



Recommendation ITU-R P.528-4
(08/2019)

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

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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.528-4*, **

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)

Scope

This Recommendation contains a method for predicting basic transmission loss in the frequency range 125 MHz to 15.5 GHz for aeronautical and satellite 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, 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, $R(0.95)$. 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 0.95 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.

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

** Radiocommunication Study Group 3 made editorial amendments to this Recommendation in the year 2020 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 an effective earth radius factor k of 4/3 (surface refractivity $N_s = 301$) was used along with compensation for the excessive ray bending associated with the $k = 4/3$ model at high altitudes. Constants for average ground horizontal polarization, 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, i.e. 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 0.50, 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.

The basic transmission loss, $L_b(0.05)$ 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 $L_b(0.50)$ values. The $L_b(0.95)$ 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, $R(0.95)$, can be estimated as follows:

$$R(0.95) = R(0.50) + Y_R(0.95) \quad (1)$$

$$R(0.50) = [P_t + G_t + G_r - L_b(0.50)]_{Wanted} - [P_t + G_t + G_r - L_b(0.50)]_{Unwanted} \quad (2)$$

and

$$Y_R = - \sqrt{[L_b(0.95) - L_b(0.50)]_{Wanted}^2 + [L_b(0.05) - L_b(0.50)]_{Unwanted}^2} \quad (3)$$

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 $R(0.95)$ 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 zip file R-REC-P.528-4-201908-I!!ZIP-E.zip, with documentation. In addition, there are select tabulated basic transmission loss values also available in the supplement zip file.

Annex 2

Step by step method

This Annex uses the convention that variables describing the low terminal will be represented with the subscript '1' (i.e. the low terminal height h_{r1}) while variables for the high terminal will be represented with the subscript '2' (i.e. the high terminal height h_{r2}).

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 $125 \leq f \leq 15\,500$ MHz
- time percentage, q , with $0.01 \leq q \leq 0.99$
- path distance, d , in km.

2 Assumptions, definitions and conventions

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

- N_s : surface refractivity, in N-Units. Set to 301 N-Units
- a_0 : actual radius of the Earth. Set to 6 370 km
- a_e : effective radius of the Earth. Set to 8 493 km (corresponding to a surface refractivity of 301 N-Units)
- ϵ_r : relative dielectric constant. Set to 15 (corresponding to average ground)
- σ : conductivity. Set to 0.005 S/m (corresponding to average ground).

Additionally, terminal antennas are assumed to be horizontally polarized.

3 Step-by-step method

Step 1: Compute the geometric 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 2. Use § 4 as follows:

given:

$h_{r1,2}$: real height of terminal above mean sea level (user input), in km;

find:

$d_{1,2}$: arc length to the smooth Earth horizon distance, in km

$\theta_{1,2}$: incident angle of the ray from the terminal to the smooth Earth horizon distance, in radians

$h_{1,2}$: adjusted height of the terminal above mean sea level used in subsequent calculations, in km

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

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

$$d_{ML} = d_1 + d_2 \quad (\text{km}) \quad (4)$$

Step 3: Smooth Earth diffraction is modelled linearly in Recommendation ITU-R P.528. 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 3.1: Compute two distances, d_3 and d_4 , that are well beyond the maximum line-of-sight distance d_{ML} from the above equation (4).

$$d_3 = d_{ML} + 0.5(a_e^2/f)^{1/3} \quad (\text{km}) \quad (5)$$

$$d_4 = d_{ML} + 1.5(a_e^2/f)^{1/3} \quad (\text{km}) \quad (6)$$

Step 3.2: Compute the diffraction losses A_{d3} and A_{d4} at the corresponding distances d_3 and d_4 . This will require using § 6 twice – once for each path distance, $d_{3,4}$. Once completed proceed to Step 3.3. Use the method in § 6 as follows:

given:

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

$d_{1,2}$: arc lengths to the smooth Earth horizon distance of the terminals, h_1 and h_2 , in km, as determined in Step 1 above

f : frequency, in MHz

find:

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

Step 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} .

$$M_d = (A_{d4} - A_{d3}) / (d_4 - d_3) \quad (\text{dB/km}) \quad (7)$$

$$A_{d0} = A_{d4} - M_d d_4 \quad (\text{dB}) \quad (8)$$

Step 3.4: Compute the diffraction loss at the distance d_{ML} and the distance d_d , in km, at which the diffraction line predicts 0 dB loss.

$$A_{dML} = M_d d_{ML} + A_{d0} \quad (\text{dB/km}) \quad (9)$$

$$d_d = -(A_{d0} / M_d) \quad (\text{km}) \quad (10)$$

Step 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 5. Else, the path is transhorizon and go to Step 6.

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

Step 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. The following iterative process ensures that the transition between the two models occurs without discontinuity.

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

$$d' = d_{ML} + 3 \quad (\text{km}) \quad (11)$$

$$d'' = d_{ML} + 2 \quad (\text{km}) \quad (12)$$

Step 6.2: Compute the troposcatter losses $A_s^{d'}$ and $A_s^{d''}$ at distances d' and d'' respectively. Use § 7 as follows:

given:

- d : representing the path distance of interest d' and d'' , in km
- $d_{1,2}$: arc length to the smooth Earth horizon distance of the terminals, in km
- f : frequency, in MHz
- $h_{1,2}$: adjusted height of the terminal above mean sea level used in subsequent calculations, in km

find:

$A_s^{d',d''}$: troposcatter loss, A_s , in dB.

Step 6.3: Compute the slope, M_s , of the line containing the two troposcatter points ($d', A_s^{d'}$) and ($d'', A_s^{d''}$) from Step 6.2. This line is approximately tangent to the troposcatter loss at distance d' .

$$M_s = \frac{A_s^{d'} - A_s^{d''}}{d' - d''} \quad (\text{dB/km}) \quad (13)$$

Step 6.4: Compare the slope M_s to the slope of the diffraction line, M_d , from equation (7). If $M_s > M_d$, then increase d' and d'' by 1 km and return to Step 6.2 to continue iterating. Else, proceed to Step 6.5.

Step 6.5: With $M_s \leq M_d$, the distance d' represents the approximate distance where either:

Case 1: Smooth Earth diffraction losses are predicted to be less than the losses due to troposcatter, and the diffraction model is guaranteed to intersect the troposcatter model at some distance $\geq d'$. The transhorizon region propagation loss is physically consistent.

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

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

$$A_d^{d''} = M_d d'' + A_{d0} \quad (\text{dB}) \quad (14)$$

If $A_s^{d''} \geq A_d^{d''}$, then Case 1 in Step 6.5 is true and calculation proceeds to Step 7. Else, the slope of the diffraction line should be adjusted to the tangent point d' , ensuring physical consistency. The adjustment is done by pinning one end of the diffraction line at

$(d_{ML}, A_{d_{ML}})$ and the other end at $(d'', A_s^{d''})$, then re-compute the new smooth Earth diffraction line.

$$M_d = \frac{A_s^{d''} - A_{d_{ML}}}{d'' - d_{ML}} \quad (\text{dB/km}) \quad (15)$$

$$A_{d0} = A_s^{d'} - M_d d' \quad (\text{dB}) \quad (16)$$

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

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

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

$$A_d = M_d d + A_{d0} \quad (\text{dB}) \quad (17)$$

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

- d : path distance of interest, in km
- $d_{1,2}$: arc length to the smooth Earth horizon distance of the terminals, in km
- f : frequency, in MHz
- $h_{1,2}$: adjusted height of the terminal above mean sea level used in subsequent calculations, in km

find:

- A_s : troposcatter loss, in dB
- h_v : height to the common volume, in km
- d_s : the scattering distance, in km
- d_z : half the scattering distance, in km
- θ_A : cross-over angle

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

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

$$A_T = A_d \quad (\text{dB}) \quad (18)$$

Else, depending on whether Case 1 or Case 2 was true in Step 6.5:

$$A_T = \begin{cases} \text{Min}(A_d, A_s), & \text{Case 1 is TRUE} \\ A_s, & \text{Case 2 is TRUE} \end{cases} \quad (\text{dB}) \quad (19)$$

Step 8: Compute the free space loss, A_{fs} , in dB, for the path:

$$r_{1,2} = [h_{r1,2}^2 + 4(a_0 + h_{r1,2}) * a_0 \sin^2(0.5 d_{1,2}/a_0)]^{0.5} \quad (\text{km}) \quad (20)$$

$$r_{fs} = r_1 + r_2 + d_s \quad (\text{km}) \quad (21)$$

$$A_{fs} = -32.45 - 20 \log_{10} f - 20 \log_{10} r_{fs} \quad (\text{dB}) \quad (22)$$

Step 9: Compute the atmospheric absorption loss, A_a , for a transhorizon path, using § 13. Then proceed to Step 10. Use the method presented in § 13 as follows:

given:

- $h_{1,2}$: terminal heights, in km
- $d_{1,2}$: terminal horizon distances, in km

$\theta_{1,2}$: terminal grazing ray take off angle, in radians
 f : frequency, in MHz
 h_v : height to the common volume, in km, from Step 7.2
 θ_A : cross-over angle, from Step 7.2
 d_z : half the scattering distance, in km, from Step 7.2

find:

A_a : atmospheric absorption loss, in dB

Step 10: Compute the long-term variability loss, $Y_{total}(q)$, for the time quantile q . Use § 10. Then proceed to Step 11.

Given:

$h_{r1,2}$: actual terminal heights, in km
 d : path distance of interest, in km
 f : frequency, in MHz
 q : time percentage

find:

$Y(q)$: Long-term variability loss, in dB.

Step 11: Compute the basic transmission loss, A , in dB.

$$A = A_{fs} + A_a + A_T + Y(q) \quad (\text{dB}) \quad (23)$$

This completes the step by step procedure for the given user defined input parameters.

4 Terminal geometry

This section computes the following geometric parameters associated with a terminal.

Given:

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

find:

d : arc length to the smooth Earth horizon distance, in km
 θ : incident angle of the ray from the terminal to the smooth Earth horizon, in radians
 h : adjusted height of the terminal above mean sea level used in subsequent calculations, in km
 Δh : terminal height correction term, in km

As previously defined, the effective radius of the Earth, a_e , is 8 493 km.

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

given:

h_r : real height of terminal above mean sea level (user input), in km
 N_s : surface refractivity of 301 N-Units

find:

d_r : real arc distance (real smooth Earth horizon), in km
 θ_r : ray incident angle on the terminal, in radians

Step 2: Compute the effective height of the terminal, h_e , in km, using the small angle approximation if required.

$$\phi = \frac{d_r}{a_e} \quad (\text{rad}) \quad (24)$$

$$h_e = \begin{cases} d_r^2/2a_e, & \phi \leq 0.1 \\ \frac{a_e}{\cos \phi} - a_e, & \phi > 0.1 \end{cases} \quad (\text{km}) \quad (25)$$

Step 3: When the effective height, h_e , is greater than the real height, h_r , the effect of ray bending can be overestimated. Therefore, compare h_e with h_r to determine the values of h , d , and θ to be used to define the terminal's geometric parameters.

$$h = \begin{cases} h_e, & h_e \leq h_r \\ h_r, & h_e > h_r \end{cases} \quad (\text{km}) \quad (26)$$

$$d = \begin{cases} d_r, & h_e \leq h_r \\ \sqrt{2a_e h_r}, & h_e > h_r \end{cases} \quad (\text{km}) \quad (27)$$

$$\theta = \theta_r \quad (\text{rad}) \quad (28)$$

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

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

Step 5: If $\Delta h = 0$ km, then make the following adjustments to θ and d :

$$\theta = \sqrt{2h_r/a_e} \quad (\text{rad}) \quad (30)$$

$$d = \sqrt{2h_r a_e} \quad (\text{km}) \quad (31)$$

This concludes the section to compute the terminal geometry.

5 Ray tracing

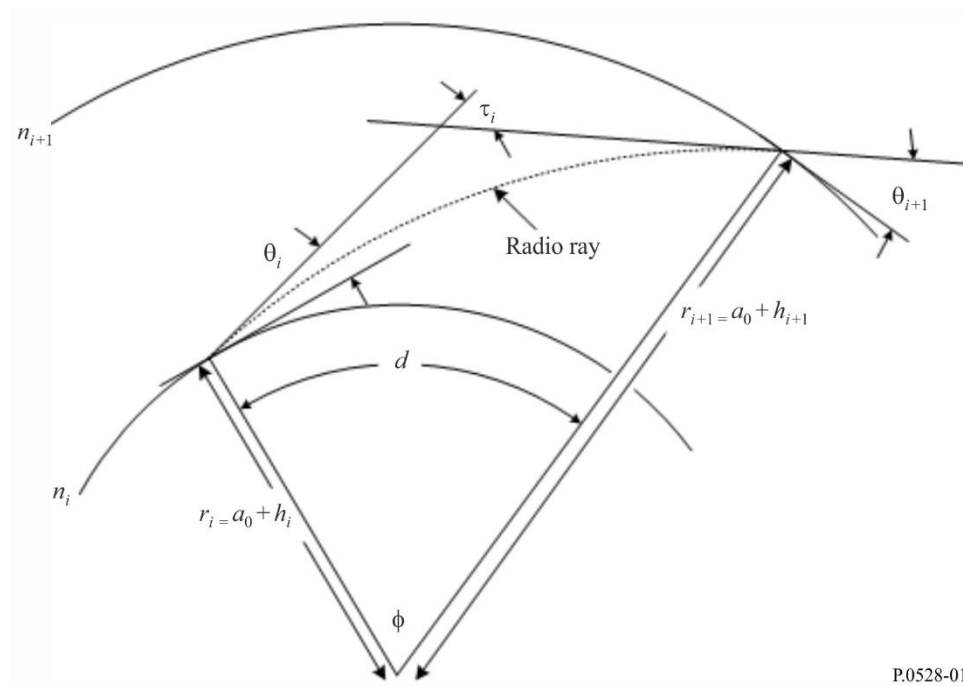
Radio waves traveling through the atmosphere bend due to changes in the atmospheric refractivity. In traditional terrestrial models, this is normally accounted for using the standard “4/3 Earth” method, which models a linear atmospheric refractivity gradient and is a valid approximation for paths near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

Recommendation ITU-R P.528 utilizes ray tracing techniques to compute the path of the ray through the atmosphere. The atmosphere is modelled as a set of concentric atmospheric shells, with exponentially decreasing refractivity. Applications of Snell's Law in a spherical environment, shown in equation (32), are then applied to trace the ray.

$$n_i r_i \cos \theta_i = n_{i+1} r_{i+1} \cos \theta_{i+1} \quad (32)$$

Figure 1 presents a generalized geometry of a ray through a single layer of the atmosphere.

FIGURE 1
Geometry of tracing a ray through a layer of atmosphere



For the atmospheric model, Recommendation ITU-R P.528 uses the 25-layer reference atmosphere shown in Table 1. Rays above 475 km are assumed to travel in a straight line.

TABLE 1
Details of the 25-layer reference atmosphere

Layer, i	Height (AGL), h_i	Layer, i	Height (AGL), h_i	Layer, i	Height (AGL), h_i
0	0 km	9	1.00 km	18	50.00 km
1	0.01 km	10	1.524 km	19	70.00 km
2	0.02 km	11	2.00 km	20	90.00 km
3	0.05 km	12	3.048 km	21	110.00 km
4	0.10 km	13	5.00 km	22	225.00 km
5	0.20 km	14	7.00 km	23	350.00 km
6	0.305 km	15	10.00 km	24	475.00 km
7	0.50 km	16	20.00 km		
8	0.70 km	17	30.48 km		

Given:

h_r : the real terminal height above ground, in km

N_s : the surface refractivity, in N-Units

find:

d_r : arc length to the smooth Earth horizon distance, in km

θ_r : the incident angle of the grazing ray at the terminal, in radians

As previously defined, the actual radius of the Earth, a_0 , is 6 370 km.