2 \quad \text{(km)} \tag{15}$$

Step 3-6.2: Compute the troposcatter losses A'_s and A''_s at distances d' and d'' respectively. This requires using the steps presented in § 11 for both distances d' and d''. Use § 11 as follows:

given:

$\quad d$:   representing the distance of interest d' and d'', in km;

$\quad d_{r1,2}$:   great-circle distance to the terminal's smooth Earth horizon, in km;

$\quad f$:   frequency, in MHz;

$\quad h_{e1,2}$:   effective height of the terminal, in km;

find:

$\quad A_s$:   troposcatter losses corresponding to d' and d'' in dB

Step 3-6.3: Compute the slope, M_s, of the line containing the two troposcatter points (d', A'_s) and (d'', A''_s) from Step 3-6.2. This line is approximately tangent to the troposcatter model at distance d'.

$$M_s = \frac{A'_s - A''_s}{d' - d''} \quad \text{(dB/km)} \tag{16}$$

Step 3-6.4: Compare the slope M_s to the slope of the diffraction line, M_d, from equation (10). If $M_s > M_d$, then increase both d' and d'' by 1 km and return to Step 3-6.2 to continue iterating. Else, proceed to Step 3-6.5.

Step 3-6.5: The results of the troposcatter model are not valid if they are less than 20 dB. If either A'_s or A''_s is less than 20 dB, then increase both d' and d'' by 1 km and return to Step 3-6.2 to continue iterating. Else, proceed to Step 3-6.6.

Step 3-6.6: With $M_s \leq M_d$, the distance d' represents the approximate distance where either:

Case 1: The diffraction model is guaranteed to intersect the troposcatter model at some distance $\geq d'$ due to the submodel's behavior. The transhorizon region propagation loss is therefore physically consistent.

Case 2: The diffraction line is parallel to the tangent of the troposcatter model. However, the transhorizon region propagation loss may not physically consistent, i.e. there could be a potential discontinuity.

To determine which of the above cases is true, find the diffraction loss at distance d''.

$$A''_d = M_d d'' + A_{d0} \quad \text{(dB)} \tag{17}$$

If $A_s'' \geq A_d''$, then Case 1 in Step 3-6.6 is true and calculation proceeds to Step 3-7. Else, the slope of the diffraction line needs to be adjusted to the tangent point d', ensuring physical consistency of the transhorizon propagation model. The adjustment is done by pinning one end of the diffraction line at $(d_{ML}, A_{d_{ML}})$ and the other end at (d'', A_s''), then re-computing the new smooth Earth diffraction line.

$$M_d = \frac{A_s'' - A_{d_{ML}}}{d'' - d_{ML}} \quad \text{(dB/km)} \tag{18}$$

$$A_{d0} = A_s' - M_d d' \quad \text{(dB)} \tag{19}$$

At this point the transhorizon region is physically consistent. Proceed to Step 3-7.

Step 3-7: Compute, A_T, the loss not represented by free space loss and atmospheric absorption loss. This is determined based on the diffraction and troposcatter models, including any adjustments that were performed in Step 3-6.

Step 3-7.1: Compute the predicted smooth Earth diffraction loss, A_d, for the path distance d.

$$A_d = M_d d + A_{d0} \quad \text{(dB)} \tag{20}$$

Step 3-7.2: Compute the troposcatter loss, A_s, for the path distance d. Use § 7 as follows:

given:

d: great-circle path distance between the two terminals, in km;

$d_{r1,2}$: great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, in MHz;

$h_{e1,2}$: effective height of the terminals, in km ;

find:

A_s: troposcatter loss, in dB;

h_v: height to the common volume, in km;

θ_s: scattering angle, in rad.

Step 3-7.3: Select the loss value based on the following:

If $d < d'$ (with d' originating from the final iteration in Step 3-6), then:

$$A_T = A_d \quad \text{(dB)} \tag{21}$$

Else, depending on whether Case 1 or Case 2 was true in Step 3-6.6:

$$A_T = \begin{cases} \text{Min}(A_d, A_s), & \text{Case 1 is TRUE} \\ A_s, & \text{Case 2 is TRUE} \end{cases} \quad \text{(dB)} \tag{22}$$

Step 3-8: Use ray tracing, as defined in § 5, to determine the following:

given:

h_v: height to the common volume, in km, from Step 3-7.2;

f: frequency, in MHz;

find:

A_{av}: median atmospheric absorption loss for the ray path from the horizon to the common volume, in dB;

r_v: length of the ray path from the horizon to the common volume, in km.

Step 3-9: Compute the total median atmospheric absorption loss, A_a, in dB, for the path using the results from Step 3-1 and Step 3-8:

$$A_a = A_{a1} + A_{a2} + 2A_{av} \quad \text{(dB)} \tag{23}$$

Step 3-10: Compute the free space loss, A_{fs}, in dB, for the path:

$$r_{fs} = r_1 + r_2 + 2r_v \quad \text{(km)} \tag{24}$$

$$A_{fs} = 20 \log_{10} f + 20 \log_{10} r_{fs} + 32.45 \quad \text{(dB)} \tag{25}$$

Step 3-11: Compute the long-term variability loss, $Y(p)$, for the time percentage p. Use § 12. Then proceed to Step 3-12.

  Given:

  $h_{r1,2}$:   terminal heights above mean sea level, in km;

  d: great-circle path distance between terminals, in km;

  f: frequency, in MHz;

  p: time percentage;

  A_T :   loss from Step 3-7.3, in dB;

  θ_s: scattering angle from Step 3-7.2, in rad;

  find:

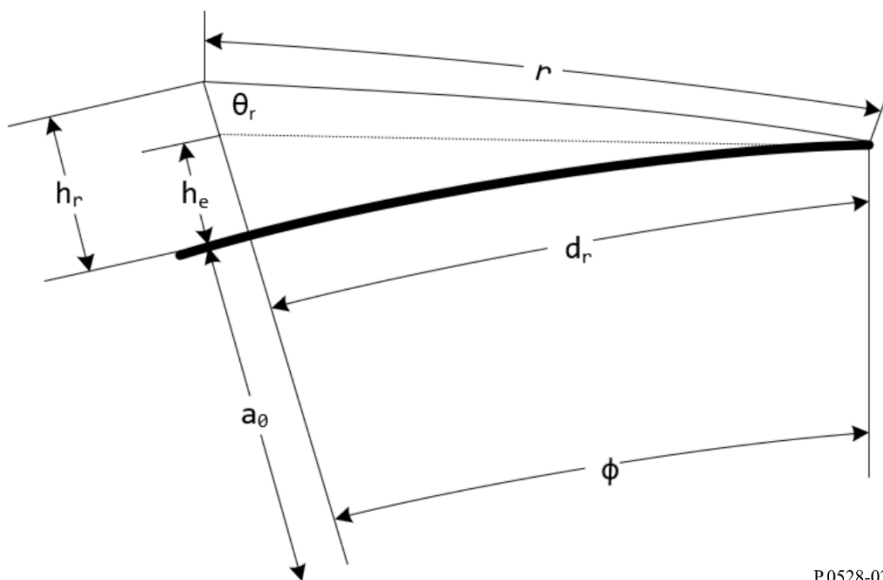 $Y(p)$:   Long-term variability loss, $Y_{total}(p)$, in dB.

Step 3-12: Compute the basic transmission loss, L_b, in dB.

$$L_b = A_{fs} + A_a + A_T + Y(p) \quad \text{(dB)} \tag{26}$$

This completes the step-by-step procedure for a transhorizon path for the given user defined input parameters.

4   Terminal parameters

FIGURE 2

Terminal geometry

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This section computes the following parameters associated with a terminal, as shown in Fig. 2.

Given:

h_r: terminal height above mean sea level, in km;

f: frequency, in MHz;

find:

d_r: great-circle distance to the terminal's smooth Earth horizon, in km;

θ_r: incident angle of the grazing ray from the terminal's smooth Earth horizon, in rad;

h_e: effective height of the terminal, in km;

Δh: terminal height correction term, in km;

A_a: median atmospheric absorption loss for the ray from the terminal to its smooth Earth horizon, in dB;

r: length of the ray path from the terminal to its smooth Earth horizon, in km.

Step 4-1: Use ray tracing, as defined in § 5, to determine the following:

given:

h_r: height of terminal above mean sea level, in km;

f: frequency, in MHz;

find:

d_r: great-circle distance to the terminal's smooth Earth horizon, in km;

θ_r: incident angle of the grazing ray from the terminal's smooth Earth horizon, in rad;

A_a: median atmospheric absorption loss for the ray from the terminal to its smooth Earth horizon, in dB;

r: length of the ray path from the terminal to its smooth Earth horizon, in km.

Step 4-2: Compute the terminal's effective height, h_e, in km

$$\phi = d_r/a_e \quad \text{(rad)} \tag{27}$$

$$h_e = \frac{a_e}{\cos \phi} - a_e \quad \text{(km)} \tag{28}$$

Step 4-3: Compute the terminal height correction term, Δh.

$$\Delta h = h_r - h_e \quad \text{(km)} \tag{29}$$

This concludes the section to compute the terminal parameters.

5 Ray tracing

Radio waves traveling through the atmosphere bend due to changes in the atmospheric refractivity. In traditional terrestrial models, this is normally accounted for using the standard "4/3 Earth" method, which models a linear atmospheric refractivity gradient and is a valid approximation for paths near the surface. However, the actual atmospheric gradient is exponential, and in air-to-ground propagation paths, the use of a linear model can incur substantial errors.

This Recommendation utilizes ray tracing techniques defined in Annex 1 of Recommendation ITU-R P.676-12 to compute the path of the ray through the atmosphere. The atmosphere is the mean annual global reference atmosphere defined in Recommendation ITU-R P.835-6.

Given:

h_r: terminal height above mean sea level, in km;

f: frequency, in MHz;

find:

d_r: great-circle distance to the terminal's smooth Earth horizon, in km;

θ_r: incident angle of the grazing ray from the terminal's smooth Earth horizon, in rad;

A_a: median atmospheric absorption loss for the ray from the terminal to its smooth Earth horizon, in dB;

r: length of the ray path from the terminal to its smooth Earth horizon, in km (designated as a in Recommendation ITU-R P.676-12);

τ: bending angle of the ray path (designated as *bending* in Recommendation ITU-R P.676-12).

Step 5-1: Using Annex 1 of Recommendation ITU-R P.676-12, trace a grazing ray ($\beta = \pi/2$) from the surface of the Earth to the terminal height h_r.

During the ray tracing process, compute the total bending angle of the ray τ (referred to as *bending* in Recommendation ITU-R P.676-12), the atmospheric absorption of the ray path, A_a, and the length of the ray path, r (referred to as a in Recommendation ITU-R P.676-12).

Step 5-2: Compute the incidence angle, θ_r, of the ray upon the terminal. Step 5-1 results in a final angle of α_i, which is relative to zenith.

$$\theta_r = \frac{\pi}{2} - \alpha_i \quad \text{(rad)} \tag{30}$$

Step 5-3: Compute the great-circle distance along the surface of the Earth between the terminal and its smooth Earth horizon by using the central angle ϕ.

$$\phi = \theta_r + \tau \quad \text{(rad)} \tag{31}$$

$$d_r = \phi a_0 \quad \text{(km)} \tag{32}$$

This completes the section on ray tracing.

6   Line-of-sight region

This section describes the steps to compute the propagation loss for a line-of-sight path.

Given:

d_{ML}:   maximum line-of-sight distance, in km, from equation (7);

d_d: distance at which diffraction model predicts 0 dB of loss, in km, from equation (13);

$h_{e1,2}$:   effective height of the terminals, in km;

$d_{r1,2}$:   great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, in MHz;

A_{dML}:   diffraction loss at distance d_{ML}, in dB, from equation (12);

p: time percentage;

d: great-circle path distance between terminals, in km;

find:

L_b: basic transmission loss, in dB;

K: value used in later variability calculations.

Step 6-1: Compute the wavelength, λ.

$$\lambda = 0.2997925/f \quad \text{(km)} \tag{33}$$

Step 6-2: Determine ψ_{limit}, the reflecting angle corresponding to the distance at which $\Delta r = \lambda/2$, where Δr is the difference in ray length between the direct and indirect ray. To determine ψ_limit, apply the ray optics method described in § 7 in a reoccurring manner to perform a binary search for the value of ψ_{limit}. Update the value of ψ_{limit} based on the relationship that an increase in ψ results in an increase in Δr. Use § 7 as follows:

given:

ψ :   ray reflection angle, in rad;

$h_{r1,2}$:   terminal heights above mean sea level, in km;

$\Delta h_{1,2}$:   terminal height correction terms, in km;

find:

Δr: ray length distance between the direct ray and the indirect ray, in km;

d: great-circle path distance between the terminals for a reflecting angle of ψ , in km.

Step 6-3: Determine $d_{\lambda\backslash 6}$, the distance at which the difference in path lengths between the direct and reflected wave is $\lambda/6$ metres. As in Step 6-2, determine this distance by applying the ray optics method described in § 7 in a reoccurring manner to perform a binary search of ψ. Use § 7 as follows:

given:

ψ :   ray reflection angle, in rad;

$h_{r1,2}$:   terminal heights above mean sea level, in km;

$\Delta h_{1,2}$:   terminal height correction terms, in km;

find:

$d_{\lambda\backslash 6}$:   great-circle distance between the terminals corresponding to a reflection angle of ψ, in km.

Step 6-4: Determine the distance d_0, in km.

If $d \geq d_d$ or $d_d \geq d_{ML}$,

$$d_o = \begin{cases} d_1, & d > d_{\lambda/6} \text{ or } d_{\lambda/6} > d_{ML} \\ d_{\lambda/6}, & else \end{cases} \quad \text{(km)} \tag{34}$$

Else if $d_d < d_{\lambda/6}$ and $d_{\lambda/6} < d_{ML}$,

$$d_o = \begin{cases} d_{\lambda/6}, & d_d < d_{\lambda/6} \text{ and } d_{\lambda/6} < d_{ML} \\ d_d, & else \end{cases} \quad \text{(km)} \tag{35}$$

Step 6-5: The current value of d_0 can be a course approximation for certain paths. In order to tune it, iteratively convert the distance into a reflection angle ψ using Step 6-3 and compute the ray optics as defined in § 7. If the resulting d from § 7 is greater than or equal to the original d_0, or if increasing the distance 1 metre causes it to be beyond d_{ML}, use the ray optics output distance as the value for d_0. Else, increase the distance by 1 meter and re-compute the ray optics method.

Step 6-6: Compute the line-of-sight loss at the distance d_0. First again apply § 7 to determine the value of ψ_{d0}. Then use § 8 to determine the loss, A_{d0}.

Step 6-7: Convert the desired distance d into its corresponding reflection angle ψ by applying § 7 in a reoccurring manner. Let the final resulting ray optics distance be called d_{ro}.

Step 6-8: Use §§ 7 and 8 to compute the line-of-sight loss. Then proceed to Step 6-11. Use §§ 7 and 8 as follows:

given:

ψ: ray reflection angle, in rad;

$h_{r1,2}$:   terminal heights above mean sea level, in km;

$\Delta h_{1,2}$:   terminal height correction terms, in km;

find:

Δr: ray length distance between the direct ray and the indirect ray, in km;

d: distance between the terminals corresponding to a reflection angle of ψ, in km.

Step 6-9: Compute the median atmospheric absorption loss, A_a, for the path by applying Annex 1 of Recommendation ITU-R P.676. Trace the ray from the low terminal to the high terminal using θ_{h1} as the elevation angle (taking care to note that θ_{h1} is referenced from the terminal's horizontal, while Recommendation ITU-R P.676 is referenced from zenith). The angle θ_{h1} is from equation (53) computed during Step 6-8. During the ray trace, also compute the total length of the ray, r_{LOS}, in km.

Step 6-10: Compute the free space loss, A_{fs}, in dB.

$$A_{fs} = 20 \log_{10} r_{LOS} + 20 \log_{10} f + 32.45 \quad \text{(dB)} \tag{36}$$

Step 6-11: Compute the contribution of variability to the total loss. Use § 13 to compute Y_{total}. Then proceed to Step 6-12. Use § 13 as follows:

given:

$h_{r1,2}$:   terminal heights above mean sea level, in km;

d: great-circle path distance between terminals, in km;

f: frequency, in MHz;

p: time percentage;

find:

$Y(p)$:   long-term variability loss, in dB.

Step 6-12: Compute the basic transmission loss.

$$A = A_{fs} + A_a + A_{LOS} + Y(p) \quad \text{(dB)} \tag{37}$$

Step 6-13: The statistics associated with variability in Recommendation ITU-R P.528 represent the expected changes in signal level over time. These statistics can be treated as independent from the statistics related to clutter loss as described in Recommendation ITU-R P.2108. Therefore, if one end of a link is within man-made clutter, as described and required by Recommendation ITU-R P.2108, the clutter loss method and its corresponding statical distribution of signal loss described in § 3.3 of Recommendation ITU-R P.2108 can be combined with the statistical results of Recommendation ITU-R P.528.

If losses resulting from clutter are desired, compute the value of L_{ces} as described in § 3.3 of Recommendation ITU-R P.2108, using the value of θ_{h1} (from equation (53)) as the elevation angle. The resulting L_{ces} can then be added to the result of equation (37).

This completes the step-by-step procedure for a line-of-sight path for the given user defined input parameters.

7   Line-of-sight ray optics

This section describes how to perform the geometric path parameters for two terminals within line-of-sight distance of each other using ray optics.

The inputs for this section are:

ψ: ray reflection angle, in rad;

$h_{r1,2}$:   terminal heights above mean sea level, in km;

$\Delta h_{1,2}$:   terminal height correction terms, in km;

The output for this section is:

Δr: ray length distance between the direct ray and the indirect ray, in km;

d: great-circle distance between the terminals for a reflection angle of ψ, in km.

Step 7-1: Compute the adjusted earth radius, a_a:

$$z = (a_0/a_e) - 1 \tag{38}$$

$$k_a = 1/(1 + z \cos \psi) \tag{39}$$

$$a_a = a_0 k_a \quad \text{(km)} \tag{40}$$

Step 7-2: Compute the adjusted earth terminal height correction terms, $\Delta h_{a1,2}$.

$$\Delta h_{a1,2} = \Delta h_{1,2}(a_a - a_0)/(a_e - a_o) \quad \text{(km)} \tag{41}$$

Step 7-3: Compute the heights, $H_{1,2}$.

$$H_{1,2} = h_{r1,2} - \Delta h_{a1,2} \quad \text{(km)} \tag{42}$$

Step 7-4: Compute the terminal geometric parameters $z_{1,2}$, $\theta_{1,2}$, $D_{1,2}$, and $H'_{1,2}$.

$$z_{1,2} = a_a + H_{1,2} \quad \text{(km)} \tag{43}$$

$$\theta_{1,2} = \arccos\left(a_a \cos \psi / z_{1,2}\right) - \psi \quad \text{(rad)} \tag{44}$$

$$D_{1,2} = z_{1,2} \sin \theta_{1,2} \quad \text{(km)} \tag{45}$$

$$H'_{1,2} = \begin{cases} H_{1,2}, & \psi > 1.56 \\ D_{1,2} \tan \psi, & \psi \le 1.56 \end{cases} \quad \text{(km)} \tag{46}$$

Step 7-5: Compute Δz, the difference in the terminal radials.

$$\Delta z = |z_1 - z_2| \quad \text{(km)} \tag{47}$$

Step 7-6: Compute the path distance between the two terminals for a reflection angle of ψ.

$$d = \max(a_a(\theta_1 + \theta_2), 0) \quad \text{(km)} \tag{48}$$

Step 7-7: With the geometric parameters computed, determine the length of the direct ray, r_0, and the indirect ray, r_{12}.

$$\alpha = \arctan((H'_2 - H'_1)/(D_1 + D_2)) \quad \text{(rad)} \tag{49}$$

$$r_0 = \max(\Delta z, (D_1 + D_2)/\cos \alpha) \quad \text{(km)} \tag{50}$$

$$r_{12} = (D_1 + D_2)/\cos \psi \quad \text{(km)} \tag{51}$$

Step 7-8: Compute the difference in length between the two rays.

$$\Delta r = 4\, H_1' H_2' / (r_0 + r_{12}) \quad \text{(km)} \tag{52}$$

Step 7-9: Compute the angles $\theta_{h1,2}$.

$$\theta_{h1} = \alpha - \theta_1 \quad \text{(rad)} \tag{53}$$

$$\theta_{h2} = -(\alpha + \theta_2) \quad \text{(rad)} \tag{54}$$

This completes this section.

8   Line-of-sight loss calculations

This section describes how to compute the loss calculations for a line-of-sight path.

Given:

d: path distance of interest, in km;

ψ: ray reflection angle, in rad;

d_0:   path distance at which diffraction begins to affect the line-of-sight region, in km (from Step 6-5);

f: frequency, in MHz;

find:

A_{LOS}:   line-of-sight loss, in dB.

Step 8-1: If the path distance, d, is greater than d_0, then the path is within the LOS-Diffraction blending region and the loss A_{LOS} is determined using equation (55) and this section is completed. Else, $d \leq d_0$ and proceed to Step 8-2.

$$A_{LOS} = ((d - d_0)(A_{dML} - A_{d0})/(d_{ML} - d_0)) + A_{d0} \quad \text{(dB)} \tag{55}$$

Step 8-2: Using ψ_{limit}, from Step 6-2, if the reflection angle $\psi > \psi_{limit}$, then set $A_{LOS} = 0$ dB and this section is completed, as Recommendation ITU-R P.528 does not consider a 2-ray model within this region. Else, $\psi \leq \psi_{limit}$ and proceed to Step 8-3.

Step 8-3: The path length d, is such that Recommendation ITU-R P.528 uses a 2-ray model. Compute the wavelength, λ.

$$\lambda = 0.2997925/f \quad \text{(km)} \tag{56}$$

Step 8-4: Compute the complex reflection coefficients, R_g and ϕ_g using § 9.

Step 8-5: The divergence factor, D_v, takes into account that a reflection from a smooth curved Earth surface is less efficient than from a flat Earth. Compute the divergence factor for the path, using $D_{1,2}$ from equation (45).

$$r_{1,2} = D_{1,2}/\cos\psi \quad \text{(km)} \tag{57}$$

$$R_r = (r_1 r_2)/r_{1,2} \quad \text{(km)} \tag{58}$$

$$D_v = \left[1 + \frac{2R_r(1+\sin^2\psi)}{a_a \sin\psi} + \left(\frac{2R_r}{a_a}\right)^2 \right]^{-1/2} \tag{59}$$

Step 8-6: The ray length factor, F_r, takes into account geometries in which the direct ray is significantly of larger magnitude (and shorter distance) than the indirect ray, such as when both terminals are high and close in the case of two aircraft. Compute F_r, with r_{12} from equation (51):

$$F_r = \min(r_0/r_{12},\ 1) \tag{60}$$

Step 8-7: Compute the effective reflection coefficients R_{Tg} and ϕ_{Tg}.

$$R_{Tg} = R_g D_v F_r \tag{61}$$

$$\phi_{Tg} = (2\,\pi\Delta r/\lambda) + \phi_g \tag{62}$$

Step 8-8: Compute the loss, A_{LOS}.

$$R = R_{Tg} \cos \phi_{Tg} - R_{Tg} \sin \phi_{Tg} \tag{63}$$

$$W_{RL} = \min(|1 + R|, 1) \tag{64}$$

$$W_{R0} = W_{RL}^2 \tag{65}$$

$$A_{LOS} = 10 \log_{10} W_{R0} \tag{66}$$

This completes this section.

9   Ground reflection coefficients

This section describes the steps taken to compute the ground reflection coefficients.

Given:

  ψ: reflection angle, in rad;

  f: frequency, in MHz;

  T_{pol}: parameter indicating either horizontal or vertical linear polarization;

find:

  R_g: real part of the reflection coefficient;

  ϕ_g: imaginary part of the reflection coefficient.

With the previously stated assumptions for the electrical properties of the ground of $\sigma = 0.005$ S/m and $\varepsilon_r = 15$ (corresponding to average ground).

Step 9-1: Compute the following values,

$$X = 18\,000\,\sigma/f \tag{67}$$

$$Y = \epsilon_r - \cos^2 \psi \tag{68}$$

$$T = [Y^2 + X^2]^{0.5} + Y \tag{69}$$

$$P = (0.5T)^{0.5} \tag{70}$$

$$Q = X/2P \tag{71}$$

Step 9-2: Compute B and A based on the polarization parameter, T_{pol},

$$B = \begin{cases} 1/(P^2 + Q^2), & \text{horizontal} \\ (\epsilon^2 + X^2)/(P^2 + Q^2), & \text{vertical} \end{cases} \tag{72}$$

$$A = \begin{cases} 2P/(P^2 + Q^2), & \text{horizontal} \\ (2(P\epsilon + QX))/(P^2 + Q^2), & \text{vertical} \end{cases} \tag{73}$$

Step 9-3: Compute the real and imaginary parts of the reflection coefficient.

$$R_g = \left[\left((1 + B \sin^2 \psi) - A \sin \psi \right) \big/ \left((1 + B \sin^2 \psi) + A \sin \psi \right) \right]^{0.5} \tag{74}$$

$$\alpha = \begin{cases} \text{arctan2}(-Q, \sin \psi - P), & \text{horizontal} \\ \text{arctan2}\big((\epsilon \sin \psi) - Q, \epsilon \sin \psi - P\big), & \text{vertical} \end{cases} \tag{75}$$

$$\beta = \begin{cases} \arctan2(Q, \sin\psi + P), & \text{horizontal} \\ \arctan2((X\sin\psi) + Q, \epsilon\sin\psi + P), & \text{vertical} \end{cases} \tag{76}$$

$$\phi_g = \alpha - \beta \tag{77}$$

This concludes this section.

10   Smooth Earth diffraction

This section describes the steps taken to compute the smooth Earth diffraction loss at a specified distance within the diffraction region. The model assumes an "average ground" with a conductivity of 0.005 S/m (σ) and a relative dielectric constant of 15 (ε_r).

Given:

d_0: path distance of interest, in km;

$d_{r1,2}$: great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, in MHz;

T_{pol}: parameter indicating either horizontal or vertical linear polarization;

find:

A_d: smooth Earth diffraction loss, in dB.

Smooth Earth diffraction is computed using equation (78):

$$A_d = G(x_0) - F(x_1) - F(x_2) - 20 \quad \text{(dB)} \tag{78}$$

Step 10-1: Compute the term K, depending on the polarization parameter, T_{pol}.

$$s = 18\,000\,\sigma/f \tag{79}$$

$$K = \begin{cases} 0.01778\,f^{-1/3}[(\varepsilon_r - 1)^2 + s^2]^{-1/4}, & \text{horizontal} \\ 0.01778 f^{-1/3}\left[\dfrac{\varepsilon_r^2 + s^2}{\sqrt{(\varepsilon_r - 1)^2 + s^2}}\right]^{1/2}, & \text{vertical} \end{cases} \tag{80}$$

Step 10-2: Compute the normalized distances.

$$x_{0,1,2} = (1.607 - K)f^{1/3}d_{0,1,2} \quad \text{(km)} \tag{81}$$

Step 10-3: Compute the distance-dependent term for all three normalized distances.

$$G(x_{0,1,2}) = 0.05751x_{0,1,2} - 10\log_{10}x_{0,1,2} \quad \text{(dB)} \tag{82}$$

Step 10-4: Compute the term $y_{1,2}$.

$$y_{1,2} = 40\log_{10}x_{1,2} - 117 \quad \text{(dB)} \tag{83}$$

Step 10-5: Compute the height functions.

If $x_{1,2} \geq 2\,000$ km:

$$F(x_{1,2}) = G(x_{1,2}) \quad \text{(dB)} \tag{84}$$

Else if $200 < x_{1,2} < 2\,000$ km:

$$W_{1,2} = 0.0134x_{1,2}e^{(-0.005x_{1,2})} \tag{85}$$

$$F(x_{1,2}) = W_{1,2}y_{1,2} + (1 - W_{1,2})G(x_{1,2}) \quad \text{(dB)} \tag{86}$$

Else, $x \leq 200$.

$$x_t = 450/-(\log_{10}K)^3 \quad \text{(km)} \tag{87}$$

$$F(x_{1,2}) = \begin{cases} \begin{cases} y_{1,2}, & \text{abs}(y_{1,2}) < 117 \\ -117, & \text{Else} \end{cases}, & x_{1,2} \geq x_t \\ 20 \log K - 15 + (0.000025 \, x_{1,2}^2/K), & x_{1,2} \leq x_t \end{cases} \quad \text{(dB)} \tag{88}$$

Step 10-6: With $G(x_0)$ and $F(x_{1,2})$ computed, use equation (78) to compute the smooth Earth diffraction loss.

This completes this section.

11 Troposcatter

This section describes the steps taken to compute the troposcatter for a given distance. The computation of troposcatter loss is performed using mathematical techniques that consider the curved ray paths bounding the common volume of the two terminals. Troposcatter is computed using equation (89) (described below).

$$A_s = S_e + S_V + 10 \, \log_{10}(\kappa \theta_s^3/\ell) \quad \text{(dB)} \tag{89}$$

given:

$d_{r1,2}$:   great-circle distance to the terminal's smooth Earth horizon, in km;

$h_{e1,2}$:   effective terminal heights, in km;

f: frequency, in MHz;

d: path distance of interest, in km;

find:

A_s: troposcatter loss, in dB;

h_v: height to the common volume, in km;

θ_s: scattering angle, in rad.

Step 11-1: Compute the scatter distance, d_s, in km.

$$d_s = d - d_{r1} - d_{r2} \quad \text{(km)} \tag{90}$$

Step 11-2: If $d_s = 0$, there is no common volume in the path geometry and thus propagation via troposcatter is not supported. Set the below results and go to Step 3-7.3 in § 3. Else $d_s > 0$ and continue to Step 11-3.

$$A_s = 0 \quad \text{(dB)} \tag{91}$$

$$h_v = 0 \quad \text{(km)} \tag{92}$$

$$\theta_s = 0 \quad \text{(rad)} \tag{93}$$

Step 11-3: The smooth Earth distance from each terminal's grazing ray to the centre of the common volume, d_z, is:

$$d_z = 0.5d_s \quad \text{(km)} \tag{94}$$

Step 11-4: Compute the atmospheric gradient parameters:

$$A_m = 1/a_0 \tag{95}$$

$$dN = A_m - 1/a_e \tag{96}$$

$$\Gamma_e = N_s \times 10^{-6}/ dN \tag{97}$$

Step 11-5: The following equations are used to determine the geometric parameters associated with troposcatter, including the height of the common volume, h_v, in km, and the ray slopes at the cross-over angle, θ_A, in radians.

$$z_a = \frac{1}{2a_e}\left(\frac{d_z}{2}\right)^2 \quad \text{(km)} \tag{98}$$

$$z_b = \frac{1}{2a_e}(d_z)^2 \quad \text{(km)} \tag{99}$$

$$Q_o = A_m - dN \tag{100}$$

$$Q_{a,b} = A_m - dN * e^{-z_{a,b}/\gamma_e} \tag{101}$$

$$z_a' = (7Q_o + 6Q_a - Q_b)\frac{d_z^2}{96} \quad \text{(km)} \tag{102}$$

$$z_b' = (Q_o + 2Q_a)\frac{d_z^2}{6} \quad \text{(km)} \tag{103}$$

$$Q_{A,B} = A_m - dN * e^{-z_{a,b}'/\gamma_e} \tag{104}$$

$$h_v = (Q_o + 2Q_A)\frac{d_z^2}{6} \quad \text{(km)} \tag{105}$$

$$\theta_A = (Q_o + 4Q_A + Q_B)\frac{d_z}{6} \quad \text{(rad)} \tag{106}$$

$$\theta_s = 2\,\theta_A \quad \text{(rad)} \tag{107}$$

Step 11-6: Compute the scattering efficiency term, S_e.

$$\epsilon_1 = (5.67 \times 10^{-6})N_s^2 - 0.00232N_s + 0.031 \tag{108}$$

$$\epsilon_2 = 0.0002N_s^2 - 0.06N_s + 6.6 \tag{109}$$

$$\gamma = 0.1424\left(1 + \frac{\epsilon_1}{\exp[(h_v/4)^6]}\right) \tag{110}$$

$$S_e = 83.1 - \frac{\epsilon_2}{1+0.07716h_v^2} + 20\log_{10}[(0.1424/\gamma)^2 e^{\gamma h_v}] \quad \text{(dB)} \tag{111}$$

Step 11-7: Compute the scattering volume term, S_V.

$$X_{A1,2} = h_{1,2}^2 + 4(a_e + h_{1,2})a_e \sin^2\left(\frac{d_{1,2}}{2a_e}\right) \tag{112}$$

$$\ell_{1,2} = \sqrt{X_{A1,2}} + d_z \quad \text{(km)} \tag{113}$$

$$\ell = \ell_1 + \ell_2 \quad \text{(km)} \tag{114}$$

$$s = \frac{\ell_1 - \ell_2}{\ell} \tag{115}$$

$$\eta = \gamma\theta_s\ell/2 \tag{116}$$

$$\kappa = f/0.0477 \tag{117}$$

$$\rho_{1,2} = 2\,\kappa\,\theta_s h_{1,2} \quad \text{(km)} \tag{118}$$

$$S_V = 10\log_{10}\left(\frac{(A\eta^2 + B_s\eta)q_1q_2}{\rho_1^2\rho_2^2} + C_S\right) \quad \text{(dB)} \tag{119}$$

where:

$$X_{v1} = (1 + s)^2\eta \tag{120}$$

$$X_{v2} = (1 - s)^2\eta \tag{121}$$

$$q_1 = X_{v1}^2 + \rho_1^2 \tag{122}$$

$$q_2 = X_{v2}^2 + \rho_2^2 \tag{123}$$

$$A = (1 - s^2)^2 \tag{124}$$

$$B_S = 6 + 8s^2 + (8(1-s)X_{v1}^2\rho_1^2)/q_1^2 + (8(1+s)X_{v2}^2\rho_2^2)/q_2^2 + 2(1-s^2)(1 + 2X_{v1}^2/q_1)(1 + 2X_{v2}^2/q_2) \tag{125}$$

$$C_S = 12 \left(\frac{\rho_1 + \sqrt{2}}{\rho_1}\right)^2 \left(\frac{\rho_2 + \sqrt{2}}{\rho_2}\right)^2 \left(\frac{\rho_1 + \rho_2}{\rho_1 + \rho_2 + 2\sqrt{2}}\right) \tag{126}$$

Step 11-8: Compute the troposcatter loss using equation (89).

This completes this section.

12   Total variability for transhorizon paths

This section defines how to compute the total contribution of variability to the median basic transmission loss for a transhorizon path.

Given:

$h_{r1,2}$:   terminal heights above mean sea level, in km;

p: time percentage;

f: frequency, MHz;

d: great-circle path distance between terminals, in km;

A_T: loss predicted by either diffraction or troposcatter, in dB;

θ_s: the scattering angle, in rad;

find:

$Y_{total}(p)$:   total variability loss, in dB.

Step 12-1: Compute the contribution of long-term variability for the time percentage p by using § 14. Then proceed to Step 12-2. Use § 14 as follows:

given:

$h_{r1,2}$:   terminal heights above mean sea level, in km;

d: great-circle path distance between terminals, in km;

$d_{r1,2}$:   great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, MHz;

p: time percentage;

$f_{\theta h}$:   set to the value $f_{\theta h} = 1$;

A_T: loss predicted by either diffraction or troposcatter, in dB;

find:

$Y_e(p)$:   long term variability loss, in dB.

Step 12-2: In order to correctly combine the effects of long-term variability and tropospheric multipath, both of which are distributions, the mean value of the long-term variability distribution is required. Compute the contribution of long term variability for time percentage 50 by using § 14. Then proceed to Step 12-3. Use § 14 as follows:

given:

$h_{r1,2}$:   terminal heights above mean sea level, in km;

d: great-circle path distance between terminals, in km;

$d_{r1,2}$: great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, MHz;

50: the mean time percentage ($p = 50$);

$f_{\theta h}$: set to the value $f_{\theta h} = 1$;

A_T: loss predicted by either diffraction or troposcatter, in dB;

find:

$Y_e(50)$: long term variability loss, in dB.

Step 12-3: In order to smoothly transition the effects of tropospheric multipath from the line-of-sight region to the transhorizon region, the value of K, from which tropospheric multipath is determined, should be determined at transition point between line-of-sight and non-line-of-sight. Compute the line-of-sight loss calculations, as described in § 6. Then proceed to Step 12-4. Use § 6 as follows:

given:

d_{ML}: maximum line-of-sight distance, in km;

d_d: distance at which diffraction model predicts 0 dB of loss, in km, from equation (13);

$h_{r1,2}$: height of terminal above mean sea level, in km;

$d_{1,2}$: great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, in MHz;

A_{dML}: diffraction loss at distance d_{ML}, in dB;

p: time percentage;

d: path distance of interest;

find:

A: basic transmission loss, in dB;

K_{LOS}: value used in later variability calculations.

Step 12-4: Compute the value K_t which is used to determine the effects of tropospheric multipath. Let $\theta_{1.5} = 0.02617993878$ radians (1.5 degrees).

$$K_t = \begin{cases} 20, \theta_s \geq \theta_{1.5} \\ K_{LOS}, \theta_s \leq 0 \\ (\theta_s(20 - K_{LOS})/\theta_{1.5}) + K_{LOS}, 0 < \theta_s < \theta_{1.5} \end{cases} \quad (127)$$

Step 12-5: Compute the contribution of tropospheric multipath for time percentage p using § 15. Then proceed to Step 12-6. Use § 15 as follows:

given:

K_t: value K_{LOS}

p: time percentage

find:

$Y_\pi(p)$: contribution of tropospheric multipath at time percentage p, in dB.

Step 12-6: Combine the effects long-term variability with tropospheric multipath to get the total variability contribution, $Y_{total}(p)$, using the previously computed values $Y_e(p)$, $Y_e(50)$, and $Y_\pi(p)$. The mean of tropospheric multipath is $Y_\pi(50) = 0$.

$$Y_{total}(50) = Y_e(50) + Y_\pi(50) \quad (128)$$

$$Y = [(Y_e(p) - Y_e(50))^2 + (Y_\pi(p) - Y_\pi(50))^2]^{0.5} \tag{129}$$

$$Y_{total} = \begin{cases} Y_{total}(50) + Y, \ p < 50 \\ Y_{total}(50) - Y, \ p \geq 50 \end{cases} \quad \text{(dB)} \tag{130}$$

This completes this section.

13 Total variability for line-of-sight paths

This section defines how to compute the contribution of variability to the median basic transmission loss.

Given:

$h_{r1,2}$: height of terminal above mean sea level, in km;

p: time percentage;

f: frequency, MHz;

d: great-circle path distance between terminals, in km;

A_{LOS}: loss predicted, in dB;

θ_s: the scattering angle, in radians;

$f_{\theta h}$: input value;

find:

$Y_{total}(p)$: Total variability loss, in dB.

Step 13-1: Compute the value $f_{\theta h}$ using the value of θ_{h1} from the ray optics calculations previously.

$$f_{\theta h} = \begin{cases} 1, \theta_{h1} \leq 0 \\ 0, \theta_{h1} \geq 1 \\ \max(0.5 - (1/\pi) \arctan(20 \log_{10}(32 \, \theta_{h1})), 0), \text{else} \end{cases} \tag{131}$$

Step 13-2: Compute the contribution of long-term variability for the time percentage p by using § 14. Then proceed to Step 13-3. Use § 14 as follows:

given:

$h_{r1,2}$: height of terminal above mean sea level, in km;

d: great-circle path distance between terminals, in km;

$d_{r1,2}$: great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, MHz;

p: time percentage;

$f_{\theta h}$: input value to this section;

A_{LOS}: loss predicted, in dB;

find:

$Y_e(p)$: long term variability loss, in dB.

Step 13-3: In order to correctly combine the effects of long-term variability and tropospheric multipath, both of which are distributions, the mean value of the long-term variability distribution is required. Compute the contribution of long-term variability for time percentage 50 by using § 14. Then proceed to Step 13-4. Use § 14 as follows:

given:

$h_{r1,2}$: height of terminal above mean sea level, in km;

d: great-circle path distance between terminals, in km;

$d_{r1,2}$:   great-circle distance to the terminal's smooth Earth horizon, in km;

f: frequency, MHz;

50:      the mean time percentage ($p = 50$);

$f_{\theta h}$:   input value to this section;

A_{LOS}:   loss predicted, in dB;

find:

$Y_e(50)$:   Long-term variability loss, in dB.

Step 13-4: Compute the following value of K_{LOS}, used for determining the effects of tropospheric multipath, using A_Y from equation (166) and R_{Tg} from equation (61), as follows:

$$F_{AY} = \begin{cases} 1, A_Y \leq 0 \\ 0.1, A_Y \geq 9 \\ (1.1 + 0.9\cos(\pi A_Y / 9))/2\,, \text{else} \end{cases} \tag{132}$$

$$F_{\Delta r} = \begin{cases} 1, \Delta r \geq \lambda/2 \\ 0.1, \Delta r \leq \lambda/6 \\ 0.5[1.1 - 0.9\cos((3\pi/\lambda)\,(\Delta r - \lambda/6))\,]\,, \text{else} \end{cases} \tag{133}$$

$$R_S = R_{Tg} F_{\Delta r} F_{AY} \tag{134}$$

Compute the value of $Y_\pi(99)$, as:

$$Y_\pi(99) = 10\log_{10}(f\,r_{LOS}^3) - 84.26 \quad \text{(dB)} \tag{135}$$

where r_{LOS} is the ray length path computed during the ray trace between the line-of-sight terminals.

Then use Table 5 to interpolate for the value of K corresponding to $Y_\pi(99)$, and use that value K to compute W_a as:

$$W_a = 10^{0.1K} \tag{136}$$

With W_a computed, complete the computation of K_{LOS} as:

$$W_R = R_S^2 + 0.01^2 \tag{137}$$

$$W = W_R + W_a \tag{138}$$

$$K_{LOS} = \begin{cases} 0, \ W \leq 0 \\ 10\log_{10} W\,, \ W > 0 \end{cases} \tag{139}$$

Step 13-5: Compute the contribution of tropospheric multipath for time percentage p using § 15. Then proceed to Step 13-6. Use § 15 as follows:

given:

K: value set as K_{LOS};

p: time percentage;

find:

$Y_\pi(p)$:   contribution of tropospheric multipath at time percentage p, in dB.

Step 13-6: Combine the effects of long-term variability with tropospheric multipath to get the total variability contribution, $Y_{total}(p)$, using the previously computed values $Y_e(p)$, $Y_e(50)$, and $Y_\pi(p)$. The mean of tropospheric multipath is $Y_\pi(50) = 0$.

$$Y_{total}(50) = Y_e(50) + Y_\pi(50) \tag{140}$$

$$Y = [(Y_e(p) - Y_e(50))^2 + (Y_\pi(p) - Y_\pi(50))^2]^{0.5} \tag{141}$$

$$Y_{total} = \begin{cases} Y_{total}(50) + Y, & p < 50 \\ Y_{total}(50) - Y, & p \geq 50 \end{cases} \quad \text{(dB)} \tag{142}$$

This completes this section.

14 Long-term variability

This section describes the steps taken to compute the statistical distribution of long-term variability for the desired time percentage, p. Long-term variability utilizes a normalized effective distance, d_e, which is a function of the terminal smooth Earth horizon distances and a frequency-dependent distance[1]. This section relies on statistical parameters that are based on long-term empirical measurement data.

Given:

$h_{r1,2}$: height of terminal above mean sea level, in km;

$d_{r1,2}$: great-circle distance to the terminal's smooth Earth horizon, in km;

p: time percentage;

f: frequency, MHz;

d: great-circle path distance between terminals, in km;

$f_{\theta h}$: constant or previously calculated parameter, depending on the type of path;

$A_{T,LOS}$: loss predicted by either Line-of-Sight, Diffraction, or Troposcatter submodels (previously calculated), in dB;

find:

$Y_e(p)$: long term variability loss, in dB.

Note: The inverse complementary cumulative normal distribution function, $Q^{-1}(q)$, is used in various places in this section. A technique to approximate its value for this step-by-step procedure is included in Recommendation ITU-R P.1057. The function $Q^{-1}(q)$ is defined such that $q = p/100$.

Step 14-1: Compute d_e, the effective distance in kilometres between the two terminals.

$$d_{qs} = 65(100/f)^{1/3} \quad \text{(km)} \tag{143}$$

$$d_{Lq} = d_{r1} + d_{r2} \quad \text{(km)} \tag{144}$$

$$d_q = d_{Lq} + d_{qs} \quad \text{(km)} \tag{145}$$

$$d_e = \begin{cases} (130\,d)/d_q, & d \leq d_q \\ 130 + d - d_q, & d > d_q \end{cases} \quad \text{(km)} \tag{146}$$

Step 14-2: Compute g_{10} and g_{90}.

$$g_{10} = \begin{cases} 0.21\sin(5.22\log_{10}(f/200)) + 1.28, & f \leq 1600 \\ 1.05, & f > 1600 \end{cases} \tag{147}$$

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[1] The previous method for calculating long-term variability statistics relied on an effective Earth with a surface refractivity value of 329 N-Units. Investigation and testing showed that utilizing the mean annual global reference atmosphere in these calculated produced nearly identical results and provided a more physical description of the methods being described.

$$g_{90} = f(x) = \begin{cases} 0.18 \sin(5.22 \log_{10}(f/200)) + 1.23, & f \le 1600 \\ 1.05, & f > 1600 \end{cases} \tag{148}$$

Step 14-3: Compute $V(50)$, $Y_0(10)$, and $Y_0(90)$ using the below equations and the values from Table 1.

TABLE 1

Values to compute long term variability equations

	$V(50)$	$Y_0(10)$	$Y_0(90)$
c_1	1.59e-5	5.25e-4	2.93e-4
c_2	1.56e-11	1.57e-6	3.75e-8
c_3	2.77e-8	4.70e-7	1.02e-7
n_1	2.32	1.97	2.00
n_2	4.08	2.31	2.88
n_3	3.25	2.90	3.15
f_∞	0.0	5.4	3.2
f_m	3.9	10.0	8.2

$$f_2 = f_\infty + (f_m - f_\infty) \exp\left(-c_2 d_e^{n_2}\right) \tag{149}$$

$$\left. \begin{array}{l} V(50) \\ Y_0(10) \\ Y_0(90) \end{array} \right\} = \left[c_1 d_e^{n_1} - f_2 \right] \exp\left(-c_3 d_e^{n_3}\right) + f_2 \quad \text{(dB)} \tag{150}$$

Step 14-4: Compute $Y_e(p)$, the variability associated with long-term (hour-to-hour) power fading, based on the desired time percentage, p.

If $p = 50$, then:

$$Y_p = V(50) \quad \text{(dB)} \tag{151}$$

If $p > 50$, then:

$$z_{90} = Q^{-1}(90/100) \tag{152}$$

$$z_p = Q^{-1}(p/100) \tag{153}$$

$$c_p = z_p/z_{90} \tag{154}$$

$$Y = c_p(-Y_0(90)g_{90}) \quad \text{(dB)} \tag{155}$$

$$Y_p = Y + V(50) \quad \text{(dB)} \tag{156}$$

If $p < 50$, then additional steps should be taken. If $p \ge 10$, then:

$$z_{10} = Q^{-1}(10/100) \tag{157}$$

$$z_p = Q^{-1}(p/100) \tag{158}$$

$$c_p = z_p/z_{10} \tag{159}$$

$$Y = c_p(Y_0(10)g_{10}) \quad \text{(dB)} \tag{160}$$

$$Y_p = Y + V(50) \quad \text{(dB)} \tag{161}$$

Else, $1 \le p < 10$. Use Table 2 of values to linearly interpolate c_p from p. Then apply equations (160) and (161) to get Y_p.

TABLE 2

Low probability values for c_p

p	c_p
10	1.000 0
5	1.326 5
2	1.716 6
1	1.950 7

Step 14-5: Compute Y_{10}, the variability associated with long-term (hourly) power fading for $p = 10$.

$$Y_{10} = (Y_0(10)g_{10}) + V(50) \quad \text{(dB)} \tag{162}$$

Step 14-6: Compute $Y_{eI}(p)$ and $Y_{eI}(10)$.

$$Y_{eI}(p) = f_{\theta h} \, Y_p \quad \text{(dB)} \tag{163}$$

$$Y_{eI}(10) = f_{\theta h} Y_{10} \quad \text{(dB)} \tag{164}$$

Step 14-7: Compute A_Y, which is used to prevent available signal powers from exceeding levels expected for free-space propagation by an unrealistic amount when the variability around the median is large and near its free-space level.

$$A_{YI} = Y_{eI}(10) - A_T - 3 \quad \text{(dB)} \tag{165}$$

$$A_Y = \max(A_{YI}, 0) \quad \text{(dB)} \tag{166}$$

Step 14-8: If $p \geq 10$, compute the total variability loss, completing this section. Else, proceed to Step 14-9 and continue.

$$Y_e(p) = Y_{eI}(p) - A_Y \quad \text{(dB)} \tag{167}$$

Step 14-9: For time percentages less than 10%, an additional correction may be required. Compute the value Y_{temp}.

$$Y_{temp} = Y_{eI}(p) - A_Y - A_{T,LOS} \quad \text{(dB)} \tag{168}$$

Step 14-10: Use Table 3 to linearly interpolate c_{Yp} from p.

TABLE 3

Low probability correction values

p	c_{Yp}
10	0.00
5	−3.70
2	−4.50
1	−5.00

Step 14-11: Compute the total variability loss.

$$Y_e(p) = \begin{cases} -c_{Yp} + A_{T,LOS}, & Y_{temp} > -c_{Yp} \\ Y_{temp} + A_{T,LOS}, & \text{else} \end{cases} \tag{169}$$

This concludes the long term variability section.

15 Tropospheric multipath

This section describes how to compute the contribution to the total variability due to tropospheric multipath.

Given:

K: input parameter;

p: time percentage;

find:

$Y_\pi(p)$: contribution of tropospheric multipath at time percentage p, in dB.

This section utilizes tabular data of the Nakagami-Rice distribution. Table 4 presents the data for $p < 50$ and Table 5 presents the data for $p > 50$. For all values of $p = 50$, $Y_\pi(p) = 0$ dB.

TABLE 4

Low time percentage values for the Nakagami-Rice distribution

K	$Y_\pi(1)$	$Y_\pi(2)$	$Y_\pi(5)$	$Y_\pi(10)$	$Y_\pi(15)$	$Y_\pi(20)$	$Y_\pi(30)$	$Y_\pi(40)$
−40	−0.1417	−0.1252	−0.1004	−0.0784	−0.0634	−0.0515	−0.0321	−0.0155
−25	−0.7676	−0.6811	−0.5497	−0.4312	−0.3504	−0.2856	−0.1790	−0.0870
−20	−1.3183	−1.1738	−0.9524	−0.7508	−0.6121	−0.5003	−0.3151	−0.1537
−18	−1.6263	−1.4507	−1.1805	−0.9332	−0.7623	−0.6240	−0.3940	−0.1926
−16	−1.9963	−1.7847	−1.4573	−1.1557	−0.9462	−0.7760	−0.4916	−0.2410
−14	−2.4355	−2.1829	−1.7896	−1.4247	−1.1695	−0.9613	−0.6113	−0.3007
−12	−2.9491	−2.6507	−2.1831	−1.7455	−1.4375	−1.1846	−0.7567	−0.3737
−10	−3.5384	−3.1902	−2.6407	−2.1218	−1.7535	−1.4495	−0.9307	−0.4619
−8	−4.1980	−3.7974	−3.1602	−2.5528	−2.1180	−1.7565	−1.1345	−0.5662
−6	−4.9132	−4.4591	−3.7313	−3.0306	−2.5247	−2.1011	−1.3655	−0.6855
−4	−5.6559	−5.1494	−4.3315	−3.5366	−2.9578	−2.4699	−1.6150	−0.8154
−2	−6.3810	−5.8252	−4.9219	−4.0366	−3.3871	−2.8364	−1.8638	−0.9455
0	−7.0247	−6.4249	−5.4449	−4.4782	−3.7652	−3.1580	−2.0804	−1.0574
2	−7.5229	−6.8862	−5.8424	−4.8090	−4.0446	−3.3927	−2.2344	−1.1347
4	−7.8532	−7.1880	−6.0963	−5.0145	−4.2145	−3.5325	−2.3227	−1.1774
6	−8.0435	−7.3588	−6.2354	−5.1234	−4.3022	−3.6032	−2.3656	−1.1975
20	−8.2238	−7.5154	−6.3565	−5.2137	−4.3726	−3.6584	−2.3979	−1.2121

TABLE 5

High time percentage values for the Nakagami-Rice distribution

K	$Y_\pi(60)$	$Y_\pi(70)$	$Y_\pi(80)$	$Y_\pi(85)$	$Y_\pi(90)$	$Y_\pi(95)$	$Y_\pi(98)$	$Y_\pi(99)$
−40	0.0156	0.0323	0.0518	0.0639	0.0791	0.1016	0.1271	0.1441
−25	0.0878	0.1828	0.2953	0.3651	0.4537	0.5868	0.7390	0.8420
−20	0.1564	0.3269	0.5308	0.6585	0.8218	1.0696	1.3572	1.5544
−18	0.1969	0.4127	0.6722	0.8355	1.0453	1.3660	1.7417	2.0014
−16	0.2478	0.5209	0.8519	1.0615	1.3326	1.7506	2.2463	2.5931
−14	0.3114	0.6573	1.0802	1.3505	1.7028	2.2526	2.9156	3.3872
−12	0.3903	0.8281	1.3698	1.7198	2.1808	2.9119	3.8143	4.4714
−10	0.4874	1.0404	1.7348	2.1898	2.7975	3.7820	5.0373	5.9833
−8	0.6045	1.2999	2.1887	2.7814	3.5868	4.9288	6.7171	8.1319
−6	0.7415	1.6078	2.7374	3.5059	4.5714	6.4060	8.9732	11.0973
−4	0.8935	1.9530	3.3611	4.3363	5.7101	8.1216	11.5185	14.2546
−2	1.0458	2.2979	3.9771	5.1450	6.7874	9.6276	13.4690	16.4251
0	1.1723	2.5755	4.4471	5.7363	7.5266	10.5553	14.5401	17.5511
2	1.2535	2.7446	4.7144	6.0581	7.9073	11.0003	15.0270	18.0526
4	1.2948	2.8268	4.8377	6.2021	8.0724	11.1869	15.2265	18.2566
6	1.3130	2.8619	4.8888	6.2610	8.1388	11.2607	15.3047	18.3361
20	1.3255	2.8855	4.9224	6.2992	8.1814	11.3076	15.3541	18.3864

Step 15-1: Using Tables 4 and 5, linearly interpolate to determine $Y_\pi(p)$ for the desired values K and p. Remember that $Y_\pi(0) = 0$.

This concludes this section.

Annex 3

Experimental results

Propagation tests at 930 MHz were conducted on air-to-ground paths in Japan in November 1982 and April and June 1983. According to the test results, propagation losses within line-of-sight agreed well with free space values. The line-of-sight distance as calculated from the measured data at an altitude of 10 000 m was shorter than the distance implied.