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Method for calculating link performance in the space research service

SA Series
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REPORT ITU-R SA.2183

Method for calculating link performance in the space research service

(2010)

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1 Introduction

This Report presents a method of calculating attenuation, noise temperature, and link performance, based on ITU-R Recommendations concerning the characteristics of radio wave propagation. The method can be extended to include equipment characteristics.

The method includes consideration of some effects that become important for systems with noise temperatures below about 30 K when operated in frequency bands below about 15 GHz. These factors are cosmic background noise, galactic noise, and the effect of atmospheric attenuation on their values. For many other systems with higher noise temperatures, these factors may be neglected.

The method will be explained in the context of providing data for the selection of preferred frequency bands on the basis of link performance.

2 References

The method and calculations to be described are based in part on the following Recommendations:

Recommendation ITU-R P.837-5 – Characteristics of precipitation for propagation modelling

Recommendation ITU-R P.618-9 – Propagation data and prediction methods required for the design of Earth-space telecommunications systems

Recommendation ITU-R P.676-7 – Attenuation by atmospheric gases

Recommendation ITU-R P.838-3 – Specific attenuation model for rain for use in prediction methods

Recommendation ITU-R P.372-9 – Radio noise

Recommendation ITU-R P.839-3 – Rain height model for prediction methods

Recommendation ITU-R P.525-2 – Calculation of free-space attenuation.

3 Types of analysis for frequency selection

For links between a spacecraft and the Earth, four types of analysis may be identified:

– space-to-Earth, as limited only by natural phenomena;
– space-to-Earth, including the effects of equipment;
– Earth-to-space, as limited only by natural phenomena;
– Earth-to-space, including the effects of equipment.

For the Earth-to-space link, contributions to the noise temperature of the spacecraft receiving system also include the cosmic and galactic backgrounds, but the contribution from the atmosphere of the Earth may be relatively small. For deep-space probes the Earth occupies such a small portion of the receiving antenna pattern that the noise temperature contribution of the atmosphere is negligible. The attenuation of the atmosphere must nevertheless be included in the link analysis since it directly affects the received signal power.

It is useful to consider links using two types of antennas. The first link assumes fixed diameter transmitting and receiving antennas. In this case the gain of both antennas varies with frequency. The second type of link assumes the use of one fixed diameter antenna and one fixed beamwidth antenna. In this case the gain of the fixed beam width antenna is nearly independent of frequency. An example of this case is the use of an omnidirectional antenna on a space station in order to allow communication during course correction maneuvers or loss of attitude control.

The shape of link performance curves depends on the antenna types assumed.

4 Method for calculating link performance

The method for calculating link performance of space-to-Earth link under conditions of atmospheric attenuation and atmosphere plus rain attenuation is described. Tables 1 to 5 list the several parameters included in the calculation. The tables are:

1. Attenuation by atmospheric gasses and noise temperature as a function of frequency, elevation angle and water vapour density for atmospheric propagation.
2. Attenuation and noise temperature due to rainfall alone, as a function of frequency, elevation angle, and rain rate.
3. Attenuation and noise temperature for a propagation path including atmosphere plus rain, using data from Table 2.
4. Link performance for an assumed set of transmitter, antenna, and distance parameters, and considering the attenuation and noise temperature data from Table 1.
5. Link performance for an assumed set of transmitter, antenna, and distance parameters, considering the attenuation and noise temperature data from Table 3.

The tables are merely examples which show the various parameters and values for a few frequencies.

Values given in the tables are the result of analytic calculations. It should not be inferred that listing of these values to a precision of several decimal places is an indication of the accuracy or precision of the underlying propagation data or associated analytic expressions. Prediction of actual link performance to the indicated precision is not generally possible.

For a space-Earth propagation path through a rainy atmosphere, the attenuation is equal to the attenuation caused by the clear atmosphere along the path, plus the additional attenuation caused by the rainfall along the path. The attenuation caused by the atmosphere alone, and the attenuation caused by the rainfall alone are separately calculated (see Recommendation ITU-R P.618).

The sky noise temperature attributed to the rainy atmosphere is calculated with respect to the total attenuation, and is not equal to the sum of the noise temperatures that could be calculated for each of the two components of the total attenuation.

For each line in each table there is a description of the parameter or calculation and, usually, a particular information source is referenced.

5 Calculations for atmospheric attenuation (no rain or clouds)

Table 1 presents calculated values of attenuation caused by the atmosphere, and of noise temperature caused by the combined effects of the cosmic background noise, galactic background noise, and the noise temperature related to attenuation by the atmosphere. The calculations shown in Table 1 are for conditions of atmospheric attenuation (no rain or clouds). Referring to the line numbers given at the left side of the table, the calculations are made as follows:

Line 7 Water vapour density (g/m^3)

Water vapour density in the atmosphere that is assumed for the particular calculation.

Line 8 Station height above sea level (km)

Height of the earth station above sea level. The example given in Table 1 is 0.81 km for the deep-space earth station at Madrid, Spain.

Line 10 Frequency (GHz)

Radio frequency for the particular calculation.

Line 12 h_0 (km)

Equivalent oxygen height at the earth station location. The equivalent oxygen height from sea level up to an altitude of about 10 km is given by:

$$h_0 = \frac{6.1}{1 + 0.17 r_p^{-1.1}} (1 + t_1 + t_2 + t_3) \qquad \text{km}$$

$$t_1 = \frac{4.64}{1 + 0.066 r_p^{-2.3}} \exp\left[-\left(\frac{f - 59.7}{2.87 + 12.4 \ \exp(-7.9 r_p)} \right)^2 \right]$$

$$t_2 = \frac{0.14 \ \exp(2.12 r_p)}{(f - 118.75)^2 + 0.031 \ \exp(2.2 r_p)}$$

$$t_3 = \frac{0.0114}{1 + 0.14 r_p^{-2.6}} f \frac{-0.0247 + 0.0001 f + 1.61 \times 10^{-6} f^2}{1 - 0.0169 f + 4.1 \times 10^{-5} f^2 + 3.2 \times 10^{-7} f^3}$$

$$h_0 \leq 10.7 r_p^{0.3} \text{ when } f < 70 \text{ GHz}$$

where:

f: frequency (GHz)

$r_p =$ p/1 013

p: pressure (hPa) at the station location.

See § 2.2, Recommendation ITU-R P.676-7.

Line 13 γ_0 (dB/km)

Specific attenuation at ground level due to dry air, from sea level up to an altitude of 10 km, and for frequencies ≤ 54 GHz is given by:

$$\gamma_0 = \left[\frac{7.2 \ r_t^{2.8}}{f^2 + 0.34 \ r_p^2 \ r_t^{1.6}} + \frac{0.62 \xi_3}{(54 - f)^{1.16 \xi_1} + 0.83 \ \xi_2} \right] f^2 r_p^2 \times 10^{-3} \qquad \text{dB/km}$$

with:

$$\xi_1 = \varphi(r_p, r_t, 0.0717, -1.8132, 0.0156, -1.6515)$$

$$\xi_2 = \varphi(r_p, r_t, 0.5146, -4.6368, -0.1921, -5.7416)$$

$$\xi_3 = \varphi(r_p, r_t, 0.3414, -6.5851, 0.2130, -8.5854)$$

$$\varphi(r_p, r_t, a, b, c, d) = r_p^a r_t^b \exp[c(1 - r_p) + d(1 - r_t)]$$

where:

$r_t =$ 288/(273 + t)

t: temperature (°C), where mean temperature values can be obtained from map given in Recommendation ITU-R P.1510, when no adequate temperature data are available.

See § 2.1, Recommendation ITU-R P.676-7.

Line 14 h_w (km)

Equivalent water vapour height at the earth station elevation. For frequencies < 350 GHz, h_w is given by:

$$h_w = 1.66\left(1 + \frac{1.39\sigma_w}{(f-22.235)^2 + 2.56\sigma_w} + \frac{3.37\sigma_w}{(f-183.31)^2 + 4.69\sigma_w} + \frac{1.58\sigma_w}{(f-325.1)^2 + 2.89\sigma_w}\right)$$

$$\text{for} \quad f \leq 350 \text{ GHz}$$

$$\sigma_w = \frac{1.013}{1 + \exp[-8.6(r_p - 0.57)]}$$

See § 2.2, Recommendation ITU-R P.676-7.

Line 15 γ_w(dB/km)

Specific attenuation at ground level due to water vapour, from sea level up to an altitude of 10 km, and frequencies < 360 GHz is given by:

$$\gamma_w = \left\{ \begin{array}{l} \frac{3.98\eta_1 \exp[2.23(1-r_t)]}{(f-22.235)^2 + 9.42\eta_1^2} g(f,22) + \frac{11.96\eta_1 \exp[0.7(1-r_t)]}{(f-183.31)^2 + 11.14\eta_1^2} \\ + \frac{0.081\eta_1 \exp[6.44(1-r_t)]}{(f-321.226)^2 + 6.29\eta_1^2} + \frac{3.66\eta_1 \exp[1.6(1-r_t)]}{(f-325.153)^2 + 9.22\eta_1^2} \\ + \frac{25.37\eta_1 \exp[1.09(1-r_t)]}{(f-380)^2} + \frac{17.4\eta_1 \exp[1.46(1-r_t)]}{(f-448)^2} \\ + \frac{844.6\eta_1 \exp[0.17(1-r_t)]}{(f-557)^2} g(f,557) + \frac{290\eta_1 \exp[0.41(1-r_t)]}{(f-752)^2} g(f,752) \\ \frac{8.3328 \times 10^4 \eta_2 \exp[0.99(1-r_t)]}{(f-1\,780)^2} g(f,1\,780) \end{array} \right\} f^2 r_t^{2.5} \rho \times 10^{-4}$$

with:

$$\eta_1 = 0.955\, r_p r_t^{0.68} + 0.006\rho$$

$$\eta_2 = 0.735\, r_p r_t^{0.5} + 0.0353\, r_t^4 \rho$$

$$g(f, f_i) = 1 + \left(\frac{f - f_i}{f + f_i}\right)^2$$

where:

ρ : the water density (g/m^3) at the station location

See § 2-1, Recommendation ITU-R P.676-7.

Line 17 Galactic temperature @ 408 MHz (K)

Galactic temperature for a particular region of the sky used to calculate the galactic noise temperature for other frequencies for the same region of the sky. For Table 1, a value of 30 K was arbitrarily selected.

See Recommendation ITU-R P.372-9.

Line 18 Galactic temperature (K)

Temperature calculated for a particular frequency, given by:

$$(\text{Galactic temperature @ 408 MHz})\left(\frac{Frequency\ (\text{MHz})}{408}\right)^{-2.75} \quad \text{K}$$

See § 6, Recommendation ITU-R P.372-9.

Line 19 Cosmic noise power spectral density (W/Hz)

Power spectral density of the cosmic background noise given by:

$$\frac{hf}{e^{(hf/kT)}-1} \quad \text{W/Hz}$$

where:

- $h =$ 6.626×10^{-34} (J/s) (Planck's constant)
- f: frequency (Hz)
- $k =$ 1.3806×10^{-23} (J/K) (Boltzman's constant)
- T: noise temperature, taken as 2.7 K.

Line 20 Cosmic temperature (K)

Cosmic background noise temperature, given by:

$$\text{Cosmic noise power spectral density} / k \quad \text{K}$$

where k is Boltzman's constant, 1.3806×10^{-23} (J/K).

Line 21 Cosmic + galactic temperature (K)

Sum of the cosmic and galactic noise temperatures at a particular frequency, and is given by:

$$\text{Cosmic temperature + Galactic temperature} \quad \text{K}$$

Line 23 Zenith attenuation (dB)

One-way attenuation through the atmosphere in the zenith direction, given by:

$$\text{A} = h_0\,\gamma_0 + h_w\,\gamma_w \quad \text{dB}$$

See § 2.2, Recommendation ITU-R P.676-7.

Line 24 Zenith atmospheric noise temperature (K)

Noise temperature caused by the atmosphere in the zenith direction (t_b) is given by:

$$t_b = 280\,(1 - 10^{-A/10}) \quad \text{K}$$

where 280 is the mean radiating temperature of the atmosphere and A (dB) is the one-way attenuation through the atmosphere in the zenith direction.

See § 4, Recommendation ITU-R P.372-9.

Line 25 Zenith background noise temperature (K)

Sum of the cosmic and galactic noise temperature, as reduced by the zenith attenuation, and is given by:

$$(\text{Cosmic} + \text{Galactic temperature}) / 10^{A/10} \quad \text{K}$$

See § 8, Recommendation ITU-R P.372-9.

Line 26 Zenith noise temperature (K)

Sum of the zenith atmospheric noise temperature, and the zenith background noise temperature, given by:

$$\text{Zenith atmospheric noise temperature} + \text{Zenith background noise temperature} \quad \text{K}$$

Line 29 Elevation angle (degrees)

Elevation angle of the earth station antenna for the particular calculation.

Line 30 Atmospheric attenuation (dB)

One-way attenuation through the atmosphere at the particular elevation angle, and for elevation angles greater than 10° given by:

$$B = A / \sin(\text{elevation angle}) \quad \text{dB}$$

See § 2.2, Recommendation ITU-R P.676-7.

Line 31 Atmospheric noise temperature (K)

Noise temperature caused by the atmosphere in the direction of the elevation angle, and given by:

$$280\,(1 - 10^{-B/10}) \quad \text{K}$$

where 280 is the mean radiating temperature (K) of the atmosphere and B (dB) is the one-way attenuation through the atmosphere in the direction of the elevation angle.

Line 32 Background noise temperature (K)

Sum of the cosmic and galactic noise temperatures, as reduced by the attenuation at the particular elevation angle, given by:

$$(\text{Cosmic} + \text{Galactic temperature}) / 10^{B/10} \quad \text{K}$$

where B (dB) is the one-way attenuation through the atmosphere in the direction of the elevation angle.

Line 33 Noise temperature (K)

Sum of the atmospheric noise and the background noise temperatures at the particular elevation angle, given by:

$$\text{Atmospheric noise temperature} + \text{Background noise temperature} \quad \text{K}$$

Line 34 Noise power spectral density (dB(W/Hz))

Noise power spectral density corresponding to the noise temperature, and is given by:

$$-228.6 + 10 \log(\text{noise temperature}) \qquad \text{dB(W/Hz)}$$

where –228.6 is the logarithmic expression of Boltzman's constant, 1.3806×10^{-23} (J/K).

Lines 37-42 and 45-50 are similar to lines 29-34 except for the effects of different elevation angles.

TABLE 1

Data for selection of preferred frequencies

Attenuation and noise temperature, atmosphere, no rain

Water vapour density (g/m^3)	7.5			
Station height above sea level (km)	0.81			
Frequency (GHz)	1	10	20	30
h_0 (km)	5.213	5.200	5.181	5.156
γ_0 (dB/km)	0.005	0.008	0.011	0.021
h_w (km)	1.665	1.675	1.963	1.697
γ_w (dB/km)	5.668E-5	0.007	0.101	0.080
Galactic temperature @ 408 MHz (K)	30			
Galactic temperature (K)	2.549	0.005	0.001	0.000
Cosmic noise power spectral density (W/Hz)	3.69E-23	3.41E-23	3.10E-23	2.82E-23
Cosmic temperature (K)	2.676	2.467	2.248	2.044
Cosmic + galactic temperature (K)	5.225	2.472	2.249	2.044
Zenith attenuation (dB)	0.028	0.052	0.256	0.241
Zenith atmospheric noise temperature (K)	1.808	3.348	16.030	15.120
Zenith background noise temperature (K)	5.192	2.442	2.120	1.934
Zenith noise temperature (K)	7.000	5.790	18.150	17.054
Elevation angle (degrees)	15.00			
Atmospheric attenuation (dB)	0.109	0.202	0.989	0.932
Atmospheric noise temperature (K)	6.921	12.714	57.036	54.052
Background noise temperature (K)	5.096	2.359	1.791	1.649
Noise temperature (K)	12.018	15.073	58.826	55.702
Noise power spectral density (dB(W/Hz))	–217.801	–216.818	–210.90	–211.14
Elevation angle (degrees)	30.00			
Atmospheric attenuation (dB)	0.056	0.104	0.512	0.482
Atmospheric noise temperature (K)	3.604	6.655	31.142	29.424
Background noise temperature (K)	5.158	2.413	1.999	1.829
Noise temperature (K)	8.763	9.068	33.141	31.253
Noise power spectral density (dB(W/Hz))	–219.17	–219.025	–213.40	–213.65
Elevation angle (degrees)	75.00			
Atmospheric attenuation (dB)	0.029	0.054	0.265	0.250
Atmospheric noise temperature (K)	1.872	3.465	16.578	15.638
Background noise temperature (K)	5.191	2.441	2.116	1.930
Noise temperature (K)	7.062	5.906	18.694	17.568
Noise power spectral density (dB(W/Hz))	–220.11	–220.89	– 215.88	–216.15

6 Calculations for rain attenuation

Table 2 presents data showing attenuation and noise temperature resulting from the effects of rain (hydrometeors) alone, not including effects of the gaseous atmosphere. Referring to the line numbers given at the left side of the table, the calculations are made as follows:

Line 6 Station latitude (degrees)

Latitude of the earth station. The example given in Table 2 is 40° for the deep-space earth station at Madrid, Spain.

Line 7 Station height above sea level (km), h_s

h_s = Height of the earth station above sea level: 0.81 km for Madrid, Spain.

Line 8 Rain rate (mm/h)

Rain rate exceeded 0.01% of the year, and for this example is 32 mm/h for Madrid, Spain. See § 2.2.1.1, Step 4, Recommendation ITU-R P.618-9 and Fig. 1 and Table 1, Recommendation ITU-R P.837-5.

Line 9 Rain height (km) above mean sea level, h_r, is given by:

$$h_r = (0°\text{C-isotherm height}) + 0.36 \quad \text{km}$$

For easy reference the value of h_r can be obtained from Fig. 1 of Recommendation ITU-R P.839-3. See § 2.2.1.1, Step 1, Recommendation ITU-R P.618-9 and Recommendation ITU-R P.839-3.

Line 11 Frequency (GHz)

Line 13 Coefficient k_H

Coefficient used for estimating specific attenuation due to rain.

For values of k_H not given directly in Table 5 of Recommendation ITU-R P.838-3, the formula for interpolation is:

$$\log k_H = \sum_{j=1}^{4} a_j \exp\left[-\left(\frac{\log f - b_j}{c_j}\right)^2\right] + m_k \log f + c_k$$

where f is frequency (GHz). Coefficients for constants a_j, b_j, c_j, m_k, and c_k are available in Tables 1-4 of Recommendation ITU-R P.838-3.

See Recommendation ITU-R P.838-3.

Line 14 Coefficient α_H

Coefficient used for estimating specific attenuation due to rain.

For values of α_H not given directly in Table 5 of Recommendation ITU-R P.838-3, the formula for interpolation is:

$$\alpha_H = \sum_{j=1}^{5} a_j \exp\left[-\left(\frac{\log f - b_j}{c_j}\right)^2\right] + m_\alpha \log f + c_\alpha$$

Coefficients for constants a_j, b_j, c_j, m_α, and c_α are available in Tables 1-4 of Recommendation ITU-R P.838-3.

See Recommendation ITU-R P.838-3.

Line 15 Coefficient k_V

Coefficient used for estimating specific attenuation due to rain.

For values of k_V not given directly in Table 5 of Recommendation ITU-R P.838-3, the formula for interpolation is:

$$\log k_V = \sum_{j=1}^{4} a_j \exp\left[-\left(\frac{\log f - b_j}{c_j}\right)^2\right] + m_k \log f + c_k$$

where f is frequency (GHz). Coefficients for constants a_j, b_j, c_j, m_k, and c_k are available in Tables 1-4 of Recommendation ITU-R P.838-3.

Line 16 Coefficient α_V

Coefficient used for estimating specific attenuation due to rain.

For values of α_V not given directly in Table 5 of Recommendation ITU-R P.838-3, the formula for interpolation is:

$$\alpha_V = \sum_{j=1}^{5} a_j \exp\left[-\left(\frac{\log f - b_j}{c_j}\right)^2\right] + m_\alpha \log f + c_\alpha$$

Coefficients for constants a_j, b_j, c_j, m_α, and c_α are available in Tables 1-4 of Recommendation ITU-R P.838-3.

See Recommendation ITU-R P.838-3.

Line 18 Elevation angle (θ)

Line 19 Slant path (km), L_s

Length of the slant path below the rain height is given by:

For $\theta \geq 5°$

$$L_s = \frac{(h_r - h_s)}{\sin\theta} \qquad \text{km}$$

For $\theta < 5°$

$$L_s = \frac{2(h_r - h_s)}{\left(\sin^2\theta + \frac{2(h_r - h_s)}{R_e}\right)^{1/2} + \sin\theta} \qquad \text{km}$$

See § 2.2.1.1, Step 2, Recommendation ITU-R P.618-9.

Line 20 Horizontal projection (km), L_g

Horizontal projection of the slant path, given by:

$$L_g = L_s \cos(\theta) \quad \text{km}$$

See § 2.2.1.1, Step 3, Recommendation ITU-R P.618-9.

Line 21 Coefficient k

Coefficient used for estimating specific attenuation due to rain:

$$k = [k_H + k_V + (k_H - k_V)\cos^2(\theta)\cos(2\tau)] / 2$$

where τ is the polarization tilt angle relative to the horizontal (τ = 45° for circular polarization).

See Recommendation ITU-R P.838-3.

Line 22 Coefficient α

Coefficient used for estimating specific attenuation due to rain:

$$\alpha = [k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2(\theta)\cos(2\tau)] / 2k$$

See Recommendation ITU-R P.838-3.

Line 23 γ_R (dB/km)

Specific attenuation due to rain given by:

$$\gamma_R = k\,(\text{Rain Rate})^{\alpha} \quad \text{dB/km}$$

Line 24 Horizontal reduction, $r_{0.01}$ for 0.01%

Horizontal Reduction factor for 0.01% of the time, given by:

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_g\gamma_R}{f}} - 0.38\left(1 - e^{-2L_g}\right)}$$

See § 2.2.1.1, Step 6, Recommendation ITU-R P.618-9.

Line 25 Vertical reduction, $\nu_{0.01}$, for 0.01%

Vertical reduction factor for 0.01% of the time:

$$\zeta = \tan^{-1}\left(\frac{h_r - h_s}{L_g\, r_{0.01}}\right) \quad \text{degrees}$$

For $\zeta > \theta$, $$L_R = \frac{L_g\, r_{0.01}}{\cos\theta} \quad \text{km}$$

Else, $$L_R = \frac{(h_r - h_s)}{\sin\theta} \quad \text{km}$$

If $|\varphi| < 36°$, $\chi = 36 - |\varphi|$ degrees

Else, $\chi = 0$ degrees

$$\nu_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-(\theta/(1+\chi))}\right)\frac{\sqrt{L_R\,\gamma_R}}{f^2} - 0.45\right)}$$

Line 26 Effective path length, L_e

The effective path length is given by:

$$L_e = L_R\ \nu_{0.01} \quad \text{km}$$

Line 27 Attenuation 0.01% (dB)

Rain attenuation exceeded 0.01% of the year, given by:

$$A_{0.01} = \gamma_R\ L_e$$

See § 2.2.1.1, Step 7, Recommendation ITU-R P.618-9.

Line 28 Attenuation p% (dB), A_p

Rain attenuation exceeded p% of the year, and is given by:

If $p \geq 1$ or $|\varphi| \geq 36°$:

$$\beta = 0$$

If $p < 1$ and $|\varphi| < 36°$ and $\theta \geq 25°$:

$$\beta = -0.005(|\varphi| - 36)$$

Otherwise:

$$\beta = -0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta$$

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}) - \beta(1-p)\sin\theta)} \quad \text{dB}$$

NOTE 1 – The selection of a particular percentage of time is based on operational considerations. 0.1% is appropriate for some space research missions and was chosen for this example in order to illustrate the method of calculation.

See § 2.2.1.1, Step10, Recommendation ITU-R P.618-9.

Lines 31-41 and 44-54 are similar to lines 18-28 except for the effects of different elevation angles.

TABLE 2

Data for selection of preferred frequencies

Attenuation caused by rainfall alone, without atmosphere

Station latitude (degrees)	40			
Station height above sea level (km)	0.81			
Rain rate (mm/h) 0.01%	32			
Rain height (km)	3.7			
Frequency (GHz)	1	10	20	30
Coefficient k_H	0.000026	0.0122	0.092	0.240
Coefficient α_H	0.969	1.257	1.057	0.949
Coefficient k_V	0.000031	0.0113	0.096	0.229
Coefficient α_V	0.859	1.216	0.985	0.913
Elevation angle (degrees)	15	15	15	15
Slant path (km)	11.17	11.17	11.17	11.17
Horizontal projection (km)	10.79	10.79	10.79	10.79
Coefficient k	2.835E-5	0.012	0.094	0.235
Coefficient α	0.909	1.237	1.020	0.931
γ_R (dB/km)	6.63E-4	0.854	3.218	5.915
Horizontal reduction 0.01%	1.458	0.731	0.607	0.569
Vertical reduction 0.01%	0.470	0.842	1.047	1.138
Effective path length (km)	5.248	6.872	7.095	7.232
Attenuation 0.01% (dB)	0.003	5.867	22.834	42.781
Attenuation p = 0.1 (dB)	5.10E-4	1.858	8.324	16.644
Elevation angle (degrees)	30	30	30	30
Slant path (km)	5.78	5.78	5.78	5.78
Horizontal projection (km)	5.006	5.006	5.006	5.006
Coefficient k	2.835E-5	0.012	0.094	0.235
Coefficient α	0.909	1.237	1.020	0.931
γ_R (dB/km)	6.63E-4	0.854	3.218	5.915
Horizontal reduction 0.01%	1.504	0.885	0.758	0.717
Vertical reduction 0.01%	0.491	0.877	1.127	1.246
Effective path length (km)	2.836	4.487	4.934	5.164
Attenuation 0.01% (dB)	0.002	3.831	15.878	30.54
Attenuation p = 0.1 (dB)	2.585E-4	1.161	5.574	11.48
Elevation angle (degrees)	75	75	75	75
Slant path (km)	2.992	2.992	2.992	2.992
Horizontal projection (km)	0.774	0.774	0.774	0.774
Coefficient k	2.835E-5	0.012	0.094	0.235
Coefficient α	0.909	1.237	1.020	0.931
γ_R (dB/km)	6.627E-4	0.854	3.218	5.915
Horizontal reduction 0.01%	1.392	1.109	1.024	0.994
Vertical reduction 0.01%	0.522	0.957	1.259	1.429
Effective path length (km)	1.563	2.864	3.768	4.252
Attenuation 0.01% (dB)	0.001	2.445	12.126	25.153
Attenuation p = 0.1 (dB)	1.340E-4	0.707	4.140	9.262

7 Calculations for atmosphere plus rain attenuation

Table 3 presents calculated values of attenuation caused by the clear atmosphere plus rain, and of noise temperature caused by the effects of the cosmic background noise, galactic background noise, and the noise temperature related to attenuation by the combination of atmosphere and rain. Referring to the line numbers given at the left side of the table, the calculations are made as follows:

Lines 1 through 26 are as explained for Table 1.

Line 27 Rain attenuation (dB)

Attenuation due to rain along a path at the specified elevation angle. The value given is the attenuation that is exceeded 0.1% of the time at Madrid and is obtained from Table 2.

Line 28 Total attenuation (dB)

B = Sum of the attenuation due to the atmosphere and the attenuation due to rain.

Line 29 Atmospheric + rain noise temperature (K)

Noise temperature due to the total attenuation, given by:

$$280\,(1 - 10^{-B/10}) \qquad \text{K}$$

where 280 is the mean radiating temperature (K) of the atmosphere and B (dB) is the one-way total attenuation along the path.

Line 30 Background noise temperature (K)

Sum of the cosmic and galactic noise temperatures, as reduced by the attenuation at the particular elevation angle, given by:

$$(\text{Cosmic + Galactic temperature}) \,/\, 10^{B/10} \qquad \text{K}$$

where B (dB) is the one-way attenuation through the atmosphere in the direction of the elevation angle.

Line 31 Noise temperature (K)

Sum of the atmospheric and rain noise and the background noise for the particular elevation angle.

Line 32 Noise power spectral density (dB(W/Hz))

Noise power spectral density corresponding to the noise temperature, given by:

$$-228.6 + 10\log(\text{noise temperature (K)}) \qquad \text{dB(W/Hz)}$$

where –228.6 is the logarithmic expression of Boltzman's constant, 1.3806×10^{-23} (J/K).

Lines 34-50 are similar to lines 25-32 except for the effects of different elevation angles.

TABLE 3

Data for selection of preferred frequencies

Attenuation and noise temperature, atmosphere plus rain

Water vapour density (g/m^3)	7.50			
Station height above sea level (km)	0.81			
Frequency (GHz)	1	10	20	30
h_0 (km)	5.213	5.200	5.181	5.156
γ_0 (dB/km)	0.005	0.008	0.011	0.020
h_w (km)	1.665	1.675	1.963	1.696
γ_w (dB/km)	5.668E-5	0.007	0.101	0.080
Galactic temperature @ 408 MHz (K)	30			
Galactic temperature (K)	2.549	0.005	0.001	0.000
Cosmic noise power spectral density (W/Hz)	3.69E-23	3.41E-23	3.10E-23	2.82E-23
Cosmic temperature (K)	2.676	2.467	2.248	2.044
Cosmic + galactic temperature (K)	5.225	2.472	2.249	2.044
Zenith attenuation (dB)	0.028	0.052	0.256	0.241
Zenith atmospheric noise temperature (K)	1.808	3.348	16.030	15.120
Zenith background noise temperature (K)	5.192	2.442	2.120	1.934
Zenith noise temperature (K)	7.000	5.790	18.150	17.054
Elevation angle (degrees)	15.00			
Atmospheric attenuation (dB)	0.109	0.202	0.989	0.932
Rain attenuation (dB)	5.10E-4	1.858	8.324	16.644
Total attenuation dB	0.109	2.060	9.313	17.575
Atmospheric + rain noise temperature (K)	6.953	105.75	247.20	275.107
Background noise temperature (K)	5.095	1.538	0.263	0.036
Noise temperature (K)	12.049	107.29	247.47	275.14
Noise power spectral density (dB(W/Hz))	–217.79	–208.29	–204.66	–204.20
Elevation angle (degrees)	30.00			
Atmospheric attenuation (dB)	0.056	0.104	0.512	0.482
Rain attenuation (dB)	2.585E-4	1.161	5.574	11.477
Total attenuation (dB)	0.056	1.265	6.086	11.959
Atmospheric + rain noise temperature (K)	3.621	70.772	211.05	262.166
Background noise temperature (K)	5.158	1.847	0.553	0.123
Noise temperature (K)	8.779	72.618	211.61	262.30
Noise power spectral density (dB(W/Hz))	–219.17	–209.99	–205.34	–204.41
Elevation angle (degrees)	75.00			
Atmospheric attenuation (dB)	0.029	0.054	0.265	0.250
Rain attenuation (dB)	1.340E-4	0.707	4.140	9.262
Total attenuation (dB)	0.029	0.761	4.405	9.511
Atmospheric + rain noise temperature (K)	1.880	45.021	178.454	248.666
Background noise temperature (K)	5.190	2.074	0.815	0.228
Noise temperature (K)	7.071	47.095	179.27	248.894
Noise power spectral density (dB(W/Hz))	−220.11	−211.87	−206.06	−204.64

8 Link performance for atmospheric attenuation

Table 4 presents link performance calculated for an assumed set of equipment and distance parameters, using the attenuation and noise temperature values for propagation under the condition of atmosphere only. Referring to the line numbers given at the left side of the table, the calculations are made as follows:

Line 9 Frequency (GHz)

Radio frequency for which the calculation is made.

Line 11 Spacecraft transmit power P_0 (dBW)

Assumed spacecraft transponder power, in this case 25 W, given by:

$$P_0 = 10 \log 25 \quad \text{dBW}$$

Line 12 Gain, 3.7 m diameter (dBi)

Assumed gain of the spacecraft transmitting antenna, in this case a 3.7 m diameter parabola with assumed 100% efficiency, given by:

$$20.40 + 20 \log(\text{diameter(m)}) + 20 \log(\text{frequency(GHz)}) \quad \text{dBi}$$

Line 13 Free space loss (dB)

Attenuation for a free space path, in this case for a path length of 800 x 10^6 km, given by Recommendation ITU-R P.525-2:

$$32.4 + 20 \log(\text{frequency(MHz)}) + 20 \log(\text{path(km)}) =$$
$$270.51 + 20 \log(\text{frequency(GHz)}) \quad \text{dB}$$

Line 14 Gain, 70 m diameter (dBi)

Gain of the earth station receiving antenna, in this case a 70 m diameter parabola with assumed 100% efficiency, given by:

$$20.40 + 20 \log(\text{diameter(m)}) + 20 \log(\text{frequency(GHz)}) \quad \text{dBi}$$

Line 16 Elevation angle 15 (degrees)

Elevation angle of the earth station receiving antenna and propagation path through the atmosphere, in this case 15°.

Line 17 Atmospheric attenuation (dB)

Attenuation due to the atmosphere at the specified elevation angle taken from Table 1.

Line 18 Received signal power (dBW)

Power received at the terminals of the earth station antenna given by:

$$\text{Line 11} + \text{Line 12} - \text{Line 13} + \text{Line 14} - \text{Line 17}$$

Line 19 System noise power spectral density (dB(W/Hz))

Received noise power spectral density taken from Table 1. For the example presented by Table 4, the noise temperature contribution of the earth station receiving system has been assumed to be zero.

Line 20 P_r/N_0 (dBHz)

Ratio of received power to noise power spectral density given by line 18 and line 19. The variation of P_r/N_0 with frequency provides the basis for selection of preferred frequency bands in terms of link performance. Frequencies with highest P_r/N_0 provide the best performance for a given set of assumed conditions and equipment characteristics.

Lines 22-26 and 28-32 are similar to lines 16-20 except for different values of elevation angles.

TABLE 4

Data for selection of preferred frequencies

Ideal link performance, space-to-Earth, atmosphere, no rain

Line					
9	Frequency (GHz)	1	10	20	30
11	Spacecraft transmit power P_0 (dBW)	13.98	13.98	13.98	13.98
12	3.7 m antenna gain (dBi)	31.76	51.77	57.79	61.31
13	Free space loss (dB)	270.50	290.50	296.52	300.05
14	70 m antenna gain (dBi)	57.30	77.30	83.32	86.84
16	Elevation angle (degrees)	15			
17	Atmospheric attenuation (dB)	0.109	0.202	0.989	0.932
18	Received signal power (dBW)	–167.57	–147.66	–142.43	–138.85
19	System noise power spectral density (dB(W/Hz))	–217.80	–216.82	–210.90	–211.14
20	P_r/N_0 (dBHz)	50.24	69.16	68.48	72.29
22	Elevation angle (degrees)	30			
23	Atmospheric attenuation (dB)	0.056	0.104	0.512	0.482
24	Received signal power (dBW)	–167.51	–147.56	–141.95	–138.40
25	System noise power spectral density (dB(W/Hz)	–219.17	–219.02	–213.40	–213.65
26	P_r/N_0 (dBHz)	51.66	71.46	71.45	75.25
28	Elevation angle (degrees)	75			
29	Atmospheric attenuation (dB)	0.029	0.054	0.265	0.250
30	Received signal power (dBW)	–167.49	–147.51	–141.70	–138.16
31	System noise power spectral density (dB(W/Hz))	–220.11	–220.89	–215.88	–216.15
32	P_r/N_0 (dBHz)	52.62	73.38	74.18	77.99

9 Link performance for atmosphere plus rain attenuation

The calculation of link performance for atmosphere plus rain is shown in Table 5. Tables 4 and 5 are similar except that in Table 5 the values of attenuation and noise temperature are taken in part from Table 3. Also note that Table 5 includes the frequency dependent effects of earth station hardware: the variation in antenna gain, and the contributions to total noise.

TABLE 5

Data for selection of preferred frequencies

Achievable link performance, space-to-Earth, atmosphere plus rain, includes effects of earth station hardware

Frequency (GHz)	1	10	20	30
Spacecraft transmit power P_0 (dBW)	13.98	13.98	13.98	13.98
3.7 m antenna gain (dBi)	29.55	49.55	55.57	59.09
Free space loss (dB)	270.50	290.50	296.52	300.05
Elevation angle (degrees)	15	15	15	15
70 m antenna gain (dBi)	55.23	74.91	79.96	81.86
Atmosphere + rain attenuation (dB)	0.109	2.060	9.313	17.576
Received signal power (dBW)	−171.84	−154.11	−156.32	−162.69
Background noise temperature (K)	5.095	1.538	0.263	0.035
Atmospheric noise temperature with rain (K)	6.953	105.75	247.20	275.107
Receiver noise temperature (K)	14.6	20	26	32
System noise temperature (K)	26.6	127.3	273.47	307.1
System noise power spectral density (dBW/Hz)	−214.35	−207.55	−204.23	−203.73
P_r/N_0 (dBHz)	42.5	53.43	47.91	41.04
Elevation angle (degrees)	30	30	30	30
70 m antenna gain (dBi)	55.61	75.30	80.341	82.24
Atmosphere + rain attenuation (dB)	0.056	1.265	6.089	11.959
Received signal power (dBW)	−171.41	−152.94	−152.72	−156.69
Background noise temperature (K)	5.158	1.847	0.553	0.130
Atmospheric noise temperature with rain (K)	3.621	70.772	211.05	262.166
Receiver noise temperature (K)	12.9	18.3	24.3	30.3
System noise temperature (K)	21.7	90.9	235.86	292.6
System noise power spectral density (dB W/Hz)	−215.24	−209.01	−204.87	−203.94
P_r/N_0 (dBHz)	43.84	56.07	52.2	47.25
Elevation angle (degrees)	75	75	75	75
70 m antenna gain (dBi)	55.27	74.95	80.00	81.89
Atmosphere + rain attenuation (dB)	0.029	0.761	4.405	9.511
Received signal power (dBW)	−171.72	−152.78	−151.38	−154.59
Background noise temperature (K)	5.190	2.074	0.815	0.228
Atmospheric noise temperature with rain (K)	1.880	45.021	178.454	248.666
Receiver noise temperature (K)	12.1	17.5	23.5	29.5
System noise temperature (K)	19.1	64.6	202.7	278.4
System noise power spectral density (dB(W/Hz))	−215.77	−210.50	−205.53	−204.15
P_r/N_0 (dB(Hz)	44.05	57.72	54.15	49.57

10 Conclusion

The method presented in this report is recommended to be used to calculate link performance in the space research service. This method provides a ratio of received power to noise power spectral density, P_r/N_0. The variation of P_r/N_0 with frequency provides the basis for selection of preferred frequency bands. Frequencies with the highest P_r/N_0 provide the best performance for a given set of assumed conditions and equipment characteristics. The preferred frequency bands are identified within approximately 1 dB of the maximum available P_r/N_0 value.

By considering the performance of currently realizable links as well as ideal links, it is possible to identify preferred frequency bands for the present time and also for the future when equipment is further improved.

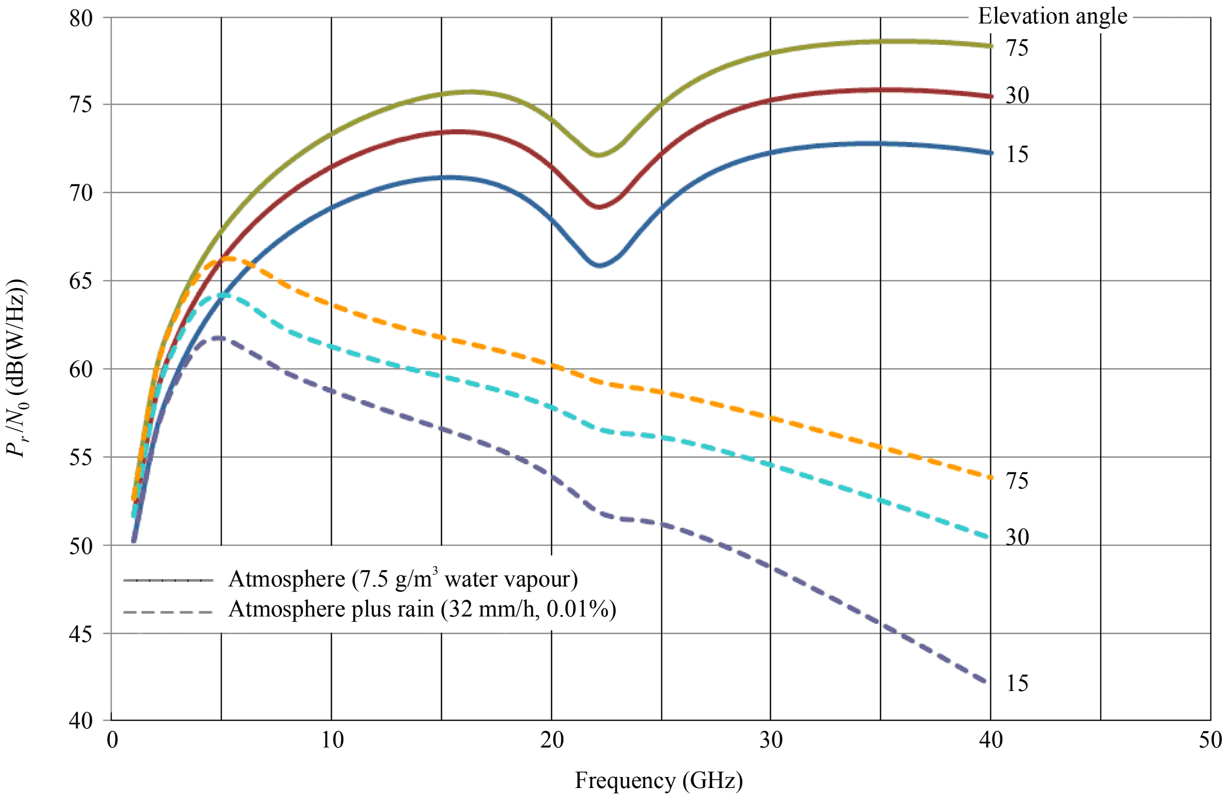
An example using this method to calculate performance achievable with different equipment characteristics is given in Fig. 1. The figure shows two sets of curves for a space-to-Earth path.

In the first set, the equipment is assumed to be perfect. The antennas are assumed to be ideal with gain that varies as the square of the frequency or with a beamwidth (gain) that is constant with respect to frequency. The transmitter power is assumed constant with respect to frequency and the noise temperature of the receiving system equipment is neglected. The purpose of these assumptions is to allow selection of preferred frequency bands as limited only by natural phenomena.

The second set of curves includes the frequency dependent variations of a particular set of equipment parameters. Some parameters of the earth station antenna also depend upon elevation angles, and these variations are included. Factors considered include antenna gain variation as a function of elevation angle; the noise temperature contribution of the warm Earth as coupled via the feed support structure and illumination spillover; and receiver equipment noise temperature. The purpose of including these factors is to allow selection of preferred frequency bands for a link that includes the characteristics of practical equipment.

FIGURE 1

Space-to-Earth link performance, P_r/N_0



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The preferred frequency bands can be identified from Fig. 1 as 11.5-19 GHz for the atmosphere only case, and 4-7 GHz for the atmosphere plus rain case.