RECOMMENDATION ITU-R P.835-4

Reference standard atmospheres

(Question ITU-R 201/3)

(1992-1994-1997-1999-2005)

The ITU Radiocommunication Assembly,

considering

a) the necessity for a reference standard atmosphere for use in calculating gaseous attenuation along an Earth-space path,

recommends

1 that the standard atmospheres in Annex 1 be used to determine temperature, pressure and water-vapour pressure as a function of altitude, for calculating gaseous attenuation when more reliable local data are not available;

2 that the experimental data in Annexes 2 and 3 be used for the locations of interest when seasonal and monthly variations are concerned.

Annex 1

1 Mean annual global reference atmosphere

The following reference standard atmosphere reflects the annual mean profiles when averaged across the globe.

1.1 Temperature and pressure

The reference standard atmosphere is based on the United States Standard Atmosphere, 1976, in which the atmosphere is divided into seven successive layers showing linear variation with temperature, as given in Fig. 1.

The temperature T at height h is given by:

$$T(h) = T_i + L_i (h - H_i) \qquad \text{K} \tag{1}$$

where:

$$T_i = T(H_i) \tag{2}$$

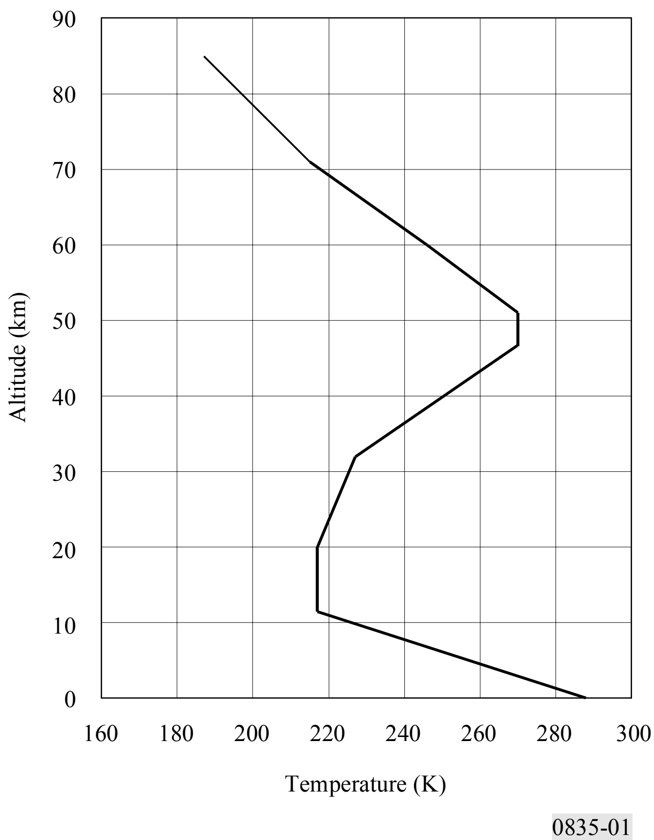
and L_i is the temperature gradient starting at altitude H_i and is given in Table 1.

TABLE 1

Subscript, i	Altitude, H_i (km)	Temperature gradient, L_i (K/km)
0	0	–6.5
1	11	0.0
2	20	+1.0
3	32	+2.8
4	47	0.0
5	51	–2.8
6	71	–2.0
7	85	

FIGURE 1

Reference profile of atmospheric temperature



When the temperature gradient $L_i \neq 0$, pressure is given by the equation:

$$P(h) = P_i \left[\frac{T_i}{T_i + L_i (h - H_i)} \right]^{34.163 / L_i} \quad \text{hPa} \tag{3}$$

and when the temperature gradient $L_i = 0$, pressure is obtained from the equation:

$$P(h) = P_i \exp \left[\frac{-34.163 (h - H_i)}{T_i} \right] \quad \text{hPa} \tag{4}$$

The ground-level standard temperature and pressure are:

$$T_0 = 288.15 \quad \text{K}$$
$$P_0 = 1\,013.25 \quad \text{hPa} \tag{5}$$

Note that above about 85 km altitude, local thermodynamic equilibrium of the atmosphere starts to break down, and the hydrostatic equation, on which the above equations are based, is no longer valid.

1.2 Water-vapour pressure

The distribution of water vapour in the atmosphere is generally highly variable, but may be approximated by the equation:

$$\rho(h) = \rho_0 \exp(-h / h_0) \quad \text{g/m}^3 \tag{6}$$

where the scale height $h_0 = 2$ km, and the standard ground-level water-vapour density is:

$$\rho_0 = 7.5 \quad \text{g/m}^3 \tag{7}$$

Vapour pressure is obtained from the density using the equation (see Recommendation ITU-R P.453):

$$e(h) = \frac{\rho(h)\, T(h)}{216.7} \quad \text{hPa} \tag{8}$$

Water-vapour density decreases exponentially with increasing altitude, up to an altitude where the mixing ratio $e(h)/P(h) = 2 \times 10^{-6}$. Above this altitude, the mixing ratio is assumed to be constant.

1.3 Dry atmosphere for attenuation calculations

The profile of the density of atmospheric gases other than water vapour (the "dry atmosphere") may be found from the temperature and pressure profiles given in § 1.1.

For attenuation calculations, this density profile may be approximated by an exponential profile according to equation (6) with:

$$h_0 = 6 \text{ km} \tag{9}$$

2 Low-latitude annual reference atmosphere

For low latitudes (smaller than 22°) the seasonal variations are not very important and a single annual profile can be used.

The temperature T (K) at height h (km) is given by:

$T(h) = 300.4222 - 6.3533\ h + 0.005886\ h^2$ for $0 \leq h < 17$

$T(h) = 194 + (h - 17)\ 2.533$ for $17 \leq h < 47$

$T(h) = 270$ for $47 \leq h < 52$

$T(h) = 270 - (h - 52)\ 3.0714$ for $52 \leq h < 80$

$T(h) = 184$ for $80 \leq h \leq 100$

while the pressure P (hPa):

$P(h) = 1012.0306 - 109.0338\ h + 3.6316\ h^2$ for $0 \leq h < 10$

$P(h) = P_{10} \exp\,[-0.147\ (h - 10)]$ for $10 \leq h < 72$

$P(h) = P_{72} \exp\,[-0.165\ (h - 72)]$ for $72 \leq h \leq 100$

where P_{10} and P_{72} are the pressures at 10 and 72 km respectively.

For water vapour (g/m^3):

$\rho(h) = 19.6542 \exp\,[-0.2313\ h - 0.1122\ h^2 + 0.01351\ h^3 - 0.0005923\ h^4]$ for $0 \leq h \leq 15$

$\rho(h) = 0$ for $h > 15$

3 Mid-latitude reference atmosphere

For mid-latitudes (between 22° and 45°) the following profiles may be used for the summer and winter.

3.1 Summer mid-latitude

The temperature T (K) at height h (km) is given by:

$T(h) = 294.9838 - 5.2159\ h - 0.07109\ h^2$ for $0 \leq h < 13$

$T(h) = 215.5$ for $13 \leq h < 17$

$T(h) = 215.5 \exp\,[(h - 17)\ 0.008128]$ for $17 \leq h < 47$

$T(h) = 275$ for $47 \leq h < 53$

$T(h) = 275 + \{1 - \exp\,[(h - 53)\ 0.06]\}\ 20$ for $53 \leq h < 80$

$T(h) = 175$ for $80 \leq h \leq 100$

while the pressure P (hPa):

$P(h) = 1012.8186 - 111.5569\ h + 3.8646\ h^2$ for $0 \leq h < 10$

$P(h) = P_{10} \exp\,[-0.147\ (h - 10)]$ for $10 \leq h < 72$

$P(h) = P_{72} \exp\,[-0.165\ (h - 72)]$ for $72 \leq h \leq 100$

where P_{10} and P_{72} are the pressures at 10 and 72 km respectively.

For water vapour (g/m^3):

$\rho(h) = 14.3542 \exp\,[-0.4174\ h - 0.02290\ h^2 + 0.001007\ h^3]$ for $0 \leq h \leq 10$

$\rho(h) = 0$ for $h > 10$

3.2 Winter mid-latitude

The temperature T (K) at height h (km) is given by:

$T(h) = 272.7241 - 3.6217\ h - 0.1759\ h^2$	for	$0 \le h < 10$
$T(h) = 218$	for	$10 \le h < 33$
$T(h) = 218 + (h - 33)\ 3.3571$	for	$33 \le h < 47$
$T(h) = 265$	for	$47 \le h < 53$
$T(h) = 265 - (h - 53)\ 2.0370$	for	$53 \le h < 80$
$T(h) = 210$	for	$80 \le h \le 100$

while the pressure P (hPa):

$P(h) = 1018.8627 - 124.2954\ h + 4.8307\ h^2$	for	$0 \le h < 10$
$P(h) = P_{10} \exp\ [-0.147\ (h - 10)]$	for	$10 \le h < 72$
$P(h) = P_{72} \exp\ [-0.155\ (h - 72)]$	for	$72 \le h \le 100$

where P_{10} and P_{72} are the pressures at 10 and 72 km respectively.

For water vapour (g/m^3):

$\rho(h) = 3.4742 \exp\ [-\ 0.2697\ h - 0.03604\ h^2 + 0.0004489\ h^3]$	for	$0 \le h \le 10$
$\rho(h) = 0$	for	$h > 10$

4 High latitude reference atmosphere

For high latitudes (higher than 45°) the following profiles may be used for the summer and winter.

4.1 Summer high latitude

The temperature T (K) at height h (km) is given by:

$T(h) = 286.8374 - 4.7805\ h - 0.1402\ h^2$	for	$0 \le h < 10$
$T(h) = 225$	for	$10 \le h < 23$
$T(h) = 225 \exp\ [(h - 23)\ 0.008317]$	for	$23 \le h < 48$
$T(h) = 277$	for	$48 \le h < 53$
$T(h) = 277 - (h - 53)\ 4.0769$	for	$53 \le h < 79$
$T(h) = 171$	for	$79 \le h \le 100$

while the pressure P (hPa):

$P(h) = 1008.0278 - 113.2494\ h + 3.9408\ h^2$	for	$0 \le h < 10$
$P(h) = P_{10} \exp\ [-0.140\ (h - 10)]$	for	$10 \le h < 72$
$P(h) = P_{72} \exp\ [-0.165\ (h - 72)]$	for	$72 \le h \le 100$

where P_{10} and P_{72} are the pressures at 10 and 72 km respectively.

For water vapour (g/m^3):

$\rho(h) = 8.988 \exp\ [-\ 0.3614\ h - 0.005402\ h^2 - 0.001955\ h^3]$	for	$0 \le h \le 15$
$\rho(h) = 0$	for	$h > 15$

4.2 Winter high latitude

The temperature T (K) at height h (km) is given by:

$$T(h) = 257.4345 + 2.3474\, h - 1.5479\, h^2 + 0.08473\, h^3 \quad \text{for} \quad 0 \le h < 8.5$$

$$T(h) = 217.5 \quad \text{for} \quad 8.5 \le h < 30$$

$$T(h) = 217.5 + (h - 30)\, 2.125 \quad \text{for} \quad 30 \le h < 50$$

$$T(h) = 260 \quad \text{for} \quad 50 \le h < 54$$

$$T(h) = 260 - (h - 54)\, 1.667 \quad \text{for} \quad 54 \le h \le 100$$

while the pressure P (hPa):

$$P(h) = 1010.8828 - 122.2411\, h + 4.554\, h^2 \quad \text{for} \quad 0 \le h < 10$$

$$P(h) = P_{10} \exp\, [-0.147\, (h - 10)] \quad \text{for} \quad 10 \le h < 72$$

$$P(h) = P_{72} \exp\, [-0.150\, (h - 72)] \quad \text{for} \quad 72 \le h \le 100$$

where P_{10} and P_{72} are the pressures at 10 and 72 km respectively.

For water vapour (g/m^3):

$$\rho(h) = 1.2319 \exp\, [0.07481\, h - 0.0981\, h^2 + 0.00281\, h^3] \quad \text{for} \quad 0 \le h \le 10$$

$$\rho(h) = 0 \quad \text{for} \quad h > 10$$

Bibliography

BRUSSAARD, G., DAMOSSO, E. and STOLA, L. [October, 1983] Characterisation of the 50-70 GHz band for space communications. *CSELT Rapporti Tecnici*, Vol. XI, **5**.

Annex 2

1 Experimental data of atmospheric vertical profiles

Monthly averages of vertical profiles of temperature, pressure and relative humidity were calculated for 353 locations over the world, using 10 years (1980-1989) of radiosonde observations. This dataset (DST.STD) is available from ITU/BR and contains the mean monthly vertical profiles, for both 00.00 UTC and 12.00 UTC, of pressure, temperature and relative humidity. These profiles, calculated in the absence of rain, range from 0 to 16 km with a step of 500 m. The mean monthly profiles are contained in ASCII files named **<*WMO_code*>.dat**, where *WMO_code* is the code name of the site according to the World Meteorological Organization (e.g.: 03496.dat, 03496 is the WMO station code for Hemsby-in-Norfolk). An example of one profile is given in Table 2. The list of locations is contained in an ASCII file (using the comma separated value file, CSV, file format) called **dst_std_lst.csv**. Each record of this file contains the following field: WMO_CODE, Station Name, Country, Latitude, Longitude, Altitude above sea level. An example of such a record is given in Table 3.

Above the maximum altitude, extrapolation can be performed by using the reference profiles given in Annex 1. To translate the relative humidity into absolute values of water-vapour density, the formulae contained in Recommendation ITU-R P.453 should be used.

TABLE 2

DST.STD data format – Example of month average profile (station 10410)

YYMMDDHH NL			
99 199 0 33			
Press (hPa)	Z (km)	Temp (K)	RH (%/100)
1 016.905	0.00	273.62	0.864E+00
956.686	0.50	273.33	0.830E+00
898.555	1.00	271.74	0.754E+00
844.014	1.50	269.59	0.665E+00
791.860	2.00	267.15	0.591E+00
742.661	2.50	264.56	0.518E+00
696.285	3.00	261.89	0.470E+00
651.977	3.50	258.94	0.458E+00
610.086	4.00	255.88	0.448E+00
570.467	4.50	252.69	0.445E+00
533.076	5.00	249.33	0.451E+00
497.767	5.50	245.90	0.453E+00
464.123	6.00	242.32	0.450E+00
432.441	6.50	238.75	0.450E+00
402.414	7.00	235.16	0.443E+00
374.177	7.50	231.59	0.437E+00
347.236	8.00	228.12	0.433E+00
322.281	8.50	224.88	0.427E+00
298.474	9.00	221.89	0.421E+00
276.492	9.50	219.27	0.416E+00
255.527	10.00	217.08	0.411E+00
236.297	10.50	215.62	0.402E+00
218.415	11.00	214.79	0.393E+00
201.366	11.50	214.14	0.348E+00
186.214	12.00	214.02	0.205E+00
172.093	12.50	214.24	0.104E+00
158.709	13.00	214.66	0.368E-01
146.492	13.50	214.94	0.351E-02
135.813	14.00	214.88	0.120E-02
125.690	14.50	214.50	0.117E-02
116.027	15.00	214.01	0.113E-02
106.798	15.50	213.56	0.110E-02
98.291	16.00	213.26	0.107E-02

Legend to Table 2:

YY = Year (99 for mean monthly profiles)

MM = Month (1 = January, 2 = February, ...)

DD = Day of the month (99 for mean monthly profiles)

HH = Hour of the day (UTC)

NL = Number of vertical levels (NL = 33 for STD.DST)

Press (hPa) = Atmospheric total pressure

Z (km) = Height above the Earth's surface

Temp (K) = Air temperature

RH (%/100) = Relative humidity (as a fraction)

NOTE 1 – The level values of Temp and Press may be set to zero if unrecorded.

TABLE 3

DST_STD_LST.CSV station information file – Example of record structure

WMO code	Station name	Country	Latitude (degrees)	Longitude (degrees)	Asl (m)
10 410	ESSEN	DL	51.4	6.967	153

NOTE 1 – Latitude and longitude values are in decimal degrees (i.e. 51.4 = 51º 24').

Annex 3

1 Numerical weather prediction data of atmospheric vertical profiles

Monthly averages, conditioned to the hour of the day, of vertical profiles of temperature, pressure and water-vapour density were calculated using the ECMWF 15-year data set (ERA15) from the re-analysis project. This dataset (ESA_STD_PROF) is available from ITU/BR and contains the mean monthly vertical profiles, for 00.00, 06.00, 12.00 and 18.00 UTC, of total air pressure, air temperature and water-vapour density. These profiles extend from a reference height located around the local Earth's surface up to about 30 km above the Earth's surface and contains 32 levels derived from ERA15 model levels. The data are from 0 to 360 in longitude and from +90 to −90 in latitude, with a resolution of 1.5º in both latitude and longitude. All the data are stored in files using the IEEE floating point single precision standard (4 bytes, 32 bits) in a Big-Endian format.

The mean monthly profiles of each meteorological parameter are contained in binary files named **<*param*>_<*hh*>.bin**, where *param* is the name of the meteorological parameter (**pres** = total air pressure [hPa], **temp** = air temperature [K], **vapd** = water-vapour density [g/m^3]) and *hh* is the hour of the day (i.e. 00, 06, 12 and 18 [UTC]). The heights of the profile levels are contained in a separate binary file, named **hght.bin**, in which vertical profiles of mean monthly level heights are contained. An example of the data contained in the database for a specific is given in Table 4.

TABLE 4

ESA_STD_PROF content – Example of profile at grid point (latitude = 45 (degrees) and longtitude = 9 (degrees)) at 12 UTC of July

Height (m)	Press (hPa)	Temp (K)	Vapd (g/m^3)
668.309	939.255	298.373	9.823
701.645	935.673	298.125	9.617
819.406	923.092	296.598	9.302
1 029.200	900.957	294.292	8.811
1 312.119	871.693	291.459	8.099
1 653.510	837.298	288.287	6.992
2 042.286	799.373	285.107	5.706
2 470.212	759.191	282.116	4.555
2 931.283	717.723	279.045	3.641
3 421.197	675.691	275.934	2.692
3 937.159	633.633	272.913	1.855
4 477.475	591.936	269.707	1.286
5 040.996	550.876	266.183	0.911
5 627.126	510.656	262.354	0.636
6 235.769	471.427	258.213	0.428
6 867.105	433.307	253.687	0.277
7 521.528	396.390	248.780	0.173
8 199.571	360.767	243.521	0.103
8 901.801	326.527	237.971	0.058
9 629.047	293.764	232.319	0.034
10 382.883	262.580	226.984	0.019
11 167.396	233.064	222.845	0.009
11 990.928	205.263	220.483	0.003
12 864.380	179.195	219.279	0.001
13 799.389	154.827	218.154	0.001
14 812.536	132.043	217.057	0.001
15 934.765	110.604	216.026	0.000
17 228.709	90.110	215.674	0.000
18 821.158	70.037	216.262	0.000
20 964.607	50.038	219.300	0.000
24 270.756	30.039	223.166	0.000
31 430.756	10.320	232.854	0.000

Legend to Table 4:

Z (m) = Height with respect to sea level

Press (hPa) = Atmospheric total pressure

Temp (K) = Air temperature

Vapd (g/m3) = Water-vapour density

NOTE 1 – The Matlab and Fortran procedures to access the ESA_STD_ PROF dataset are available from the ITU-R website dealing with Radiocommunication Study Group 3.