RECOMMENDATION ITU-R P.676-4

ATTENUATION BY ATMOSPHERIC GASES

(Question ITU-R 201/3)

(1990-1992-1995-1997-1999)

The ITU Radiocommunication Assembly,

considering

a) the necessity of estimating the attenuation by atmospheric gases on terrestrial and slant paths,

recommends

1 that, for general application, the procedures in Annex 1 be used to calculate gaseous attenuation at frequencies up to 1 000 GHz. (Software code in MATLAB is available from the Radiocommunication Bureau);

2 that, for approximate estimates of gaseous attenuation in the frequency range 1 to 350 GHz, the simpler procedure given in Annex 2 be used.

ANNEX 1

Line-by-line calculation of gaseous attenuation

1 Specific attenuation

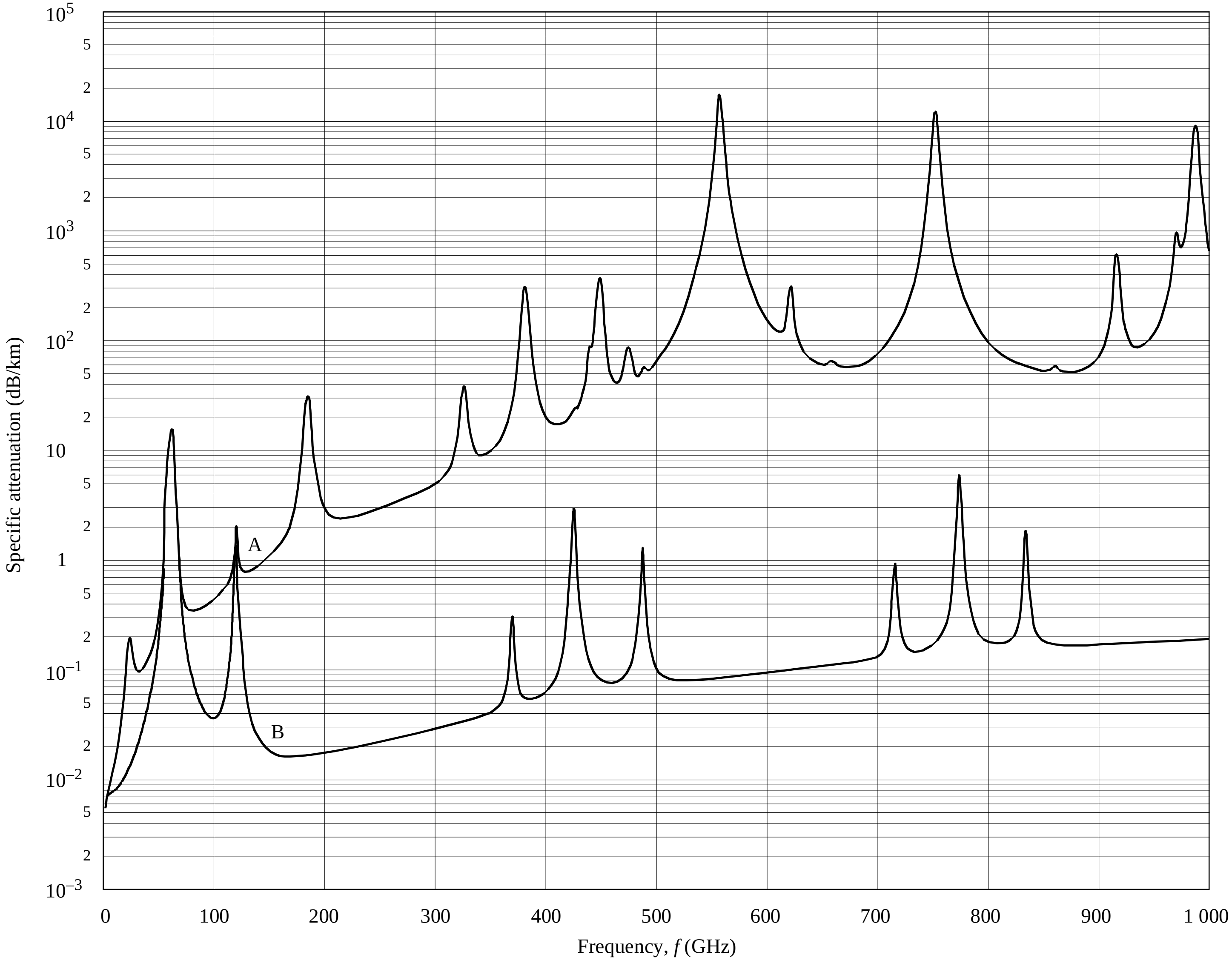
The specific attenuation at frequencies up to 1 000 GHz due to dry air and water vapour, can be evaluated most accurately at any value of pressure, temperature and humidity by means of a summation of the individual resonance lines from oxygen and water vapour, together with small additional factors for the non-resonant Debye spectrum of oxygen below 10 GHz, pressure-induced nitrogen attenuation above 100 GHz and a wet continuum to account for the excess water vapour-absorption found experimentally. Figure 1 shows the specific attenuation using the model, calculated from 0 to 1 000 GHz at 1 GHz intervals, for a pressure of 1 013 hPa, temperature of 15° C for the cases of a water-vapour density of 7.5 g/m^3 (Curve A) and a dry atmosphere (Curve B).

Near 60 GHz, many oxygen absorption lines merge together, at sea-level pressures, to form a single, broad absorption band, which is shown in more detail in Fig. 2. This Figure also shows the oxygen attenuation at higher altitudes, with the individual lines becoming resolved at lower pressures.

For quick and approximate estimates of specific attenuation at frequencies up to 350 GHz, in cases where high accuracy is not required, simplified algorithms are given in Annex 2 for restricted ranges of meteorological conditions.

FIGURE 1

Specific attenuation due to atmospheric gases, calculated at 1 GHz intervals, including line centres



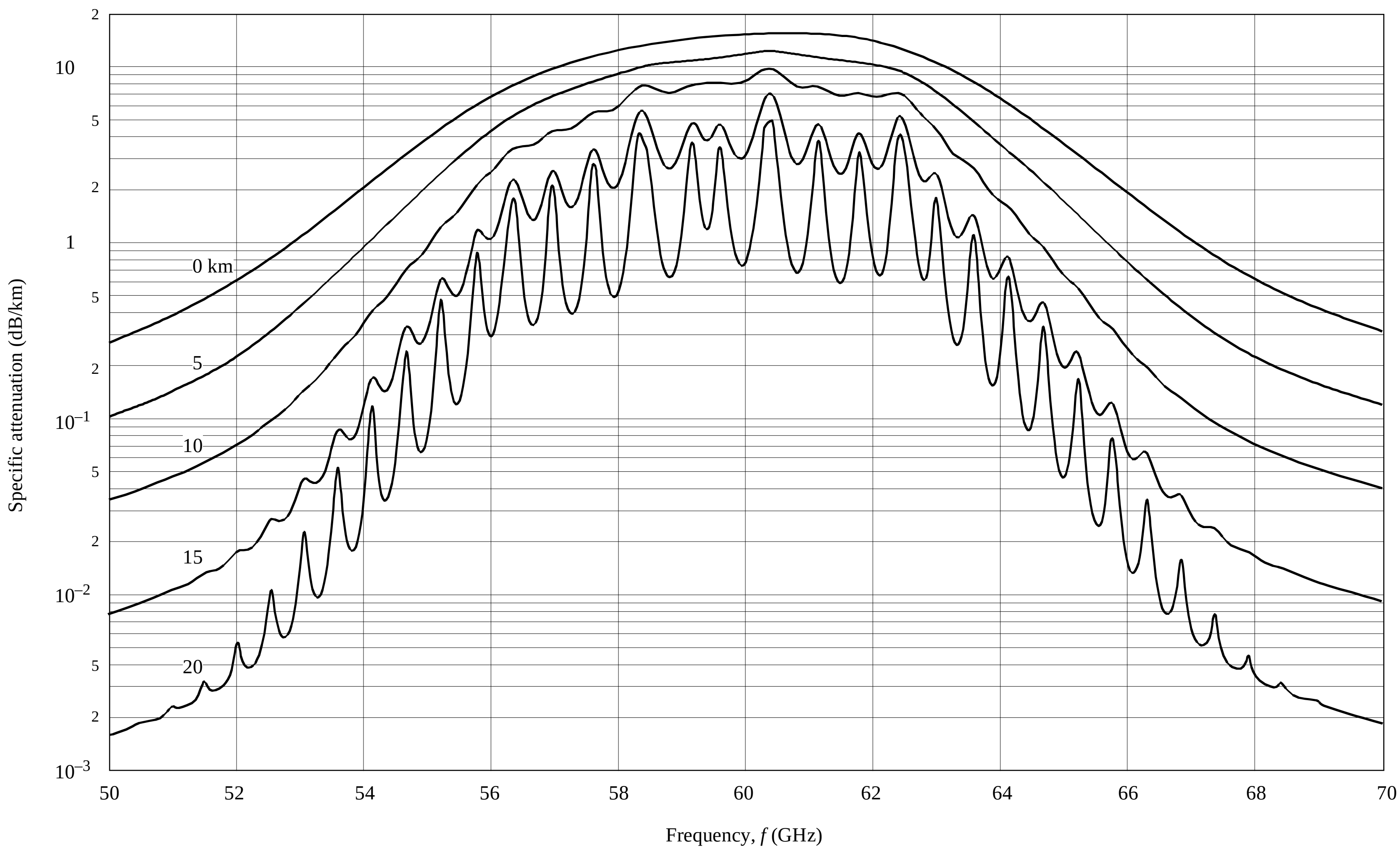
Curves A: mean global reference atmosphere (7.5 g/m^3)

B: dry atmosphere

0676-01

FIGURE 2

Specific attenuation in the range 50-70 GHz at the altitudes indicated



0676-02

The specific gaseous attenuation is given by:

$$\gamma = \gamma_o + \gamma_w = 0.1820\, f\, N''(f) \qquad \text{dB/km} \tag{1}$$

where γ_o and γ_w are the specific attenuations (dB/km) due to dry air and water vapour, respectively, and where f is the frequency (GHz) and $N''(f)$ is the imaginary part of the frequency-dependent complex refractivity:

$$N''(f) = \sum_i S_i F_i + N''_D(f) + N''_W(f) \tag{2}$$

S_i is the strength of the ith line, F_i is the line shape factor and the sum extends over all the lines; $N''_D(f)$ and $N''_W(f)$ are dry and wet continuum spectra.

The line strength is given by:

$$\begin{aligned} S_i &= a_1 \times 10^{-7}\, p\, \theta^3 \exp\left[a_2 (1 - \theta)\right] && \text{for oxygen} \\ &= b_1 \times 10^{-1}\, e\, \theta^{3.5} \exp\left[b_2 (1 - \theta)\right] && \text{for water vapour} \end{aligned} \tag{3}$$

where:

p : dry air pressure (hPa)

e : water vapour partial pressure in hPa (total barometric pressure $P = p + e$)

$\theta =$ 300/T

T : temperature (K).

Local values of p, e and T measured profiles (e.g. using radiosondes) should be used; however, in the absence of local information, the reference standard atmospheres described in Recommendation ITU-R P.835 should be used.

The water-vapour partial pressure, e, may be obtained from the water-vapour density ρ using the expression:

$$e = \frac{\rho T}{216.7} \tag{4}$$

The coefficients a_1, a_2 are given in Table 1 for oxygen, those for water vapour, b_1 and b_2, are given in Table 2.

The line-shape factor is given by:

$$F_i = \frac{f}{f_i}\left[\frac{\Delta f - \delta (f_i - f)}{(f_i - f)^2 + \Delta f^2} + \frac{\Delta f - \delta (f_i + f)}{(f_i + f)^2 + \Delta f^2}\right] \tag{5}$$

where f_i is the line frequency and Δf is the width of the line:

$$\begin{aligned} \Delta f &= a_3 \times 10^{-4} (p\, \theta^{(0.8 - a_4)} + 1.1\, e\, \theta) && \text{for oxygen} \\ &= b_3 \times 10^{-4} (p\, \theta^{b_4} + b_5\, e\, \theta^{b_6}) && \text{for water vapour} \end{aligned} \tag{6}$$

and δ is a correction factor which arises due to interference effects in oxygen lines:

$$\begin{aligned} \delta &= (a_5 + a_6\, \theta) \times 10^{-4}\, p\, \theta^{0.8} && \text{for oxygen} \\ &= 0 && \text{for water vapour} \end{aligned} \tag{7}$$

The spectroscopic coefficients are given in Tables 1 and 2.

TABLE 1

Spectroscopic data for oxygen attenuation

f_0	a_1	a_2	a_3	a_4	a_5	a_6
50.474238	0.94	9.694	8.60	0	1.600	5.520
50.987749	2.46	8.694	8.70	0	1.400	5.520
51.503350	6.08	7.744	8.90	0	1.165	5.520
52.021410	14.14	6.844	9.20	0	0.883	5.520
52.542394	31.02	6.004	9.40	0	0.579	5.520
53.066907	64.10	5.224	9.70	0	0.252	5.520
53.595749	124.70	4.484	10.00	0	–0.066	5.520
54.130000	228.00	3.814	10.20	0	–0.314	5.520
54.671159	391.80	3.194	10.50	0	–0.706	5.520
55.221367	631.60	2.624	10.79	0	–1.151	5.514
55.783802	953.50	2.119	11.10	0	–0.920	5.025
56.264775	548.90	0.015	16.46	0	2.881	–0.069
56.363389	1 344.00	1.660	11.44	0	–0.596	4.750
56.968206	1 763.00	1.260	11.81	0	–0.556	4.104
57.612484	2 141.00	0.915	12.21	0	–2.414	3.536
58.323877	2 386.00	0.626	12.66	0	–2.635	2.686
58.446590	1 457.00	0.084	14.49	0	6.848	–0.647
59.164207	2 404.00	0.391	13.19	0	–6.032	1.858
59.590983	2 112.00	0.212	13.60	0	8.266	–1.413
60.306061	2 124.00	0.212	13.82	0	–7.170	0.916
60.434776	2 461.00	0.391	12.97	0	5.664	–2.323
61.150560	2 504.00	0.626	12.48	0	1.731	–3.039
61.800154	2 298.00	0.915	12.07	0	1.738	–3.797
62.411215	1 933.00	1.260	11.71	0	–0.048	–4.277
62.486260	1 517.00	0.083	14.68	0	–4.290	0.238
62.997977	1 503.00	1.665	11.39	0	0.134	–4.860
63.568518	1 087.00	2.115	11.08	0	0.541	–5.079
64.127767	733.50	2.620	10.78	0	0.814	–5.525
64.678903	463.50	3.195	10.50	0	0.415	–5.520
65.224071	274.80	3.815	10.20	0	0.069	–5.520
65.764772	153.00	4.485	10.00	0	–0.143	–5.520
66.302091	80.09	5.225	9.70	0	–0.428	–5.520
66.836830	39.46	6.005	9.40	0	–0.726	–5.520
67.369598	18.32	6.845	9.20	0	–1.002	–5.520
67.900867	8.01	7.745	8.90	0	–1.255	–5.520
68.431005	3.30	8.695	8.70	0	–1.500	–5.520
68.960311	1.28	9.695	8.60	0	–1.700	–5.520
118.750343	945.00	0.009	16.30	0	–0.247	0.003
368.498350	67.90	0.049	19.20	0.6	0	0
424.763124	638.00	0.044	19.16	0.6	0	0
487.249370	235.00	0.049	19.20	0.6	0	0
715.393150	99.60	0.145	18.10	0.6	0	0
773.839675	671.00	0.130	18.10	0.6	0	0
834.145330	180.00	0.147	18.10	0.6	0	0

TABLE 2

Spectroscopic data for water-vapour attenuation

f_0	b_1	b_2	b_3	b_4	b_5	b_6
22.235080	0.1090	2.143	28.11	0.69	4.80	1.00
67.813960	0.0011	8.735	28.58	0.69	4.93	0.82
119.995941	0.0007	8.356	29.48	0.70	4.78	0.79
183.310074	2.3000	0.668	28.13	0.64	5.30	0.85
321.225644	0.0464	6.181	23.03	0.67	4.69	0.54
325.152919	1.5400	1.540	27.83	0.68	4.85	0.74
336.187000	0.0010	9.829	26.93	0.69	4.74	0.61
380.197372	11.9000	1.048	28.73	0.69	5.38	0.84
390.134508	0.0044	7.350	21.52	0.63	4.81	0.55
437.346667	0.0637	5.050	18.45	0.60	4.23	0.48
439.150812	0.9210	3.596	21.00	0.63	4.29	0.52
443.018295	0.1940	5.050	18.60	0.60	4.23	0.50
448.001075	10.6000	1.405	26.32	0.66	4.84	0.67
470.888947	0.3300	3.599	21.52	0.66	4.57	0.65
474.689127	1.2800	2.381	23.55	0.65	4.65	0.64
488.491133	0.2530	2.853	26.02	0.69	5.04	0.72
503.568532	0.0374	6.733	16.12	0.61	3.98	0.43
504.482692	0.0125	6.733	16.12	0.61	4.01	0.45
556.936002	510.0000	0.159	32.10	0.69	4.11	1.00
620.700807	5.0900	2.200	24.38	0.71	4.68	0.68
658.006500	0.2740	7.820	32.10	0.69	4.14	1.00
752.033227	250.0000	0.396	30.60	0.68	4.09	0.84
841.073593	0.0130	8.180	15.90	0.33	5.76	0.45
859.865000	0.1330	7.989	30.60	0.68	4.09	0.84
899.407000	0.0550	7.917	29.85	0.68	4.53	0.90
902.555000	0.0380	8.432	28.65	0.70	5.10	0.95
906.205524	0.1830	5.111	24.08	0.70	4.70	0.53
916.171582	8.5600	1.442	26.70	0.70	4.78	0.78
970.315022	9.1600	1.920	25.50	0.64	4.94	0.67
987.926764	138.0000	0.258	29.85	0.68	4.55	0.90

The dry air continuum arises from the non-resonant Debye spectrum of oxygen below 10 GHz and a pressure-induced nitrogen attenuation above 100 GHz.

$$N''_D(f) = f\, p\, \theta^2 \left[\frac{6.14 \times 10^{-5}}{d\left[1 + \left(\frac{f}{d}\right)^2\right]} + 1.4 \times 10^{-12} (1 - 1.2 \times 10^{-5}\, f^{1.5})\, p\, \theta^{1.5} \right] \tag{8}$$

where d is the width parameter for the Debye spectrum:

$$d = 5.6 \times 10^{-4} (p + 1.1\, e)\, \theta \tag{9}$$

The wet continuum, $N''_W(f)$, is included to account for the fact that measurements of water-vapour attenuation are generally in excess of those predicted using the theory described by equations (2) to (7), plus a term to include the effects of higher-frequency water-vapour lines not included in the reduced line base:

$$N''_W(f) = f (3.57\, \theta^{7.5}\, e + 0.113\, p)\, 10^{-7}\, e\, \theta^3 \tag{10}$$

2 Path attenuation

2.1 Terrestrial paths

For a terrestrial path, or for slightly inclined paths close to the ground, the path attenuation, A, may be written as:

$$A = \gamma r_0 = (\gamma_o + \gamma_w)\, r_0 \qquad \text{dB} \tag{11}$$

where r_0 is path length (km).

2.2 Slant paths

This section gives a method to integrate the specific attenuation calculated using the line-by-line model given above, at different pressures, temperatures and humidities through the atmosphere. By this means, the path attenuation for communications systems with any geometrical configuration within and external to the Earth's atmosphere may be accurately determined simply by dividing the atmosphere into horizontal layers, specifying the profile of the meteorological parameters pressure, temperature and humidity along the path. In the absence of local profiles, from radiosonde data, for example, the reference standard atmospheres in Recommendation ITU-R P.835 may be used, either for global application or for low (annual), mid (summer and winter) and high latitude (summer and winter) sites.

Figure 3 shows the zenith attenuation calculated at 1 GHz intervals with this model for the global reference standard atmosphere in Recommendation ITU-R P.835, with horizontal layers 1 km thick and summing the attenuations for each layer, for the cases of a moist atmosphere (Curve A) and a dry atmosphere (Curve B).

The total slant path attenuation, $A(h, \varphi)$, from a station with altitude, h, and elevation angle, φ, can be calculated as follows when $\varphi \geq 0$:

$$A(h, \varphi) = \int_h^\infty \frac{\gamma(H)}{\sin \Phi}\, \mathrm{d}H \tag{12}$$

where the value of Φ can be determined as follows based on Snell's law in polar coordinates:

$$\Phi = \arccos\left(\frac{c}{(r + H) \times n(H)}\right) \tag{13}$$

where:

$$c = (r + h) \times n(h) \times \cos \varphi \tag{14}$$

where $n(h)$ is the atmospheric radio refractive index, calculated from pressure, temperature and water-vapour pressure along the path (see Recommendation ITU-R P.835) using Recommendation ITU-R P.453.

On the other hand, when $\varphi < 0$, there is a minimum height, h_{min}, at which the radio beam becomes parallel with the Earth's surface. The value of h_{min} can be determined by solving the following transcendental equation:

$$(r + h_{min}) \times n(h_{min}) = c \tag{15}$$

This can be easily solved by repeating the following calculation, using $h_{min} = h$ as an initial value:

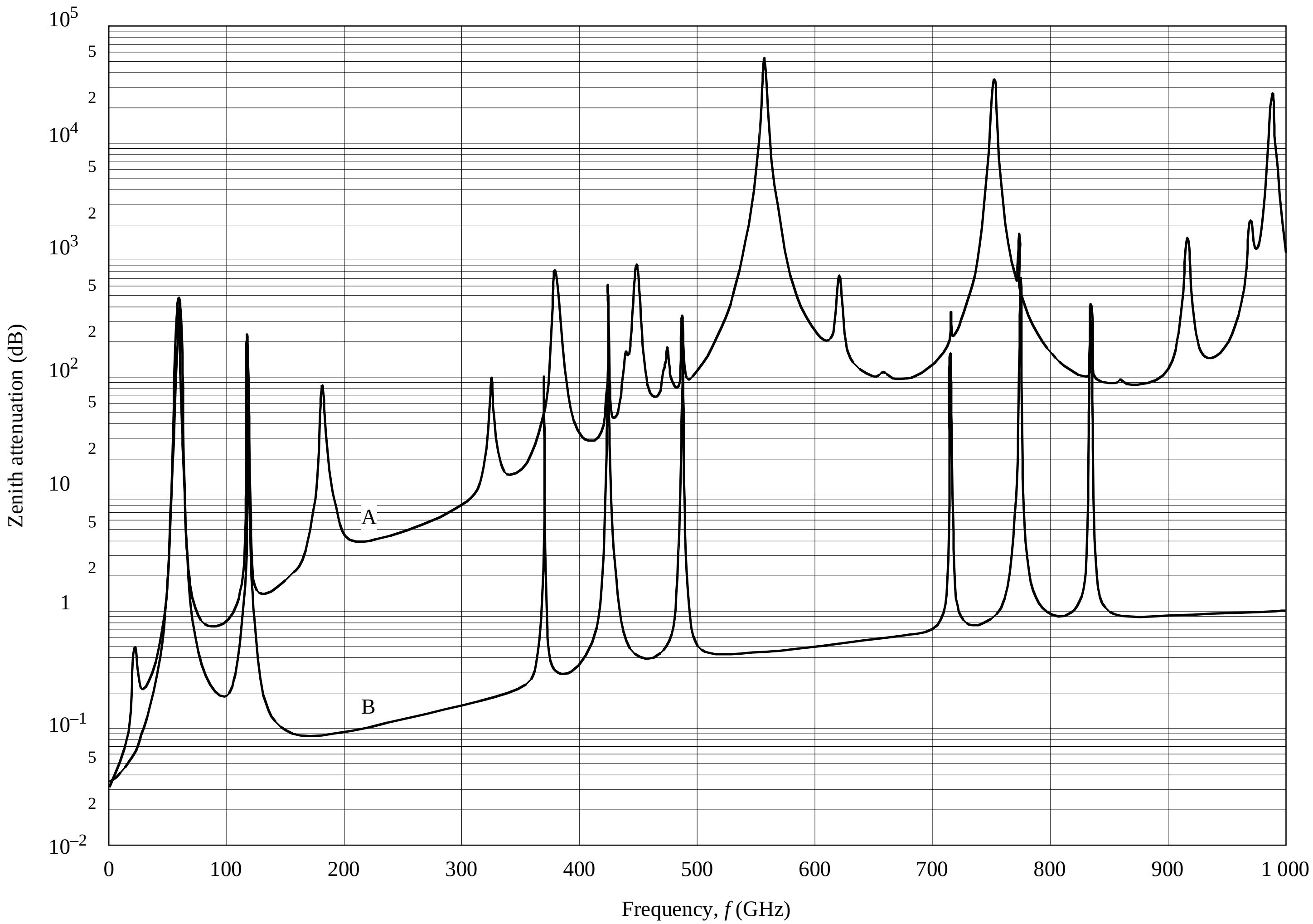
$$h'_{min} = \frac{c}{n(h_{min})} - r \tag{16}$$

Therefore, $A(h, \varphi)$ can be calculated as follows:

$$A(h, \varphi) = \int_{h_{min}}^\infty \frac{\gamma(H)}{\sin \Phi}\, \mathrm{d}H + \int_{h_{min}}^h \frac{\gamma(H)}{\sin \Phi}\, \mathrm{d}H \tag{17}$$

FIGURE 3

Zenith attenuation due to atmospheric gases, calculated in 1 GHz intervals, including line centres



Curves A: mean global reference atmosphere (7.5 g/m^3 at sea level)

B: dry atmosphere

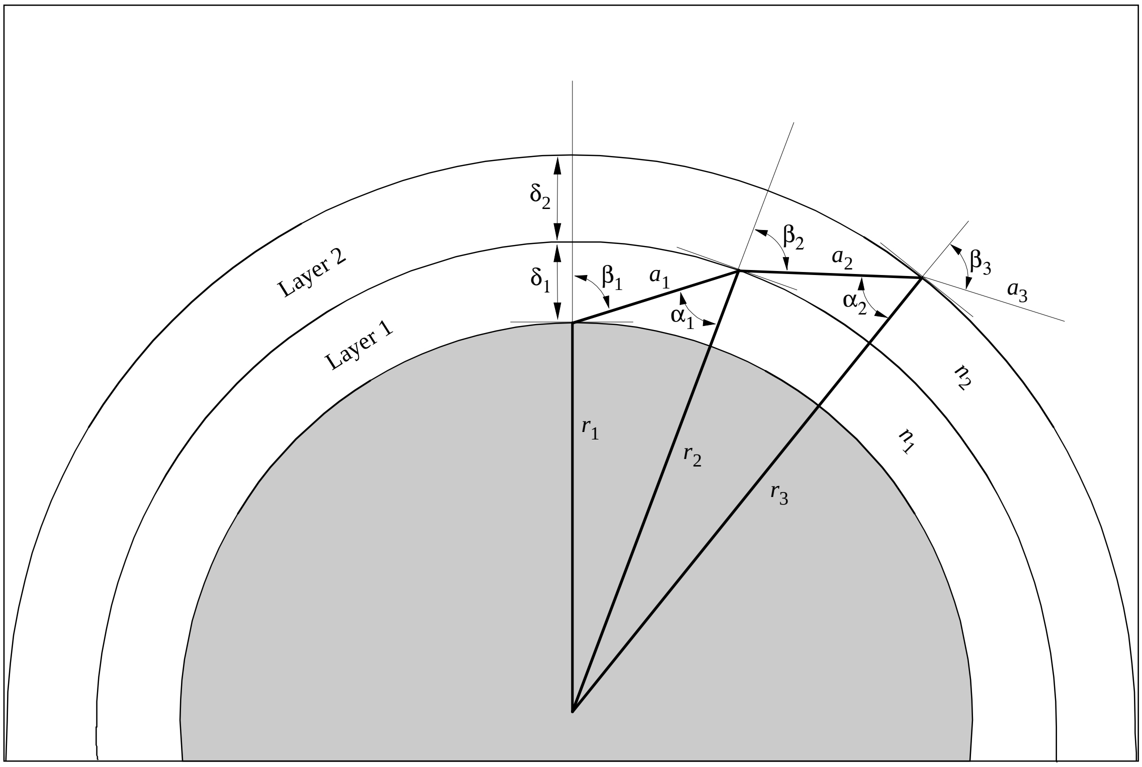
0676-03

In carrying out the integration of equations (12) and (17), care should be exercised in that the integrand becomes infinite at $\Phi = 0$. However, this singularity can be eliminated by an appropriate variable conversion, for example, by using $u^4 = H - h$ in equation (12) and $u^4 = H - h_{min}$ in equation (17).

A numerical solution for the attenuation due to atmospheric gases can be implemented with the following algorithm.

To calculate the total attenuation for a satellite link, it is necessary to know not only the specific attenuation at each point of the link but also the length of path that has that specific attenuation. To derive the path length it is also necessary to consider the ray bending that occurs in a spherical Earth.

FIGURE 4



0676-04

Using Fig. 4 as a reference, a_n is the path length through layer n with thickness δ_n that has refractive index n_n. α_n and β_n are the entry and exiting incidence angles. r_n are the radii from the centre of the Earth to the beginning of layer n. a_n can then be expressed as:

$$a_n = -r_n \cos \beta_n + \frac{1}{2}\sqrt{4 r_n^2 \cos^2 \beta_n + 8 r_n \delta_n + 4 \delta_n^2} \tag{18}$$

The angle α_n can be calculated from:

$$\alpha_n = \pi - \operatorname{arc\,cos}\left(\frac{-a_n^2 - 2 r_n \delta_n - \delta_n^2}{2 a_n r_n + 2 a_n \delta_n} \right) \tag{19}$$

β_1 is the incidence angle at the ground station (the complement of the elevation angle θ). β_{n+1} can be calculated from α_n using Snell's law that in this case becomes:

$$\beta_{n+1} = \operatorname{arc\,sin}\left(\frac{n_n}{n_{n+1}} \sin \alpha_n \right) \tag{20}$$

where n_n and n_{n+1} are the refractive indexes of layers n and $n + 1$.

The remaining frequency dependent (dispersive) term has a marginal influence on the result (around 1%) but can be calculated from the method shown in the ITU-R Handbook on Radiometeorology.

The total attenuation can be derived using:

$$A_{gas} = \sum_{n=1}^{k} a_n \ \gamma_n \qquad \text{dB} \tag{21}$$

where γ_n is the specific attenuation derived from equation (1).

To ensure an accurate estimate of the path attenuation, the thickness of the layers should increase exponentially, from 10 cm at the lowest layer (ground level) to 1 km at an altitude of 100 km, according to the following equation:

$$\delta_i = 0.0001 \ \exp\left\{\frac{i-1}{100}\right\} \qquad \text{km} \tag{22}$$

from $i = 1$ to 922, noting that $\delta_{922} \cong 1.0$ km and $\sum_{i=1}^{922} \delta_i \cong 100$ km.

For Earth-to-space applications, the integration should be performed at least up to 30 km, and up to 100 km at the oxygen line-centre frequencies.

3 Dispersive effects

The effects of dispersion are discussed in the ITU-R Handbook on Radiometeorology, which contains a model for calculating dispersion based on the line-by-line calculation. For practical purposes, dispersive effects should not impose serious limitations on millimetric terrestrial communication systems operating with bandwidths of up to a few hundred MHz over short ranges (for example, less than about 20 km), especially in the window regions of the spectrum, at frequencies removed from the centres of major absorption lines. For satellite communication systems, the longer path lengths through the atmosphere will constrain operating frequencies further to the window regions, where both atmospheric attenuation and the corresponding dispersion are low.

ANNEX 2

Approximate estimation of gaseous attenuation in the frequency range 1-350 GHz

This Annex contains simplified algorithms for quick, approximate estimation of gaseous attenuation for a limited range of meteorological conditions and a limited variety of geometrical configurations.

1 Specific attenuation

The specific attenuation due to dry air and water vapour, from sea level to an altitude of 5 km, can be estimated using the following simplified algorithms, which are based on curve-fitting to the line-by-line calculation, and agree with the more accurate calculations to within an average of about ±15% at frequencies removed from the centres of major absorption lines. The absolute difference between the results from these algorithms and the line-by-line calculation is generally less than 0.1 dB/km and reaches a maximum of 0.7 dB/km near 60 GHz. For altitudes higher than 5 km, and in cases where higher accuracy is required, the line-by-line calculation should be used.

For dry air, the attenuation γ_o (dB/km) is given by:

$$\gamma_o = \left[\frac{7.34\, r_p^2\, r_t^3}{f^2 + 0.36\, r_p^2\, r_t^2} + \frac{0.3429\, b\, \gamma_o'(54)}{(54 - f)^a + b} \right] f^2 \times 10^{-3} \tag{22a}$$

for $f \leq 54$ GHz

$$\begin{aligned} \gamma_o = \exp \{ [& 54^{-N} \ln(\gamma_o(54))(f - 57)(f - 60)(f - 63)(f - 66)/1944 \\ & - 57^{-N} \ln(\gamma_o(57))(f - 54)(f - 60)(f - 63)(f - 66)/486 \\ & + 60^{-N} \ln(\gamma_o(60))(f - 54)(f - 57)(f - 63)(f - 66)/324 \\ & - 63^{-N} \ln(\gamma_o(63))(f - 54)(f - 57)(f - 60)(f - 66)/486 \\ & + 66^{-N} \ln(\gamma_o(66))(f - 54)(f - 57)(f - 60)(f - 63)/1944] f^N \} \end{aligned} \tag{22b}$$

for $54 \text{ GHz} < f < 66$ GHz

$$\gamma_o = \left[\frac{0.2296\, d\, \gamma_o'(66)}{(f - 66)^c + d} + \frac{0.286\, r_p^2\, r_t^{3.8}}{(f - 118.75)^2 + 2.97\, r_p^2\, r_t^{1.6}} \right] f^2 \times 10^{-3} \tag{22c}$$

for $66 \text{ GHz} \leq f < 120$ GHz

$$\gamma_o = \left[3.02 \times 10^{-4} r_p^2\, r_t^{3.5} + \frac{1.5827\, r_p^2\, r_t^3}{(f - 66)^2} + \frac{0.286\, r_p^2\, r_t^{3.8}}{(f - 118.75)^2 + 2.97 r_p^2\, r_t^{1.6}} \right] f^2 \times 10^{-3} \tag{22d}$$

for $120 \text{ GHz} \leq f \leq 350$ GHz

with

$$\gamma_o'(54) = 2.128\, r_p^{1.4954}\, r_t^{-1.6032} \exp[-2.5280\,(1 - r_t)] \tag{22e}$$

$$\gamma_o(54) = 2.136\, r_p^{1.4975}\, r_t^{-1.5852} \exp[-2.5196\,(1 - r_t)] \tag{22f}$$

$$\gamma_o(57) = 9.984\, r_p^{0.9313}\, r_t^{2.6732} \exp[0.8563\,(1 - r_t)] \tag{22g}$$

$$\gamma_o(60) = 15.42\, r_p^{0.8595}\, r_t^{3.6178} \exp[1.1521\,(1 - r_t)] \tag{22h}$$

$$\gamma_o(63) = 10.63\, r_p^{0.9298}\, r_t^{2.3284} \exp[0.6287\,(1 - r_t)] \tag{22i}$$

$$\gamma_o(66) = 1.944\, r_p^{1.6673}\, r_t^{-3.3583} \exp[-4.1612\,(1 - r_t)] \tag{22j}$$

$$\gamma_o'(66) = 1.935\, r_p^{1.6657}\, r_t^{-3.3714} \exp[-4.1643\,(1 - r_t)] \tag{22k}$$

$$a = \ln(\eta_2 / \eta_1) / \ln 3.5 \tag{22l}$$

$$b = 4^a / \eta_1 \tag{22m}$$

$$\eta_1 = 6.7665\, r_p^{-0.5050}\, r_t^{0.5106} \exp[1.5663\,(1 - r_t)] - 1 \tag{22n}$$

$$\eta_2 = 27.8843\, r_p^{-0.4908}\, r_t^{-0.8491} \exp[0.5496\,(1 - r_t)] - 1 \tag{22o}$$

$$c = \ln(\xi_2 / \xi_1) / \ln 3.5 \tag{22p}$$

$$d = 4^c / \xi_1 \tag{22q}$$

$$\xi_1 = 6.9575\, r_p^{-0.3461}\, r_t^{0.2535} \exp[1.3766\,(1 - r_t)] - 1 \tag{22r}$$

$$\xi_2 = 42.1309\, r_p^{-0.3068}\, r_t^{1.2023} \exp[2.5147\,(1 - r_t)] - 1 \tag{22s}$$

$N = 0$ for $f \le 60$ GHz and $N = -15$ for $f > 60$ GHz

where:

f: frequency (GHz)

$r_p =$ $p/1013$

$r_t =$ $288/(273 + t)$

p: pressure (hPa)

t: temperature (°C).

For water vapour, the attenuation γ_w (dB/km) is given by:

$$\begin{aligned}\gamma_w = \Bigg\{ & 3.13 \times 10^{-2}\, r_p\, r_t^2 + 1.76 \times 10^{-3}\, \rho\, r_t^{8.5} + r_t^{2.5} \Bigg[\frac{3.84\, \xi_{w1}\, g_{22} \exp(2.23\,(1 - r_t))}{(f - 22.235)^2 + 9.42\, \xi_{w1}^2} \\ & + \frac{10.48\, \xi_{w2} \exp(0.7\,(1 - r_t))}{(f - 183.31)^2 + 9.48\, \xi_{w2}^2} + \frac{0.078\, \xi_{w3} \exp(6.4385\,(1 - r_t))}{(f - 321.226)^2 + 6.29\, \xi_{w3}^2} \\ & + \frac{3.76\, \xi_{w4} \exp(1.6\,(1 - r_t))}{(f - 325.153)^2 + 9.22\, \xi_{w4}^2} + \frac{26.36\, \xi_{w5} \exp(1.09\,(1 - r_t))}{(f - 380)^2} \\ & + \frac{17.87\, \xi_{w5} \exp(1.46\,(1 - r_t))}{(f - 448)^2} + \frac{883.7\, \xi_{w5}\, g_{557} \exp(0.17\,(1 - r_t))}{(f - 557)^2} \\ & + \frac{302.6\, \xi_{w5}\, g_{752} \exp(0.41\,(1 - r_t))}{(f - 752)^2} \Bigg] \Bigg\} f^2 \rho \times 10^{-4}\end{aligned} \tag{23a}$$

for $f \le 350$ GHz

with

$$\xi_{w1} = 0.9544\, r_p\, r_t^{0.69} + 0.0061\, \rho \tag{23b}$$

$$\xi_{w2} = 0.95\, r_p\, r_t^{0.64} + 0.0067\, \rho \tag{23c}$$

$$\xi_{w3} = 0.9561\, r_p\, r_t^{0.67} + 0.0059\, \rho \tag{23d}$$

$$\xi_{w4} = 0.9543\, r_p\, r_t^{0.68} + 0.0061\, \rho \tag{23e}$$

$$\xi_{w5} = 0.955\, r_p\, r_t^{0.68} + 0.006\, \rho \tag{23f}$$

$$g_{22} = 1 + (f - 22.235)^2 / (f + 22.235)^2 \tag{23g}$$

$$g_{557} = 1 + (f - 557)^2 / (f + 557)^2 \tag{23h}$$

$$g_{752} = 1 + (f - 752)^2 / (f + 752)^2 \tag{23i}$$

where ρ is the water-vapour density (g/m^3).

Figure 5 shows the specific attenuation from 1 to 350 GHz at sea-level for dry air and water vapour with a density of 7.5 g/m^3.

2 Path attenuation

2.1 Terrestrial paths

For a horizontal path, or for slightly inclined paths close to the ground, the path attenuation, A, may be written as:

$$A = \gamma\, r_0 = (\gamma_o + \gamma_w)\, r_0 \qquad \text{dB} \tag{24}$$

where r_0 is the path length (km).

2.2 Slant paths

This section contains simple algorithms for estimating the gaseous attenuation along slant paths through the Earth's atmosphere, by defining an equivalent height by which the specific attenuation calculated in § 1 may be multiplied to obtain the zenith attenuation. The resulting zenith attenuations are accurate to within ±10% from sea level up to altitudes of about 2 km, using the pressure, temperature and water-vapour density appropriate to the altitude of interest, except at frequencies within 0.5 GHz of the centres of resonance lines, where the procedure in Annex 1 should be used. The path attenuation at elevation angles other than the zenith may then be determined using the procedures described later in this section. For dry air, the equivalent height is given by:

$$h_o = 5.386 - 3.32734 \times 10^{-2}\, f + 1.87185 \times 10^{-3}\, f^2 - 3.52087 \times 10^{-5}\, f^3 + \frac{83.26}{(f - 60)^2 + 1.2} \quad \text{km} \tag{25a}$$

$$\text{for } 1\ \text{GHz} \le f \le 56.7\ \text{GHz}$$

$$h_o = 10\ \text{km} \qquad \text{for } 56.7\ \text{GHz} < f < 63.3\ \text{GHz} \tag{25b}$$

$$h_o = f\left\{\frac{0.039581 - 1.19751 \times 10^{-3}\, f + 9.14810 \times 10^{-6}\, f^2}{1 - 0.028687\, f + 2.07858 \times 10^{-4}\, f^2}\right\} + \frac{90.6}{(f - 60)^2} \quad \text{km} \tag{25c}$$

$$\text{for } 63.3\ \text{GHz} \le f < 98.5\ \text{GHz}$$

$$h_o = 5.542 - 1.76414 \times 10^{-3}\, f + 3.05354 \times 10^{-6}\, f^2 + \frac{6.815}{(f - 118.75)^2 + 0.321} \quad \text{km} \tag{25d}$$

$$\text{for } 98.5\ \text{GHz} \le f \le 350\ \text{GHz}$$

and for water-vapour, the equivalent height is:

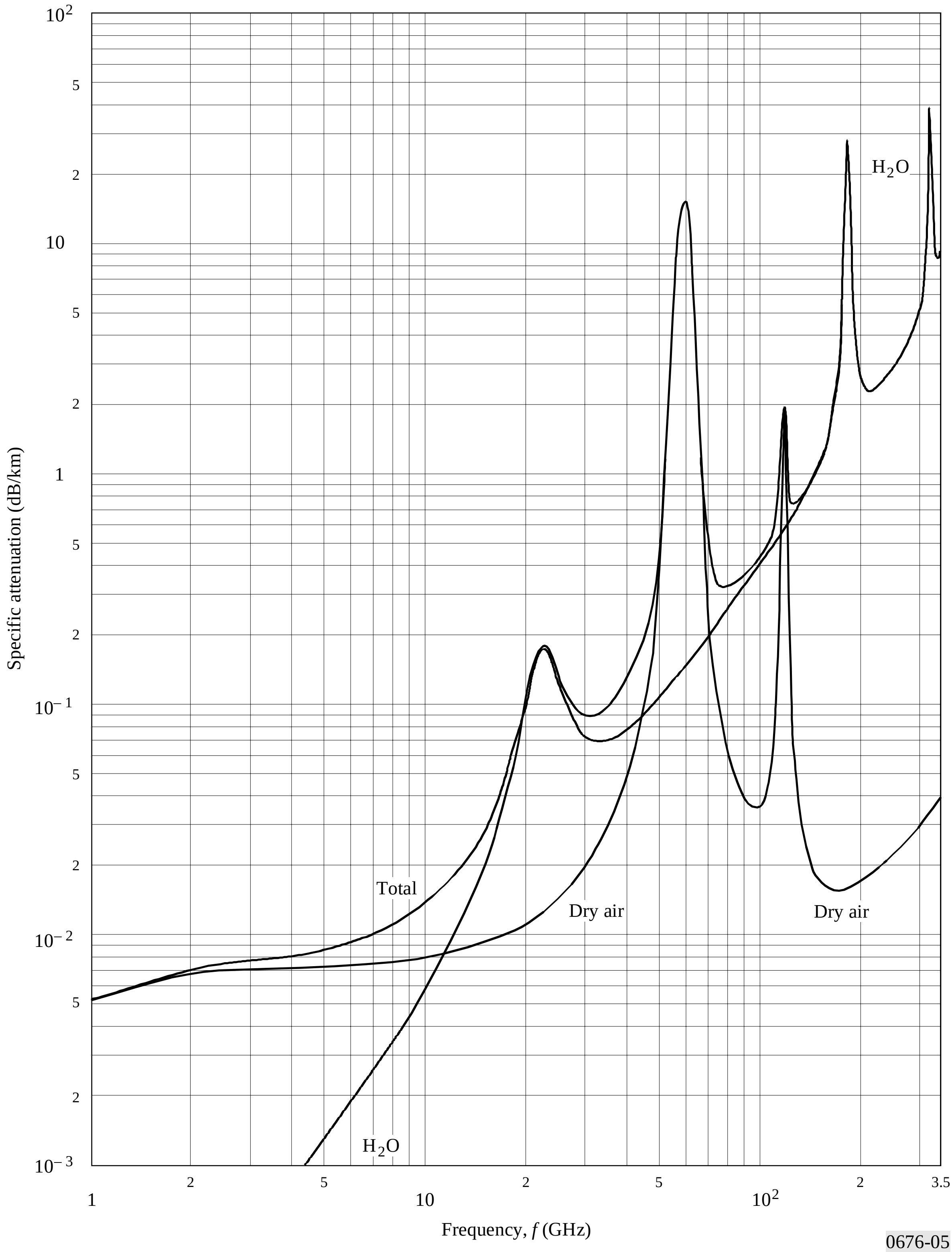
$$h_w = 1.65\left\{1 + \frac{1.61}{(f - 22.23)^2 + 2.91} + \frac{3.33}{(f - 183.3)^2 + 4.58} + \frac{1.90}{(f - 325.1)^2 + 3.34}\right\} \quad \text{km} \tag{26}$$

$$\text{for } f \le 350\ \text{GHz}$$

The zenith attenuation between 50 to 70 GHz is a complicated function of frequency, as shown in Fig. 7, and the above algorithms for equivalent height can provide only an approximate estimate, in general, of the minimum levels of attenuation likely to be encountered in this frequency range. For greater accuracy, the procedure in Annex 1 should be used.

FIGURE 5

Specific attenuation due to atmospheric gases



Pressure: 1 013 hPa
Temperature: 15° C
Water vapour: 7.5 g/m^3

The concept of equivalent height is based on the assumption of an exponential atmosphere specified by a scale height to describe the decay in density with altitude. Note that scale heights for both dry air and water vapour may vary with latitude, season and/or climate, and that water vapour distributions in the real atmosphere may deviate considerably from the exponential, with corresponding changes in equivalent heights. The values given above are applicable up to an altitude of 2 km.

The total zenith attenuation is then:

$$A = \gamma_o \, h_o + \gamma_w \, h_w \qquad \text{dB} \tag{27}$$

Figure 6 shows the total zenith attenuation at sea level, as well as the attenuation due to dry air and water vapour, using the mean annual global reference atmosphere given in Recommendation ITU-R P.835. Between 50 and 70 GHz greater accuracy can be obtained from the 0 km curve in Fig. 7 which was derived using the line-by-line calculation as described in Annex 1.

2.2.1 Elevation angles between 10° and 90°

For elevation angles between 10° and 90°, the path attenuation is obtained using the cosecant law:

$$A = \frac{h_o \, \gamma_o + h_w \, \gamma_w}{\sin \varphi} \qquad \text{dB} \tag{28}$$

where φ is the elevation angle.

To determine the attenuation values on an inclined path between a station situated at altitude h_1 and another at a higher altitude h_2, the values h_o and h_w in equation (28) must be replaced by the following h_o' and h_w' values:

$$h_o' = h_o \left[e^{-h_1 / h_o} - e^{-h_2 / h_o} \right] \qquad \text{km} \tag{29}$$

$$h_w' = h_w \left[e^{-h_1 / h_w} - e^{-h_2 / h_w} \right] \qquad \text{km} \tag{30}$$

it being understood that the value ρ of the water vapour density used in equation (23) is the hypothetical value at sea level calculated as follows:

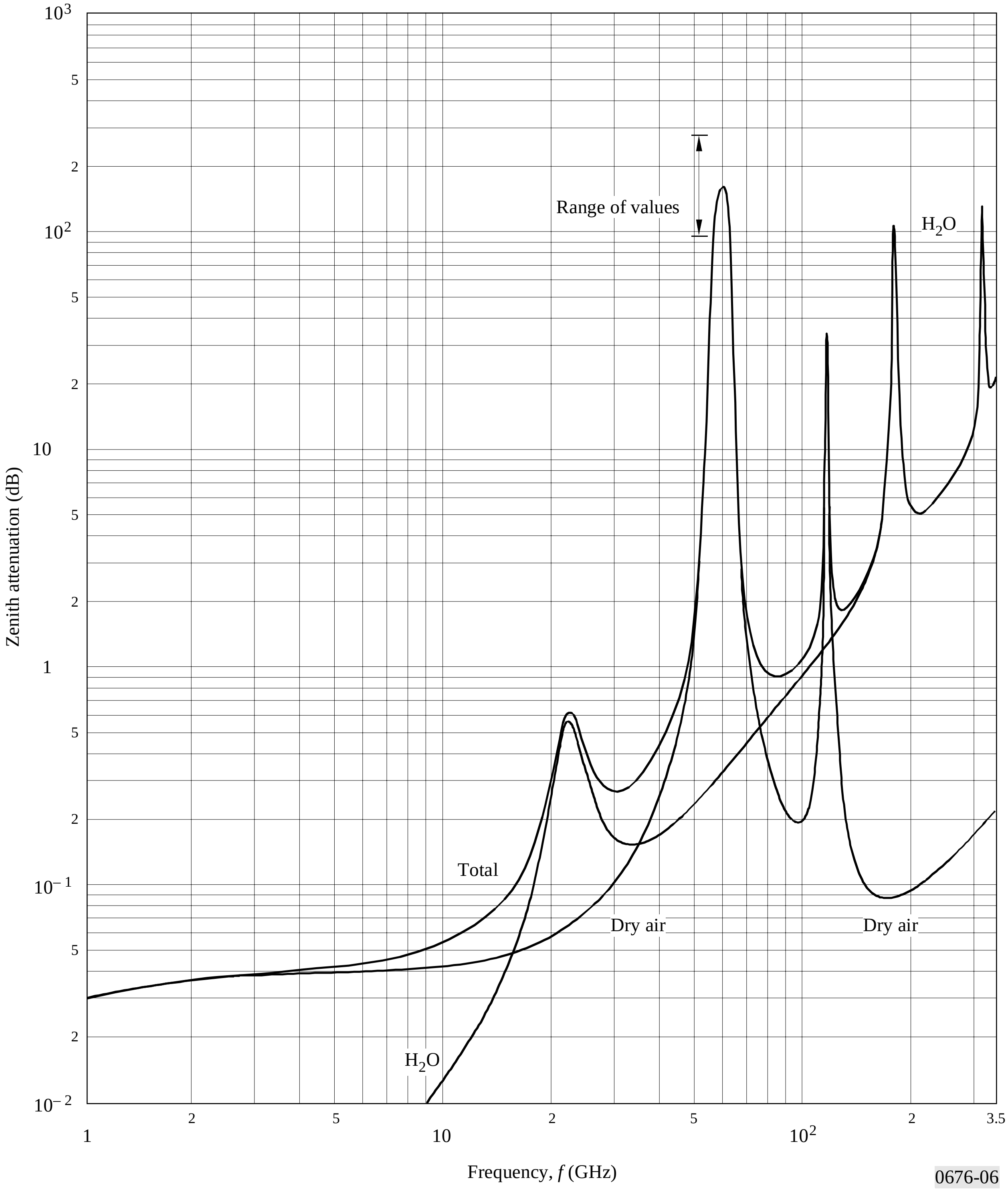
$$\rho = \rho_1 \times \exp(h_1 / 2) \tag{31}$$

where ρ_1 is the value corresponding to altitude h_1 of the station in question, and the equivalent height of water vapour density is assumed as 2 km (see Recommendation ITU-R P.835).

Equations (29), (30) and (31) use different normalizations for the dry air and water vapour equivalent heights. While the mean air pressure referred to sea level can be considered constant around the world (equal to 1 013 hPa), the water vapour density not only has a wide range of climatic variability but is measured at the surface (i.e. at the height of the ground station). For values of surface water vapour density, see Recommendation ITU-R P.836.

FIGURE 6

Total, dry air and water vapour attenuation at the zenith from sea level



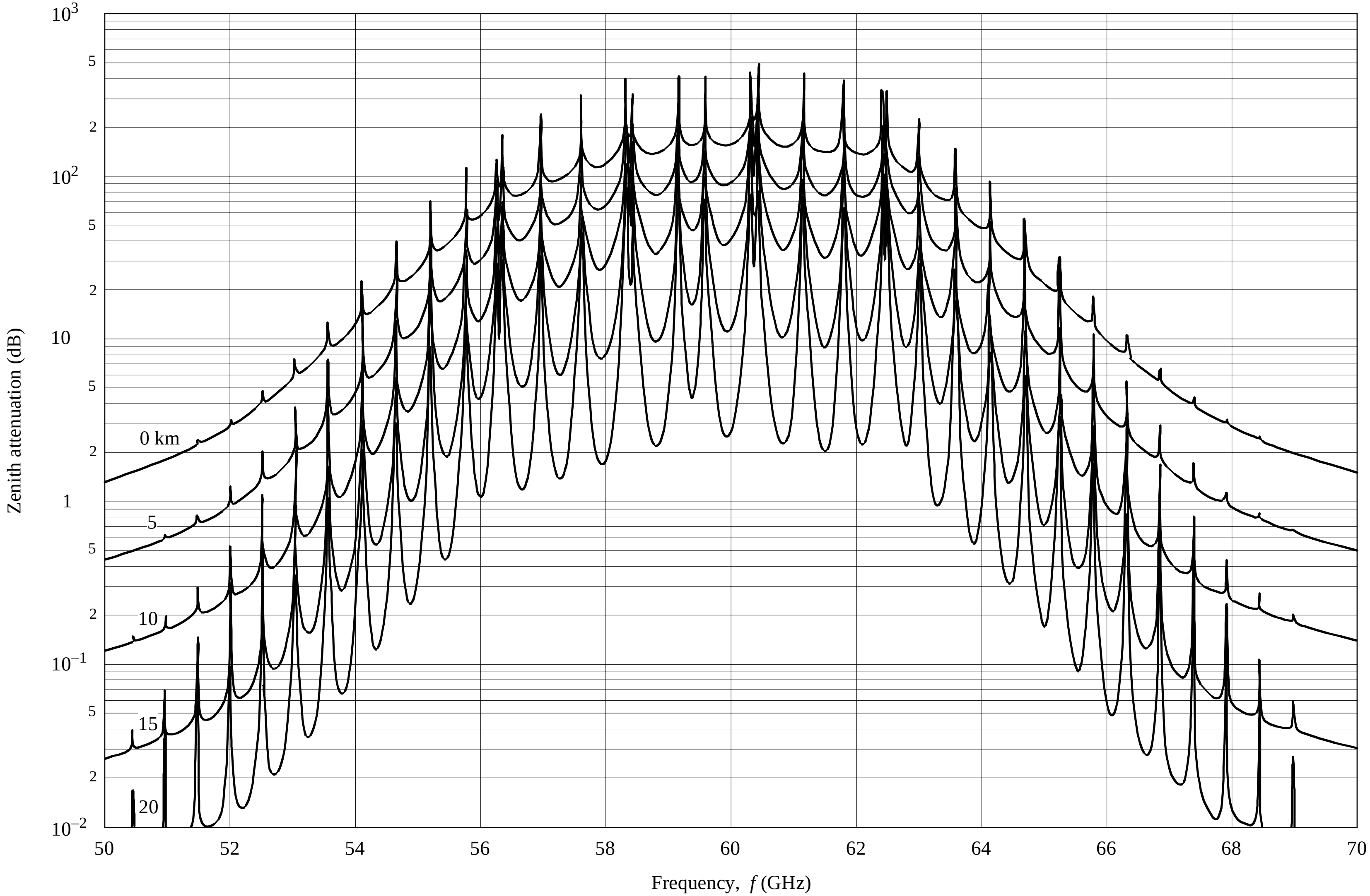
Surface pressure: 1 013 hPa

Surface temperature: 15° C

Surface humidity: 7.5 g/m^3

FIGURE 7

Zenith oxygen attenuation from the altitudes indicated, calculated at intervals of 50 MHz, including line centres



0676-07

2.2.2 Elevation angle between 0° and 10°

In this case, equations (28) to (31) must be replaced by more accurate formulae allowing for the real length of the atmospheric path. This leads to the following formulae:

$$A = \frac{\sqrt{R_e}}{\cos\varphi}\left[\gamma_o \sqrt{h_o}\ \mathrm{F}\left(\tan\varphi\sqrt{\frac{R_e}{h_o}}\right) + \gamma_w \sqrt{h_w}\ \mathrm{F}\left(\tan\varphi\sqrt{\frac{R_e}{h_w}}\right)\right] \quad \text{dB} \tag{32}$$

where:

R_e : effective Earth radius including refraction, given in Recommendation ITU-R P.834, expressed in km (a value of 8 500 km is generally acceptable for the immediate vicinity of the Earth's surface)

φ : elevation angle

F : function defined by:

$$\mathrm{F}(x) = \frac{1}{0.661\,x + 0.339\sqrt{x^2 + 5.51}} \tag{33}$$

The formula (32) is applicable to cases of inclined paths between a satellite and an earth station situated at sea level. To determine the attenuation values on an inclined path between a station situated at altitude h_1 and a higher altitude h_2 (where both altitudes are less than 1 000 km above mean sea level), equation (32) must be replaced by the following:

$$A = \gamma_o \sqrt{h_o}\left[\frac{\sqrt{R_e + h_1}\cdot \mathrm{F}(x_1)\,\mathrm{e}^{-h_1/h_o}}{\cos\varphi_1} - \frac{\sqrt{R_e + h_2}\cdot \mathrm{F}(x_2)\,\mathrm{e}^{-h_2/h_o}}{\cos\varphi_2}\right]$$

$$+\ \gamma_w \sqrt{h_w}\left[\frac{\sqrt{R_e + h_1}\cdot \mathrm{F}(x'_1)\,\mathrm{e}^{-h_1/h_w}}{\cos\varphi_1} - \frac{\sqrt{R_e + h_2}\cdot \mathrm{F}(x'_2)\,\mathrm{e}^{-h_2/h_w}}{\cos\varphi_2}\right] \quad \text{dB} \tag{34}$$

where:

φ_1 : elevation angle at altitude h_1

$$\varphi_2 = \arccos\left(\frac{R_e + h_1}{R_e + h_2}\cos\varphi_1\right) \tag{35a}$$

$$x_i = \tan\varphi_i\sqrt{\frac{R_e + h_i}{h_o}} \qquad \text{for } i = 1, 2 \tag{35b}$$

$$x'_i = \tan\varphi_i\sqrt{\frac{R_e + h_i}{h_w}} \qquad \text{for } i = 1, 2 \tag{35c}$$

it being understood that the value ρ of the water vapour density used in equation (23) is the hypothetical value at sea level calculated as follows:

$$\rho = \rho_1 \cdot \exp(h_1 / 2) \tag{36}$$

where ρ_1 is the value corresponding to altitude h_1 of the station in question, and the equivalent height of water vapour density is assumed as 2 km (see Recommendation ITU-R P.835).

Values for ρ_1 at the surface can be found in Recommendation ITU-R P.836. The different formulation for dry air and water vapour is explained at the end of § 2.2.

For elevation angles less than 0°, the line-by-line calculation in Annex 1 must be used.

2.3 Slant path water-vapour attenuation

The above method for calculating slant path attenuation by water vapour relies on the knowledge of the profile of water-vapour pressure (or density) along the path. In cases where the total columnar water vapour content along the path, V, is known, an alternative method may be used. The total water-vapour attenuation in the zenith direction can be expressed as:

$$A_w = a_v V \qquad \text{dB} \tag{37}$$

where V (kg/m^2 or mm) and a_v (dB/kg/m^2 or dB/mm) is the water-vapour mass absorption coefficient. The mass absorption coefficient can be calculated from the specific attenuation coefficient γ_w, divided by the water-vapour density ρ, which may be obtained from the water-vapour pressure using equation (4).

Values for the total columnar content V can be obtained either from radiosonde profiles or radiometric measurements. Statistics of V are given in Recommendation ITU-R P.836. For elevation angles other than the zenith, the attenuation must be divided by sin θ, where θ is the elevation angle, assuming a uniform horizontally-stratified atmosphere, down to elevation angles of about 10°.