CENTER FOR ADVANCED AVIATION SYSTEM DEVELOPMENT (CAASD)

Tropospheric Effects on GNSS

The Atmosphere and its Effect on GNSS Systems
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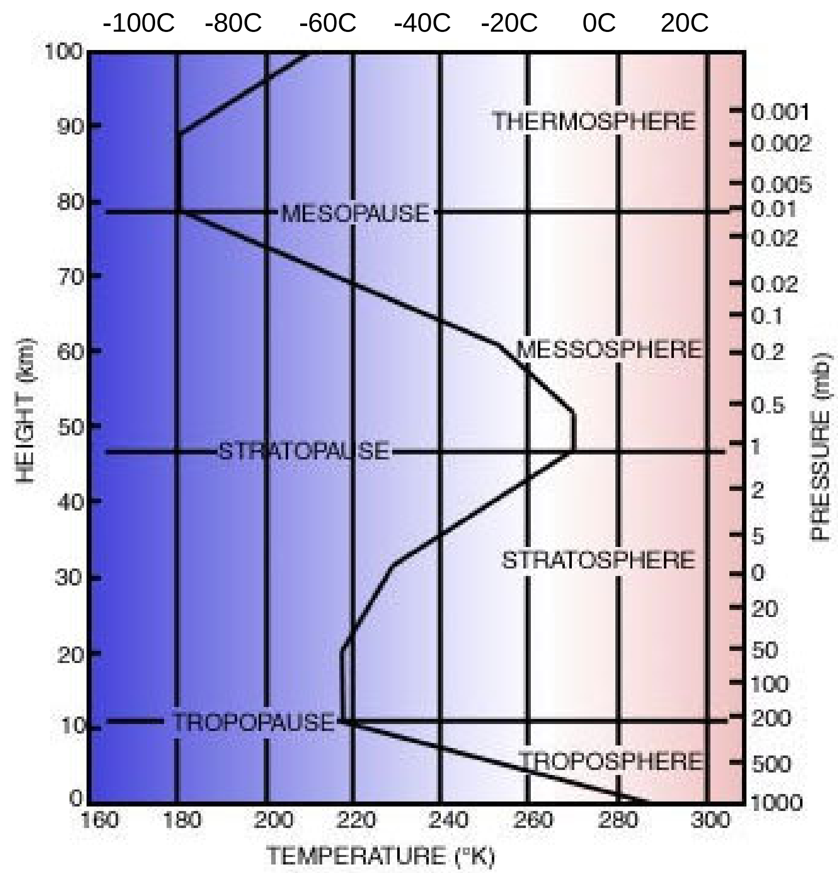
CAASD MITRE

Background

1 of 2

- **The troposphere contains about 80% of the atmosphere**
  - **It is a few kilometers above the Earth's surface**
  - **In this layer, the average temperature decreases with height (e.g., -5ºC to -7ºC/km)**
- **Vertical temperature profile of the ICAO Standard Atmosphere**
  - **Each layer is characterized by a uniform change in temperature with increasing altitude**
  - **In some layers there is an increase in temperature with altitude**
  - **In others it decreases with increasing altitude**
- **The top or boundary of each layer is denoted by a 'pause' where the temperature profile abruptly changes**

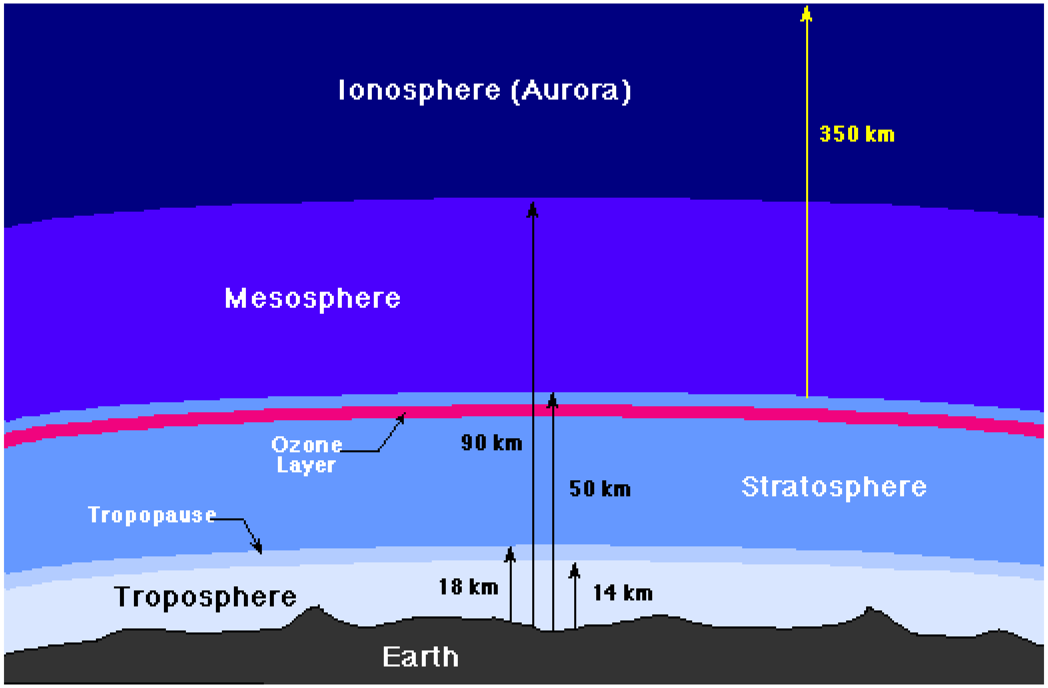


Vertical temperature profile of the ICAO Standard Atmosphere in mid-Latitude (Boundary heights increase toward Equator)

Reference [1]

Background
2 of 2

Layers of Earth's Atmosphere



Reference [2]

Tropospheric Effects On GNSS

- **Atmospheric and Rain Attenuation**
- **Tropospheric Scintillation**
- **Tropospheric Delay**

Reference [3]

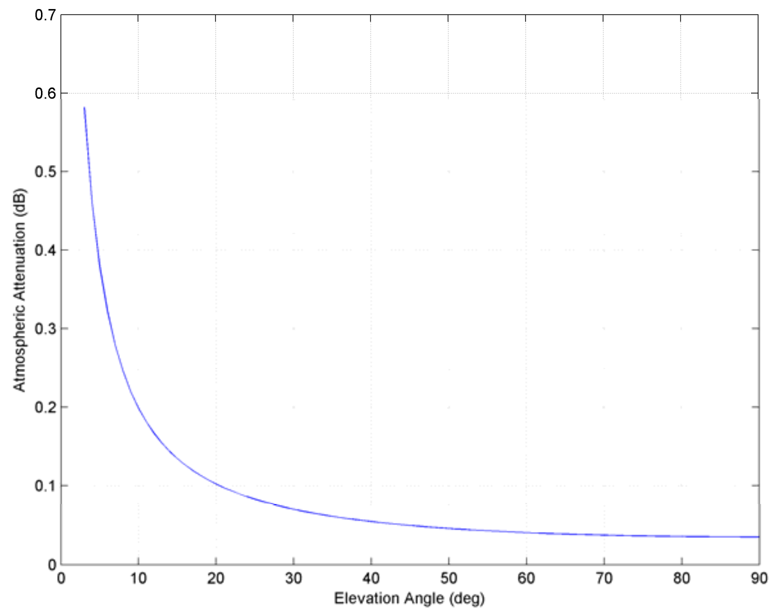
Atmospheric and Rain Attenuation

1 of 2

- **Atmospheric attenuation is dominated by oxygen attenuation in the 1-2 GHz band**

- **Very small**
  - **About 0.035dB at zenith**
  - **About 0.38 dB at 5 degrees elevation angle**

- **The effects of water vapor, rain, and nitrogen attenuation at L-band frequencies are negligible**



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Atmospheric and Rain Attenuation

2 of 2

- **Rain attenuation is very small at L-band and could be negligible**
  - **For even dense rainfall (e.g., 10 cm/hour) is less than 0.01 dB/km**

Reference [3]

Tropospheric Scintillation

1 of 2

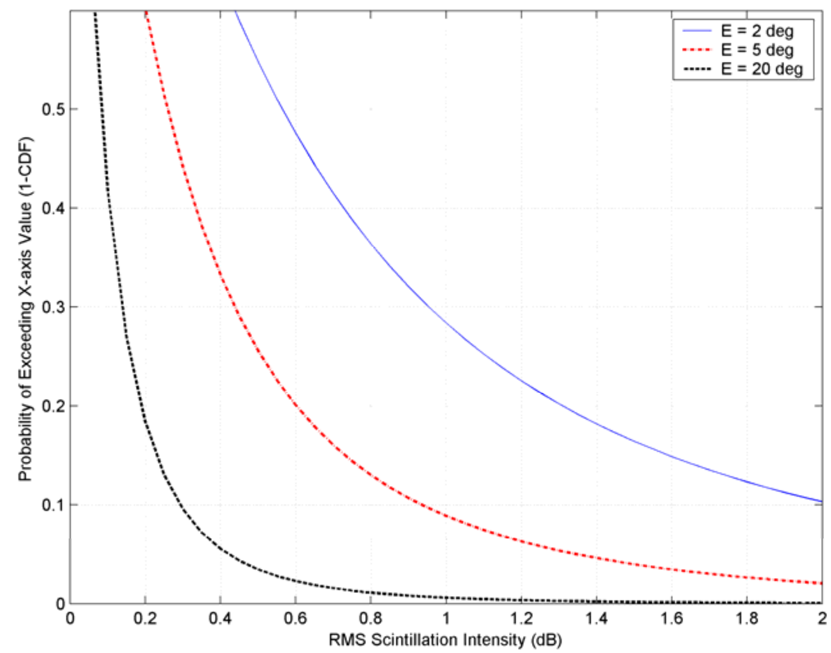
- **It is caused by irregularities and turbulence in the atmospheric refractive index in the first few kilometers above the ground**
- **The propagation link through troposphere is affected by a combination of random absorption and scattering from a continuum of signal paths that cause random amplitude and phase scintillations in the received waveform**
- **Scintillation effect varies with time and is dependent upon frequency, elevation angle, and weather conditions, especially dense clouds**
- **At L-band, these effects are small except for a small fraction of time and at low elevation angles**

Reference [3]

Tropospheric Scintillation

2 of 2

- **CCIR Model (see Appendix A):**
- **10% of the time, the RMS of Tropospheric scintillation**
  - **2 dB at E = 2 deg**
  - **0.9 dB at E = 5 deg**
  - **0.3 dB at E = 20 deg**
- **The model may not be accurate below 5 degrees**



Reference [3]

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Tropospheric Delay

1 of 2

- **Signal received by GNSS satellite is refracted by the atmosphere as travels to the user on or near the Earth's surface**

- **The atmospheric refraction causes a delay, depends on**
  - **Actual path of the curved ray**
  - **Refractive index of the gases along that path**

- **For a homogenous (or symmetric) atmosphere around the user antenna, the delay depends only on the vertical profile of the atmosphere and the elevation angle**

Reference [3]

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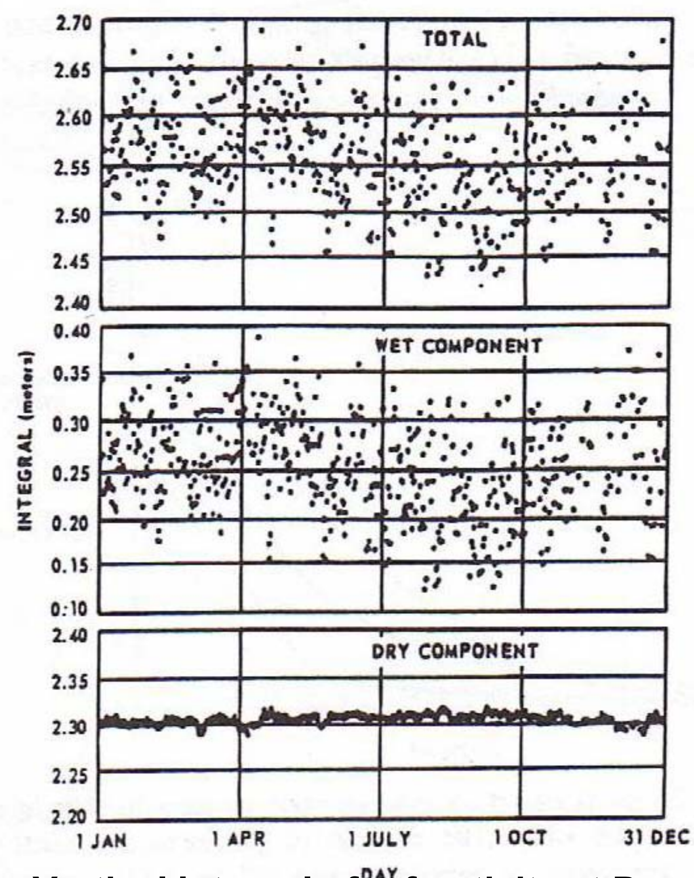
Tropospheric Delay

2 of 2

- **Excess delay = dry component (90%) + wet component (10%)**
- **$\Delta = \Delta_{zd}.m_d(E) + \Delta_{zw}.m_w(E)$**
- **Δ_{zd} = dry zenith delay**
  - **caused mainly by N2 and O2**
  - **90% of total delay**
  - **About 2.3m**
  - **Function of T & P**
  - **Predictable within 1% in a few hours**
- **Δ_{zw} = wet zenith delay**
  - **Caused by water vapor**
  - **10% of total delay**
  - **<= 0.80m**
  - **Varies 10-20% in a few hours**
  - **Less predictable**
- **$m_d(E)$ & $m_w(E)$ are mapping functions vary with elevation angle**



Vertical Integral of refractivity at Pago Pago, Samoa 1967, Balloon data, Reference [3])

Tropospheric Refraction vs. Pressure and Temperature

- **Refractivity N = (n-1)10^6 is given by:**

$$N = (n-1)10^6 = 77.604\frac{P_d}{TZ_d} + \frac{e}{TZ_w}\left(64.79 + \frac{377600}{T}\right) = N_h + N_w$$

- **Where**
  - **P_d = partial pressure of dry (hydrostatic) air (millibars)**
  - **e = partial pressure of water vapor (millibars)**
  - **T = Temperature in degrees Kelvin = 273.15 + C**
  - **Z_d and Z_w = compressibility factors correct for small departures of the moist atmosphere from an ideal gas. They are functions of P_d, e & T**
  - **Ideal gas: PV = RT**
  - **Non-ideal gas: PV = ZRT**
  - **R = Universal gas constant**

Reference [3]

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Tropospheric Empirical Models

1. Saastamoinen Total Delay Model
2. Hopfield Two Quartic Model
3. Black and Eisner (B&E) Model
4. Altshuler and Kalaghan (A&K) Model
5. Davis, Chao, and Marini Mapping Functions
6. UNB SBAS Tropospheric Model (See RTCA MOPS 229D)
7. LAAS/GBAS Tropospheric Model (See RTCA MOPS 254A)

For Models 1 to 5, see reference [3] for more details and summary in Appendix B

For Models 6 & 7 see references [4 and 5] and details in MITRE briefing tomorrow

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Appendix A
Tropospheric Scintillation

Tropospheric Scintillation

A received carrier from a satellite has the form : $A(t)\sin(\omega t + \phi)$

Define the scintillation intensity $x(t)$ as the log of the amplitude ratio $A(t)/\overline{A(t)}$,

$x(t) = 20\log_{10}\left[A(t)/\overline{A(t)}\right] dB$

$\overline{A(t)}$ = the mean (short term) amplitude of the signal.

Probability density function (pdf) of $x(t)$ (in dB) = $N(0, \sigma_x^2)$

$A(t)$ has a log-normal statistics.

The rms value of σ_x in dB is itself a random variable with a mean σ_m and its long term fluctuations have a pdf that is a log-normal :

$$p(\sigma_x) = \frac{1}{\sigma_\sigma \sigma_x \sqrt{2\pi}} \exp\left[-\frac{(\log\sigma_x - \log\sigma_m)^2}{2\sigma_\sigma^2}\right]$$

CCIR :

$\sigma_\sigma = 1$

$\sigma_m = 0.025 f^{7/12} (\sin E)^{-0.85} dB$

f = carrier frequency in GHz = 1.57542 GHz at L1

At L1 : $\sigma_m = 0.0326(\sin E)^{-0.85} dB$

Reference [3]

Appendix B
Tropospheric Models

Saastamoinen Standard Total Delay Model

- **The tropospheric delay correction (Δ) in meters is given by (E ≥ 10 degrees):**

$$\Delta = 0.002277(1 + D)\sec\psi_0 \left[P_0 + \left(\frac{1255}{T_0} + 0.005 \right) e_0 - B\tan^2\psi_0 \right] + \delta_R$$

- **Where**
  - **P_0 = partial pressure of dry (hydrostatic) air (mbars)**
  - **e_0 = partial pressure of water vapor (mbars)**
  - **T_0 = Temperature (K)**
  - **B & δ_R = correction terms are function of user height (lookup table)**
  - **ψ_0 = 90 –E = Zenith Angle**
  - **E = Elevation angle**
  - **D = 0.0026 cos(2ϕ) + 0.00028h**
  - **ϕ = local latitude**
  - **h = station height in km**

Reference [3]

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Hopfield Two Quartic Model

- **The refractivity is given as a function of height by**

$$N(h) = N_d(h) + N_w(h)$$

$$N_d(h) = N_{d0}\left(1 - \frac{h}{h_d}\right)^4 \text{ for } h \le h_d = 43km$$

$$N_w(h) = N_{w0}\left(1 - \frac{h}{h_w}\right)^4 \text{ for } h \le h_w = 12km$$

- **The tropospheric delay correction (Δ) in meters is given by**

$$\Delta = \Delta_d + \Delta_w = \frac{10^{-6}}{5}\left(N_{d0}h_d + N_{w0}h_w\right)$$

- **Where**
  - **Δ_d and Δ_w can be calculated by integrating N_d(h) and N_w(h)**
  - **h_d and h_w are the heights (km) above the surface level where N_{d0} and N_{w0} are measured**

Reference [3]

Black and Eisner (B&E) Model [3]

- **The tropospheric delay correction (Δ) in meters is given by**

$$\Delta = \left(\Delta_{dz} + \Delta_{wz}\right) m(E)$$

- **Where m(E) is the mapping function which is function of elevation angle E ≥ 7 degrees**

$$m(E) = \frac{1}{\sqrt{(0.001)^2 + 0.002 + \sin^2 E}}$$

Altshuler and Kalaghan (A&K) Model [3]

- **The tropospheric delay correction (Δ) in meters is given by**

$$\Delta(E,h,N_s) = 0.3048 \times 2.29286 m(E) H(h) F(h,N_s) \text{ meters}$$

- **Where for elevation angle E(deg), height above sea level h'(ft)**

$$m(E) = \frac{1}{2.29286}\left\{\left(0.1556 + \frac{138.8926}{E} - \frac{105.0574}{E^2} + \frac{31.507}{E^3}\right) + \left[1.0 + 10^{-4}(E-30)^2\right]\right\}$$

$$H(h) = 0.0097 - \frac{2.08809}{h+8.6286} + \frac{122.73592}{(h+8.6286)^2} - \frac{703.82166}{(h+8.6286)^3}$$

$$F(h,N_s) = 3.28084\left(\frac{6.81758}{h+3.28084} + 0.3048(h+3.28084) + 0.00423N_s - 1.33333\right)$$
$$\left(1 - 1.41723\times10^{-6}(N_s - 315)\right)$$

$$N_s = 369.03 - 0.01553h' - 0.92442\phi - 0.0016h's^2 - 0.19361\phi s^2 + 0.00063h'c - 0.05958\phi\lambda c$$

$$s = \sin\left(\frac{\pi M}{12}\right), c = \cos\left(\frac{\pi M}{12}\right), M = 1.5(\text{winter}), 4.5(\text{spring}), 7.5(\text{summer}), 10.5(\text{fall})$$

Average global surface refractivity $\overline{N} = 324.8$, st. dev. $\sigma_N = 30.1$.

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Davis, Chao, and Marini Mapping Functions

- **Marini's Mapping function is a continued fraction (a, b, c, … are constants)**

$$m(E)=\cfrac{1}{\sin E+\cfrac{a}{\sin E+\cfrac{b}{\sin E+\cfrac{c}{\sin E+\dots}}}}$$

- **Chao's Mapping functions**

$$m_d(E)=\cfrac{1}{\sin E+\cfrac{0.00143}{\tan E+0.0445}},\; m_w(E)=\cfrac{1}{\sin E+\cfrac{0.00035}{\tan E+0.017}}$$

- **Davis mapping function is similar to Marini's except a and b are function of the surface temperature and pressure and c = -0.009**

Reference [3]

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References

1. http://www.metoffice.gov.uk/education/secondary/teachers/atmosphere.html

2. http://csep10.phys.utk.edu/astr161/lect/earth/atmosphere.html

3. Spilker, J. J., "Tropospheric Effects on GPS", Chapter 13, Volume I, *Global Positioning System: Theory and Applications*, Editors B. W. Parkinson and J. J. Spilker, The American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., 1996.

4. RTCA, Inc., *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System*, DO-229D, RTCA, Inc., Washington, D.C., 2006.

5. RTCA, Inc., *Minimum Operational Performance Standards for Local Area Augmentation System*, DO-245A, RTCA, Inc., Washington, D.C., 2004.

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