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International Telecommunication Union
Radiocommunication Sector

Recommendation ITU-R P.835-7

(08/2024)

P Series: Radiowave propagation

Reference atmospheres

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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.835-7

Reference atmospheres

(Question ITU-R 214/3)

(1992-1994-1997-1999-2005-2012-2017-2024)

Scope

Recommendation ITU-R P.835 provides reference atmospheres for the calculation of gaseous attenuation and related effects on terrestrial and Earth-space paths.

Keywords

Total pressure, barometric pressure, temperature, water vapour density

Acronyms/Abbreviations

ASCII American Standard Code for Information Interchange

ECMWF European Centre for Medium-Range Weather Forecasts

ERA5 ECMWF Fifth Generation Reanalysis Product

a.m.s.l. above mean sea level

Related ITU-R Recommendations and Handbook

Handbook on Radiometeorology (Edition 2013)

Recommendation ITU-R P.528

Recommendation ITU-R P.530

Recommendation ITU-R P.618

Recommendation ITU-R P.619

Recommendation ITU-R P.676

Recommendation ITU-R P.836

Recommendation ITU-R P.1144

Recommendation ITU-R P.1510

Recommendation ITU-R P.1511

Recommendation ITU-R P.1853

Recommendation ITU-R P.2001

Recommendation ITU-R P.2041

Recommendation ITU-R P.2145

NOTE – The latest revision/edition of the Recommendation/Handbook should be used.

List of symbols

H geopotential height above mean sea level

Z geometric height above mean sea level

P total (barometric) pressure

T temperature

ρ water vapour density

e water vapour partial pressure

The ITU Radiocommunication Assembly,

considering

a) that reference atmospheres for calculating various atmospheric propagation parameters on terrestrial and Earth-space paths are needed;

b) that numerical weather prediction systems provide average annual and monthly vertical profiles of atmospheric parameters, within their temporal and spatial resolutions,

recommends

1 that the ITU-R reference atmosphere in Annex 1 should be used to determine temperature, total (barometric) pressure, and water-vapour density vs. geometric height when a single global vertical profile of atmospheric parameters is needed;

2 that the seasonal reference atmospheres in Annex 2 should be used to determine temperature, total (barometric) pressure and water vapour density vs. geometric height when average seasonal data as a function of latitude are needed;

3 that the average global profiles of temperature, total (barometric) pressure, and water vapour density vs. geometric height in Annex 3, which were derived from numerical weather forecasts, should be used when reference data for a specific location are needed.

Annex 1

1 ITU-R reference atmosphere

The following ITU-R reference atmosphere provides simple reference total (barometric) pressure, temperature, and water vapour density profiles vs. geometric height from mean sea level to 100 km above mean sea level.

1.1 Temperature and pressure

The total (barometric) pressure and temperature for the ITU-R reference atmosphere is derived from the U.S. Standard Atmosphere, 1976. The U.S. Standard Atmosphere, 1976 is an idealized steady-state hypothetical vertical distribution of atmospheric temperature and total (barometric) pressure, which is roughly representative of year-round, mid-latitude conditions. The atmospheric temperature and pressure profiles are defined in two height[1] regimes: 1) geopotential heights (H) from 0 km′ to 84.852 km′, and 2) geometric heights (Z) from 86 km to 100 km. The conversions between geopotential height, H (km), and geometric height, Z (km), adopted by the U.S. Standard Atmosphere, 1976, are:

$$H = \frac{6\,356.766 Z}{6\,356.766 + Z} \tag{1a}$$

and

[1] km′ are units of geopotential height, and km are units of geometric height.

$$Z = \frac{6\,356.766H}{6\,356.766 - H} \quad (1b)$$

where a geopotential height of 84.852 km′ corresponds to a geometric height of 86 km. Since various P-series Recommendations (e.g. Recommendation ITU-R P.676 Annex 1) use geometric height, the temperature and pressure at a geometric height $Z \leq 86$ km can be calculated by converting geometric height, Z, to the corresponding geopotential height, H, and calculating the temperature and pressure at the corresponding geopotential height, H.

In the first height regime, the temperature T (K) at geopotential height H (km′) is:

$$T(H) = 288.15 - 6.5\,H \quad \text{for} \quad 0 \leq H \leq 11 \quad (2a)$$

$$T(H) = 216.65 \quad \text{for} \quad 11 < H \leq 20 \quad (2b)$$

$$T(H) = 216.65 + (H - 20) \quad \text{for} \quad 20 < H \leq 32 \quad (2c)$$

$$T(H) = 228.65 + 2.8\,(H - 32) \quad \text{for} \quad 32 < H \leq 47 \quad (2d)$$

$$T(H) = 270.65 \quad \text{for} \quad 47 < H \leq 51 \quad (2e)$$

$$T(H) = 270.65 - 2.8\,(H - 51) \quad \text{for} \quad 51 < H \leq 71 \quad (2f)$$

$$T(H) = 214.65 - 2.0\,(H - 71) \quad \text{for} \quad 71 < H \leq 84.852 \quad (2g)$$

and the pressure P (hPa) at geopotential height H (km′) is:

$$P(H) = 1\,013.25\,\left[\frac{288.15}{288.15 - 6.5\,H}\right]^{-34.1632/6.5} \quad \text{for} \quad 0 \leq H \leq 11 \quad (3a)$$

$$P(H) = 226.3226\,\exp[-34.1632\,(H - 11)/216.65] \quad \text{for} \quad 11 < H \leq 20 \quad (3b)$$

$$P(H) = 54.74980\,\left[\frac{216.65}{216.65 + (H - 20)}\right]^{34.1632} \quad \text{for} \quad 20 < H \leq 32 \quad (3c)$$

$$P(H) = 8.680422\,\left[\frac{228.65}{228.65 + 2.8\,(H - 32)}\right]^{34.1632/2.8} \quad \text{for} \quad 32 < H \leq 47 \quad (3d)$$

$$P(H) = 1.109106\,\exp[-34.1632\,(H - 47)/270.65] \quad \text{for} \quad 47 < H \leq 51 \quad (3e)$$

$$P(H) = 0.6694167\,\left[\frac{270.65}{270.65 - 2.8\,(H - 51)}\right]^{-34.1632/2.8} \quad \text{for} \quad 51 < H \leq 71 \quad (3f)$$

$$P(H) = 0.03956649\,\left[\frac{214.65}{214.65 - 2.0\,(H - 71)}\right]^{-34.1632/2.0} \quad \text{for} \quad 71 < H \leq 84.852 \quad (3g)$$

In the second height regime, the temperature T (K) at geometric height Z (km) is:

$$T(Z) = 186.8673 \quad \text{for} \quad 86 \leq Z \leq 91 \quad (4a)$$

$$T(Z) = 263.1905 - 76.3232\,\left[1 - \left(\frac{Z - 91}{19.9429}\right)^2\right]^{\frac{1}{2}} \quad \text{for} \quad 91 < Z \leq 100 \quad (4b)$$

and the pressure P (hPa) at geometric height Z (km) is:

$$P(Z) = \exp\,(a_0 + a_1 Z + a_2 Z^2 + a_3 Z^3 + a_4 Z^4) \quad \text{for} \quad 86 \leq Z \leq 100 \quad (5)$$

where:

$a_0 = 95.571\,899$

$a_1 = -4.011\,801$

$a_2 = 6.424\,731 \times 10^{-2}$

$a_3 = -4.789\,660 \times 10^{-4}$

$a_4 = 1.340\,543 \times 10^{-6}$

For reference, the temperature and pressure vs. geometric height are shown in Figs 1 and 2, respectively.

FIGURE 1

Temperature vs. geometric height

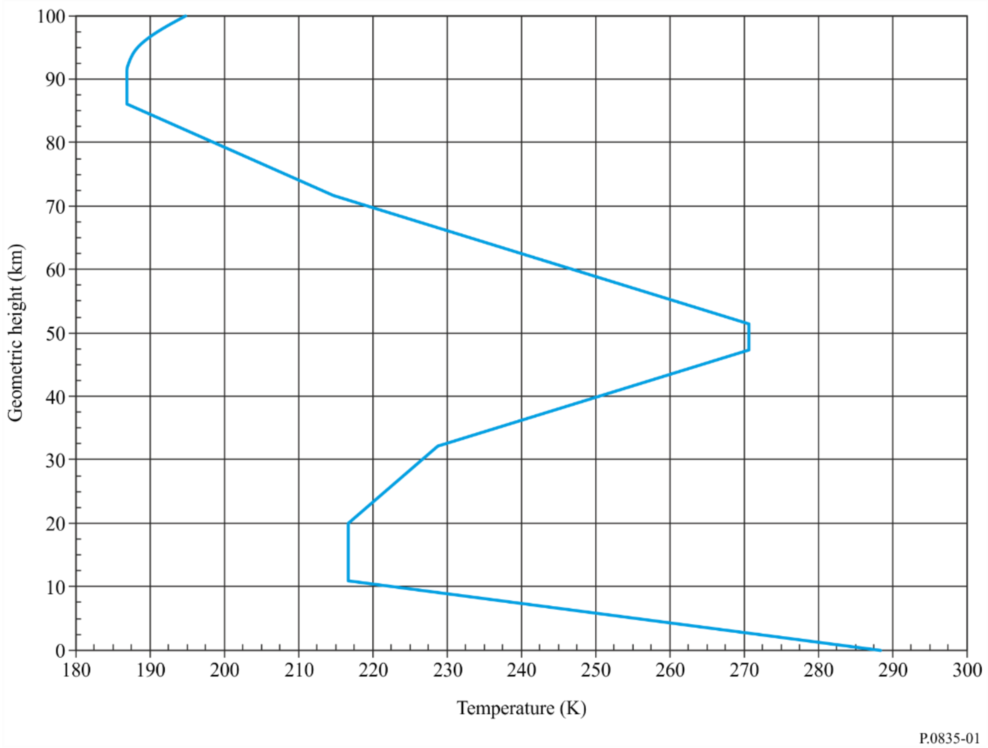
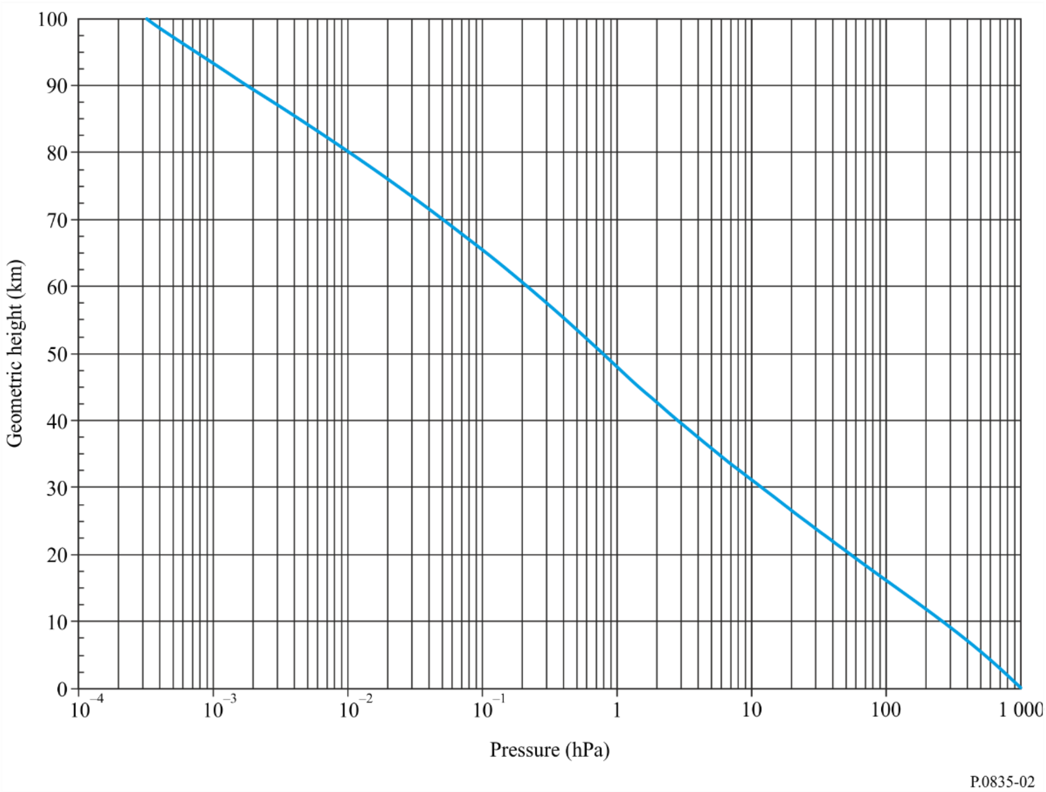


FIGURE 2

Total pressure vs. geometric height



1.2 Water-vapour density

In the absence of reliable local data, the atmospheric water vapour density, ρ, vs. geometric height may be approximated by the following negative exponential profile:

$$\rho(Z) = 7.5 \exp(-Z/2) \qquad \text{g/m}^3 \tag{6}$$

which decreases exponentially with increasing geometric height, up to a geometric height where the mixing ratio $e(Z)/P(Z) = 2 \times 10^{-6}$, and the water vapour partial pressure, $e(Z)$, is:

$$e(Z) = \frac{\rho(Z)T(Z)}{216.7} \qquad \text{hPa} \tag{7}$$

The water vapour density above this geometric height is then:

$$\rho(Z) = 2 \times 10^{-6} \frac{P(Z)\,216.7}{T(Z)} \qquad \text{g/m}^3 \tag{8}$$

Annex 2

1 Seasonal reference atmospheres

The following sections provide simple seasonal reference atmospheres for low (15° N), mid (45° N), and high (60° N) northern hemisphere latitude regimes. The low-latitude reference atmosphere is defined for all four seasons; and the mid-latitude and high-latitude reference atmospheres are defined for summer and winter.

The reference profiles for other latitudes can be derived as follows:

- For 0° N ≤ latitude ≤ 15° N and all seasons, the low-latitude annual reference atmosphere should be used.
- For 15° N < latitude < 45° N and summer and winter, the reference atmosphere should be obtained by linearly interpolating the low-latitude annual reference atmosphere and the appropriate mid-latitude seasonal reference atmosphere to the latitude of interest.
- For 45° N ≤ latitude < 60° N and summer and winter, the reference atmosphere should be obtained by linearly interpolating the appropriate seasonal mid-latitude and high-latitude reference atmospheres.
- For latitude ≥ 60° N and summer and winter, the appropriate seasonal high-latitude reference atmosphere should be used.

While these seasonal reference atmospheres were specifically derived for northern hemisphere latitudes, they may also be applicable to the corresponding southern hemisphere latitudes.

1.1 Low-latitude annual reference atmosphere

For low latitude (15° N), the following profiles may be used for all four seasons.

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

$$T(Z) = 300.4222 - 6.3533\,Z + 0.005\,886\,Z^2 \qquad \text{for} \quad 0 \le Z < 17 \tag{9a}$$

$$T(Z) = 194 + 2.533\,(Z - 17) \qquad \text{for} \quad 17 \le Z < 47 \tag{9b}$$

$$T(Z) = 270 \qquad \text{for} \quad 47 \le Z < 52 \tag{9c}$$

$$T(Z) = 270 - 3.0714\,(Z - 52) \qquad \text{for } 52 \le Z < 80 \qquad (9d)$$

$$T(Z) = 184 \qquad \text{for } 80 \le Z \le 100 \qquad (9e)$$

and the total (barometric) pressure P (hPa) at geometric height Z (km) is given by:

$$P(Z) = 1012.0306 - 109.0338\,Z + 3.6316\,Z^2 \qquad \text{for } 0 \le Z \le 10 \qquad (10a)$$

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

$$P(Z) = P_{72}\exp[-0.165\,(Z - 72)] \qquad \text{for } 72 < Z \le 100 \qquad (10c)$$

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

The water vapour density ρ (g/m³) at geometric height Z (km) is given by:

$$\rho(Z) = 19.6542\exp[-0.2313\,Z - 0.1122\,Z^2 + 0.01351\,Z^3 - 0.0005923\,Z^4]$$

$$\text{for } 0 \le Z \le 15 \qquad (11a)$$

$$\rho(Z) = 0 \qquad \text{for } Z > 15 \qquad (11b)$$

1.2 Mid-latitude reference atmosphere

For mid-latitude (45° N) the following profiles may be used for the summer and winter.

1.2.1 Summer mid-latitude

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

$$T(Z) = 294.9838 - 5.2159\,Z - 0.07109\,Z^2 \qquad \text{for } 0 \le Z < 13 \qquad (12a)$$

$$T(Z) = 215.15 \qquad \text{for } 13 \le Z < 17 \qquad (12b)$$

$$T(Z) = 215.15\exp[0.008128\,(Z - 17)] \qquad \text{for } 17 \le Z < 47 \qquad (12c)$$

$$T(Z) = 275 \qquad \text{for } 47 \le Z < 53 \qquad (12d)$$

$$T(Z) = 275 + 111.57755\{1 - \exp[0.0237\,(Z - 53)]\} \qquad \text{for } 53 \le Z < 80 \qquad (12e)$$

$$T(Z) = 175 \qquad \text{for } 80 \le Z \le 100 \qquad (12f)$$

and the total (barometric) pressure P (hPa) at geometric height Z (km) is given by:

$$P(Z) = 1012.8186 - 111.5569\,Z + 3.8646\,Z^2 \qquad \text{for } 0 \le Z \le 10 \qquad (13a)$$

$$P(Z) = P_{10}\exp[-0.147\,(Z - 10)] \qquad \text{for } 10 < Z \le 72 \qquad (13b)$$

$$P(Z) = P_{72}\exp[-0.165\,(Z - 72)] \qquad \text{for } 72 < Z \le 100 \qquad (13c)$$

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

The water vapour density ρ (g/m³) at geometric height Z (km) is given by:

$$\rho(Z) = 14.3542\exp[-0.4174\,Z - 0.02290\,Z^2 + 0.001007\,Z^3] \qquad \text{for } 0 \le Z \le 15 \qquad (14a)$$

$$\rho(Z) = 0 \qquad \text{for } Z > 15 \qquad (14b)$$

1.2.2 Winter mid-latitude

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

$$T(Z) = 272.7241 - 3.6217\,Z - 0.1759\,Z^2 \qquad \text{for } 0 \le Z < 10 \qquad (15a)$$

$$T(Z) = 218 \qquad \text{for } 10 \le Z < 33 \qquad (15b)$$

$$T(Z) = 218 + 3.3571\,(Z - 33) \qquad \text{for } 33 \le Z < 47 \qquad (15c)$$

$$T(Z) = 265 \qquad \text{for } 47 \le Z < 53 \qquad (15d)$$

$T(Z) = 265 - 2.0370\,(Z - 53)$ for $53 \le Z < 80$ (15e)

$T(Z) = 210$ for $80 \le Z \le 100$ (15f)

and the total (barometric) pressure *P* (hPa) at geometric height *Z* (km) is given by:

$P(Z) = 1018.8627 - 124.2954\,Z + 4.8307\,Z^2$ for $0 \le Z \le 10$ (16a)

$P(Z) = P_{10}\exp[-0.147\,(Z - 10)]$ for $10 < Z \le 72$ (16b)

$P(Z) = P_{72}\exp[-0.155\,(Z - 72)]$ for $72 < Z \le 100$ (16c)

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

The water vapour density ρ (g/m^3) at geometric height *Z* (km) is given by:

$\rho(Z) = 3.4742\exp[-0.2697\,Z - 0.03604\,Z^2 + 0.0004489\,Z^3]$ for $0 \le Z \le 10$ (17a)

$\rho(Z) = 0$ for $Z > 10$ (17b)

1.3 High latitude reference atmosphere

For high latitude (60° N) the following profiles may be used for the summer and winter.

1.3.1 Summer high latitude

The temperature *T* (K) at geometric height *Z* (km) is given by:

$T(Z) = 286.8374 - 4.7805\,Z - 0.1402\,Z^2$ for $0 \le Z < 10$ (18a)

$T(Z) = 225$ for $10 \le Z < 23$ (18b)

$T(Z) = 225\exp[0.008317\,(Z - 23)]$ for $23 \le Z < 48$ (18c)

$T(Z) = 277$ for $48 \le Z < 53$ (18d)

$T(Z) = 277 - 4.0769\,(Z - 53)$ for $53 \le Z < 79$ (18e)

$T(Z) = 171$ for $79 \le Z \le 100$ (18f)

and the total (barometric) pressure *P* (hPa) at geometric height *Z* (km) is given by:

$P(Z) = 1008.0278 - 113.2494\,Z + 3.9408\,Z^2$ for $0 \le Z \le 10$ (19a)

$P(Z) = P_{10}\exp[-0.140\,(Z - 10)]$ for $10 < Z \le 72$ (19b)

$P(Z) = P_{72}\exp[-0.165\,(Z - 72)]$ for $72 < Z \le 100$ (19c)

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

The water vapour density ρ (g/m^3) at geometric height *Z* (km) is given by:

$\rho(Z) = 8.988\exp[-0.3614\,Z - 0.005402\,Z^2 - 0.001955\,Z^3]$ for $0 \le Z \le 15$ (20a)

$\rho(Z) = 0$ for $Z > 15$ (20b)

1.3.2 Winter high latitude

The temperature *T* (K) at geometric height *Z* (km) is given by:

$T(Z) = 257.4345 + 2.3474\,Z - 1.5479\,Z^2 + 0.08473\,Z^3$ for $0 \le Z < 8.5$ (21a)

$T(Z) = 217.5$ for $8.5 \le Z < 30$ (21b)

$T(Z) = 217.5 + 2.125\,(Z - 30)$ for $30 \le Z < 50$ (21c)

$T(Z) = 260$ for $50 \le Z < 54$ (21d)

$T(Z) = 260 - 1.667\,(Z - 54)$ for $54 \le Z \le 100$ (21e)

and the total (barometric) pressure *P* (hPa) at geometric height *Z* (km) is given by:

$$P(Z) = 1010.8828 - 122.2411\,Z + 4.554\,Z^2 \quad \text{for } 0 \le Z \le 10 \qquad (22a)$$

$$P(Z) = P_{10}\,\exp[-0.147\,(Z - 10)] \quad \text{for } 10 < Z \le 72 \qquad (22b)$$

$$P(Z) = P_{72}\,\exp[-0.150\,(Z - 72)] \quad \text{for } 72 < Z \le 100 \qquad (22c)$$

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

The water vapour density ρ (g/m^3) at geometric height Z (km) is given by:

$$\rho(Z) = 1.2319\,\exp[0.07481\,Z - 0.0981\,Z^2 + 0.00281\,Z^3] \quad \text{for } 0 \le Z \le 10 \qquad (23a)$$

$$\rho(Z) = 0 \quad \text{for } Z > 10 \qquad (23b)$$

Annex 3

1 Global mean annual and mean monthly vertical profiles

This Annex contains mean annual and mean monthly vertical profiles of total (barometric) pressure, temperature and water vapour density at 138 altitude levels above mean sea level derived by averaging 30 years (1991-2020) of ECMWF ERA5 model level data.

These vertical profiles are integral part of this Recommendation, and are available in the form of digital maps provided as Parts 1 to 12 corresponding to each month of the year and Part 13 corresponding to the annual period. Each Part contains a zip file with four map files, P.bin, T.bin, WV.bin, and Z.bin for the applicable period. P.bin contains the pressure profiles, T.bin contains the temperature profiles, WV.bin contains the water vapour density profiles, and Z.bin contains the profiles of geometric altitude above mean sea level. The characteristics of each map file are shown in Table 1.

TABLE 1

Map file characteristics

Parameter	Value
Format	IEEE 754
Byte ordering	Little endian
Precision	Single (4 bytes/value)
Total number of bytes	573 506 472
Latitude range	−90° N to 90°N
Latitude increment	+0.25°
Longitude range	−180° E to 180° E
Longitude increment	+0.25°
Number of latitude grid points	721
Number of longitude grid points	1 441
Number of altitude levels	138
Total pressure units	hPa
Temperature units	K
Water vapour density units	g/m^3
Altitude units	km, a.m.s.l.

Each parameter is stored as a 3-dimensional matrix *parameter*(*ilevel*, *ilat*, *ilon*), where, assuming indexing starts at 1, $ilevel = 1, 2, \ldots, 138$; $ilat = 1, 2, \ldots, 721$; and $ilon = 1, 2, \ldots, 1\,441$. The first byte of the four bytes corresponding to the value of total (barometric) pressure (P), temperature (T), water vapour density (WV), or geometric altitude above mean sea level (Z) at any grid point ($Latitude\_degN$, $Longitude\_degE$) and altitude level ($ilevel$) is byte number $ipos$, where $ipos$ ranges from $ipos = 1$ to $ipos = 573\,506\,469$.

$$ipos = \{ilevel - 1 + (ilat - 1) \times 138 + (ilon - 1) \times 138 \times 721\} \times 4 + 1 \quad (24)$$

where:

$$ilat = (Latitude\_degN + 90)/0.25 + 1 \quad (25)$$

$$ilon = (Longitude\_degE + 180)/0.25 + 1 \quad (26)$$

$$ilevel = (1, 2, 3, \ \ldots \ , 138) \quad (27)$$

There are 138 pressure, temperature, and water vapour density levels at each grid point, where $P(ilevel, ilat, ilon)$, $T(ilevel, ilat, ilon)$, and $WV(ilevel, ilat, ilon)$ are the values of total pressure, temperature, and water vapour density at altitude above mean sea level, $Z(ilevel, ilat, ilon)$. $Z(138, ilat, ilon)$ is the ERA5 altitude[2] of the surface of the Earth above mean sea level, and $Z(1, ilat, ilon)$ is the maximum altitude above mean sea level at the associated grid point. $Z(138, ilat, ilon)$ may be different than the topographic altitude in Recommendation ITU-R P.1511, which was determined by a combination of high-resolution satellite radar altimetry augmented by local altimetry data.

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2 The ERA5 geometric altitude of the surface of the Earth above mean sea level was obtained by dividing the ERA5 gravitational potential energy of a unit mass at the surface of the Earth (m^2/s^2) by the gravitational acceleration (9.80665 m/s^2) and converting the resulting geopotential altitude of the surface of the Earth to a geometric altitude of the surface of the Earth.