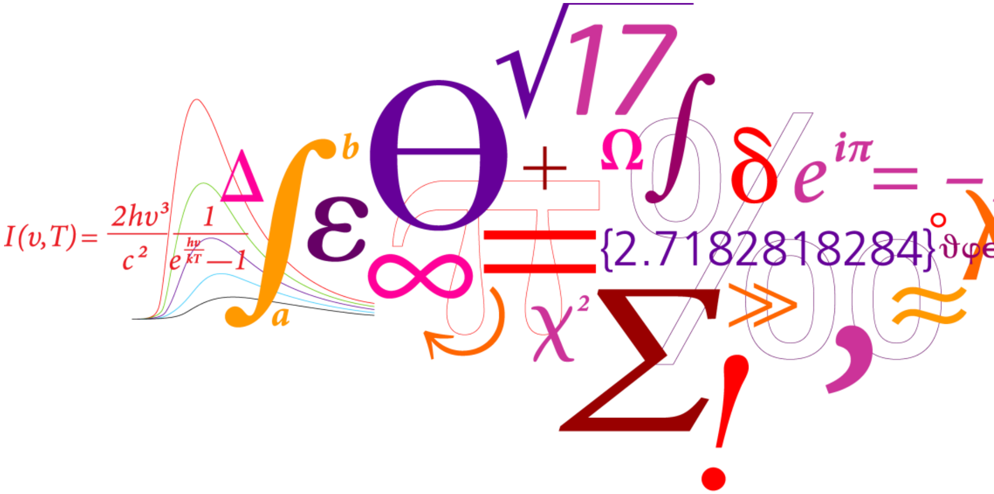
30552
Satellite Geodesy

Atmospheric effects on GNSS satellite signals

Sarah Beeck



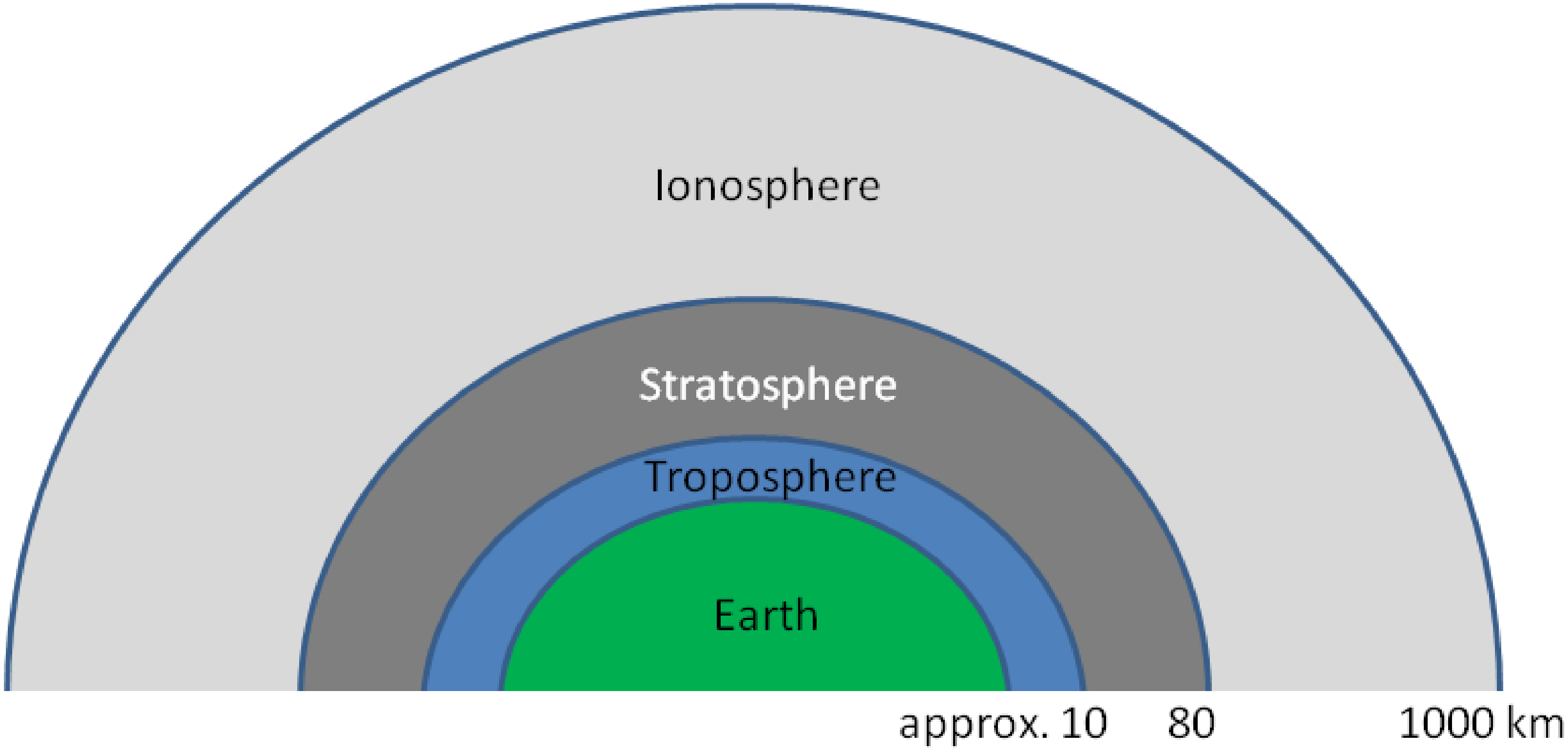
DTU Space
National Space Institute

Content

- The ionosphere
- Space weather, solar activity and variation in electron content
- Modelling of the ionospheric effect

- The neutral atmosphere
- Refractivity
- Modelling of the tropospheric effect

Earth’s atmosphere



The ionosphere (1)

- The ionosphere is composed of ionized gasses, the media as a whole is neutral, but there are many free negatively charged electrons and positively charged ions

- The composition of the ionosphere prevents some electro-magnetic waves from penetrating the ionosphere:
  - Frequencies below the HF range are reflected by the lower limit of the ionosphere
  - Frequencies in the HF range are reflected at various levels in the ionosphere
  - Frequencies in the VHF range and above penetrate the ionosphere

Atmospheric refraction

- When electromagnetic satellite signals travel from the GNSS satellites to the surface the Earth, they are affected by the media

- For the first 95% of the signal transmission the media can be considered a vacuum

- The last 5% of the signal path is through the Earth’s atmosphere, where the signal experiences refraction, bending of the signal path, and other effects

The ionosphere (2)

- The free electrons in the ionosphere affect transmission of electromagnetic waves

- The amount of electrons integrated along the signal path is given as TEC (Total Electron Content):

$$TEC = \int N_e ds$$

- Measured in TECU (TEC units):
  - 1 TECU = 10^{16} electrons pr. m^2
  - 1 TECU causes an L1 signal delay of approx. 0.16 meter on a pseudorange

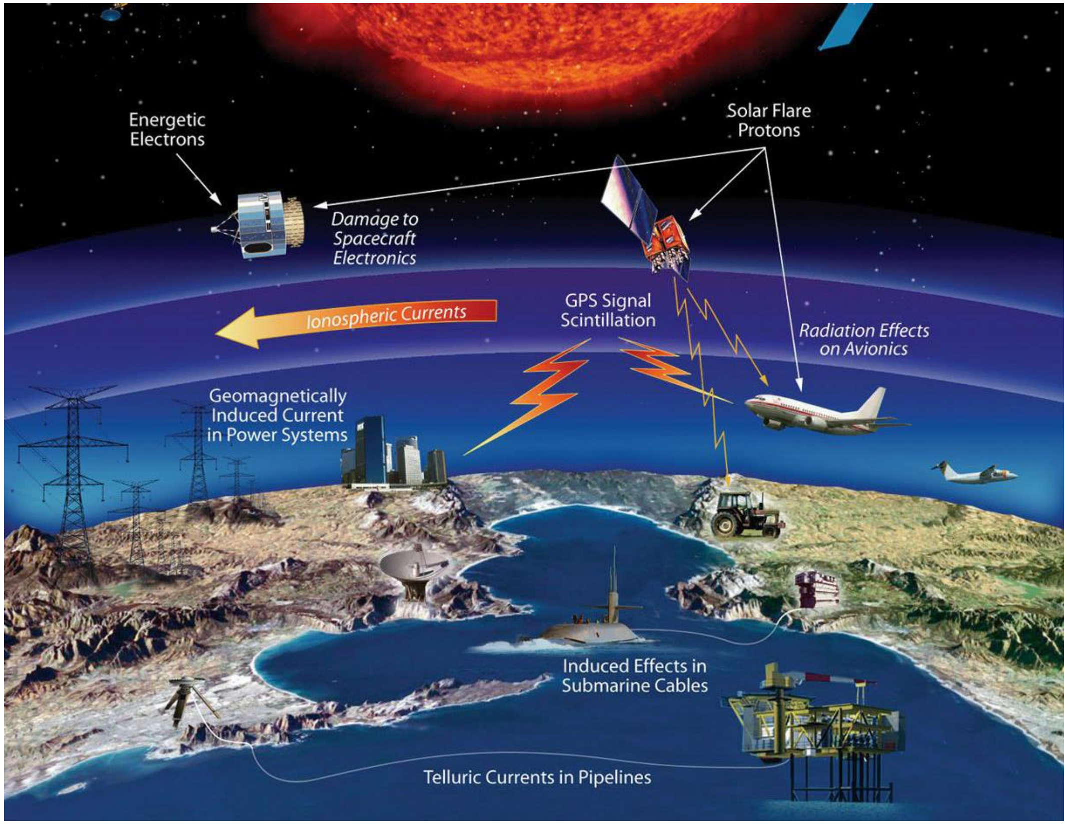
The ionosphere (3)

- The amount of ionization and thereby the number of free electrons is driven mainly by ultra-violet radiation from the sun. Radiation from outer space plays a minor role
- The sun emits:
  - Radiation, charged particles (the solar wind), and the Interplanetary Magnetic Field (IMF)
- The solar wind is a continuous flow of particles, mainly H+ and He++
- The density of the solar wind is correlated with the *sunspot* number

Space Weather

The term space weather generally refers to conditions on the sun, in the solar wind, and within Earth's magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health

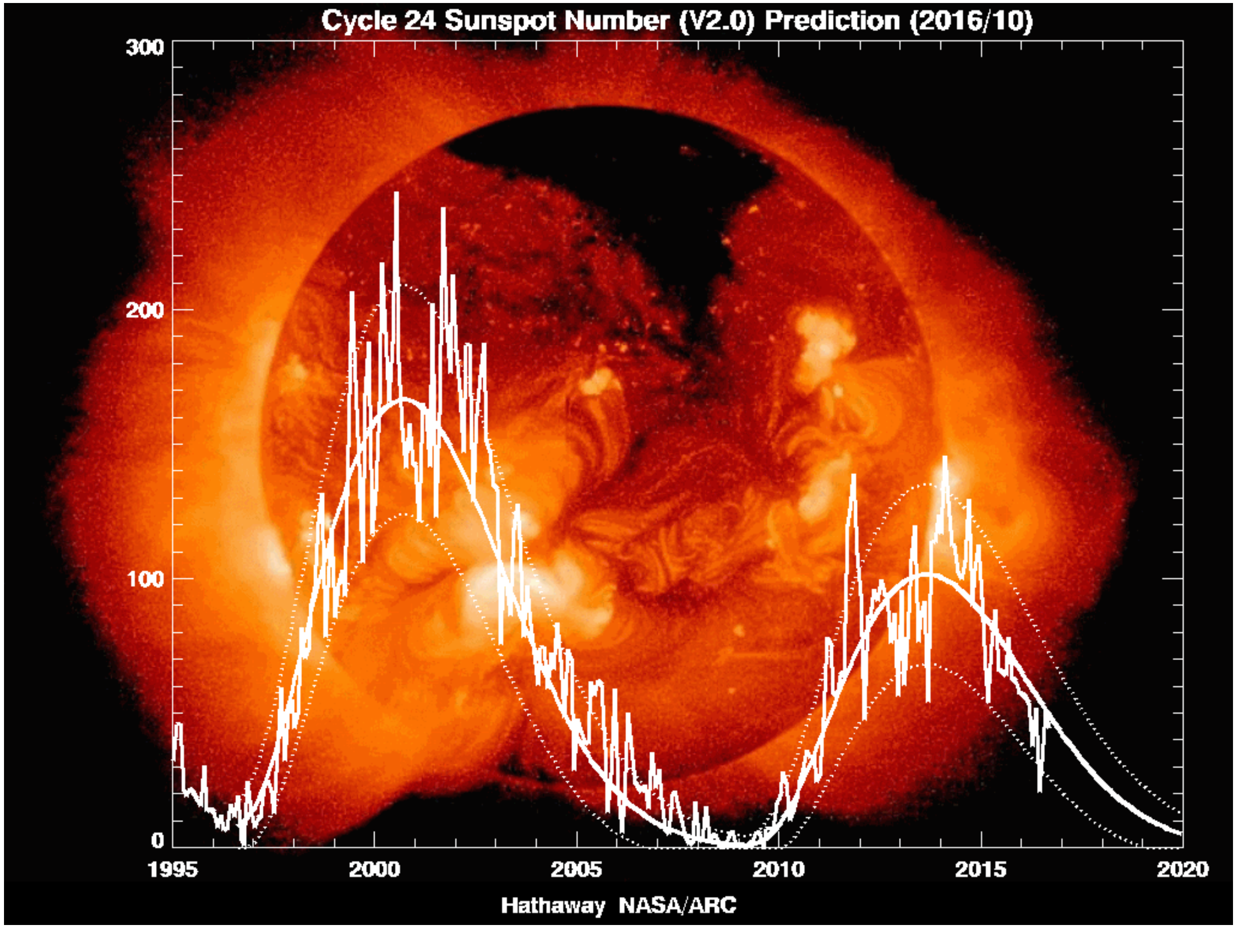
- Definition by NASA



Credits: NASA

Solar cycle

- The number of sunspots varies with an 11 year cycle



From: http://solarscience.msfc.nasa.gov/images/ssn_predict_l.gif

Sunspots

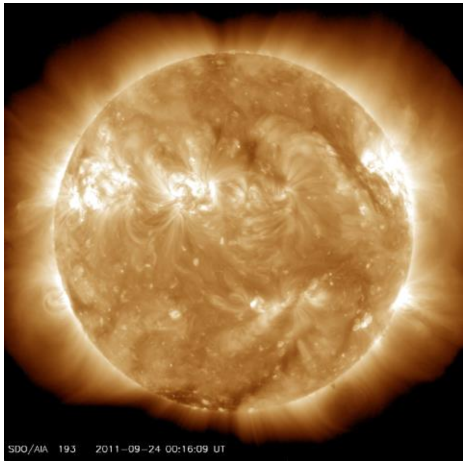
- The generation of sunspots is not well understood, but is related to anomalies in the solar magnetic fields that occur if the magnetic field lines are twisted
- The temperature in a sunspot is lower than in the surroundings => sunspots look like dark spots on the surface of the sun
- Sunspots are counted –> the sunspot number

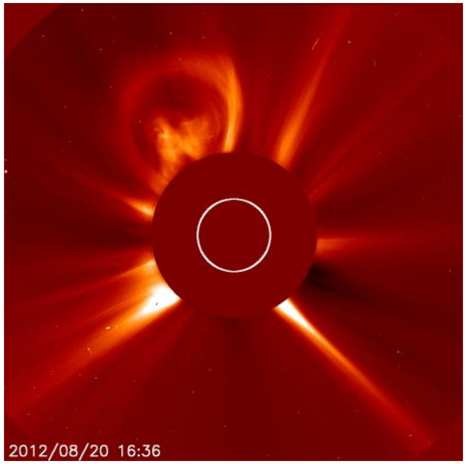
Solar activity

- The activity level and amount of emissions from the sun are correlated with the number of sunspots
- The density of the solar wind is increased with increasing sunspot number
- With a large sunspot number sudden eruptions of the sun e.g. *solar flares* and *coronal mass ejections* (CME) happen more frequent

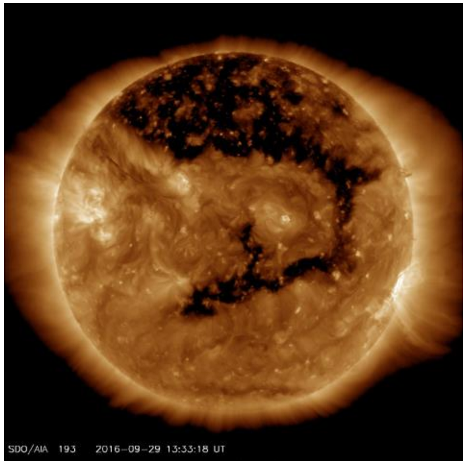
  => increased ionization activity

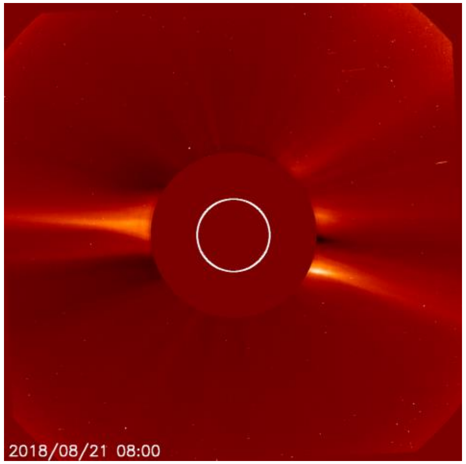
Solar Activity





The active Sun

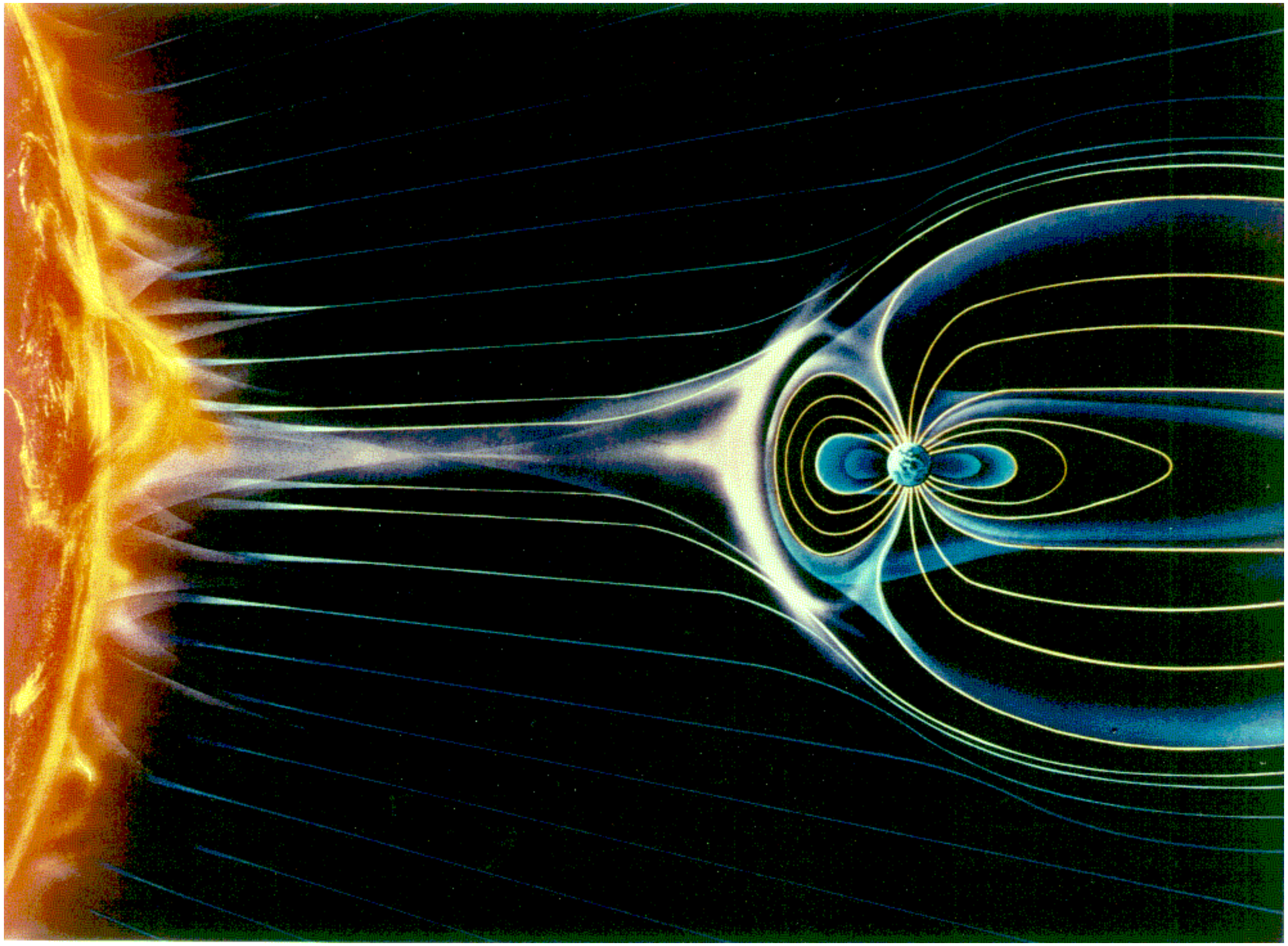




The quiet Sun

https://iswa.ccmc.gsfc.nasa.gov/IswaSystemWebApp/

The solar wind and the geomagnetic field



From: http://unix.cc.wmich.edu/korista/sun-images/sunearth_lg.gif

Ionospheric activity and GNSS positioning (2)

- Iononspheric storms are more frequent with high solar activity

- High sun spot number:
  - => more disturbances of ionospheric activity
  - => ionospheric models become insufficient
  - => larger errors in GNSS positioning

- TEC is used as a general indicator of the level of ionospheric activity

Temporal variation of TEC

- The TEC reaches a maximum when the ionization rate in the ionosphere is high, and the recombination rate is low

- The TEC varies with the following general cycles:
  - A daily cycle, peak at 14:00 hours local time
  - A yearly cycle, peak at spring and fall Equinoxes
  - The 11 year solar cycle

- Sudden variations during ionospheric storms can also occur and they do not follow a well described pattern

Ionospheric vertical regions

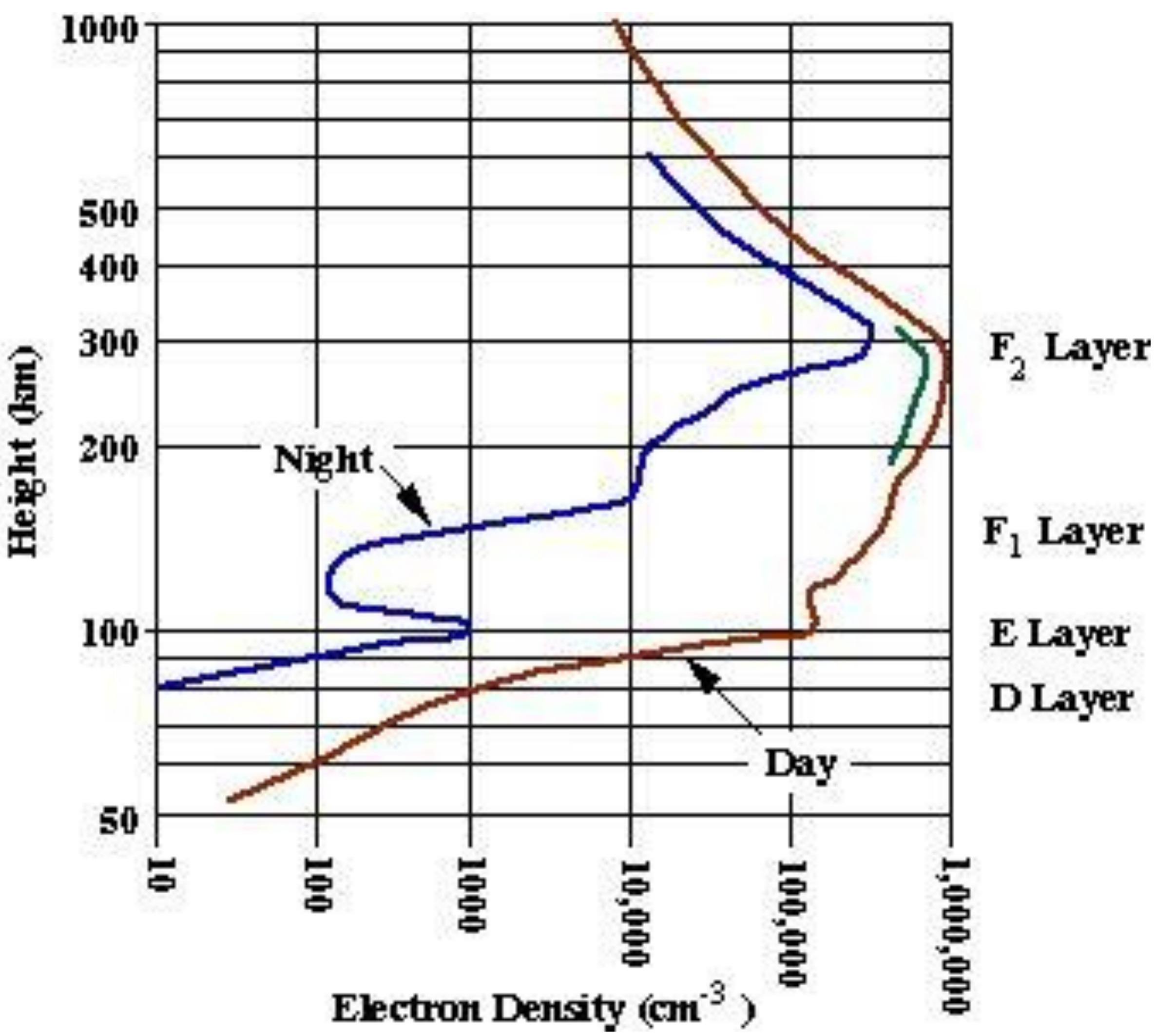


Figure from: https://fas.org/man/dod-101/navy/docs/es310/propagat/Propagat.htm

Temporal variation of TEC in Denmark

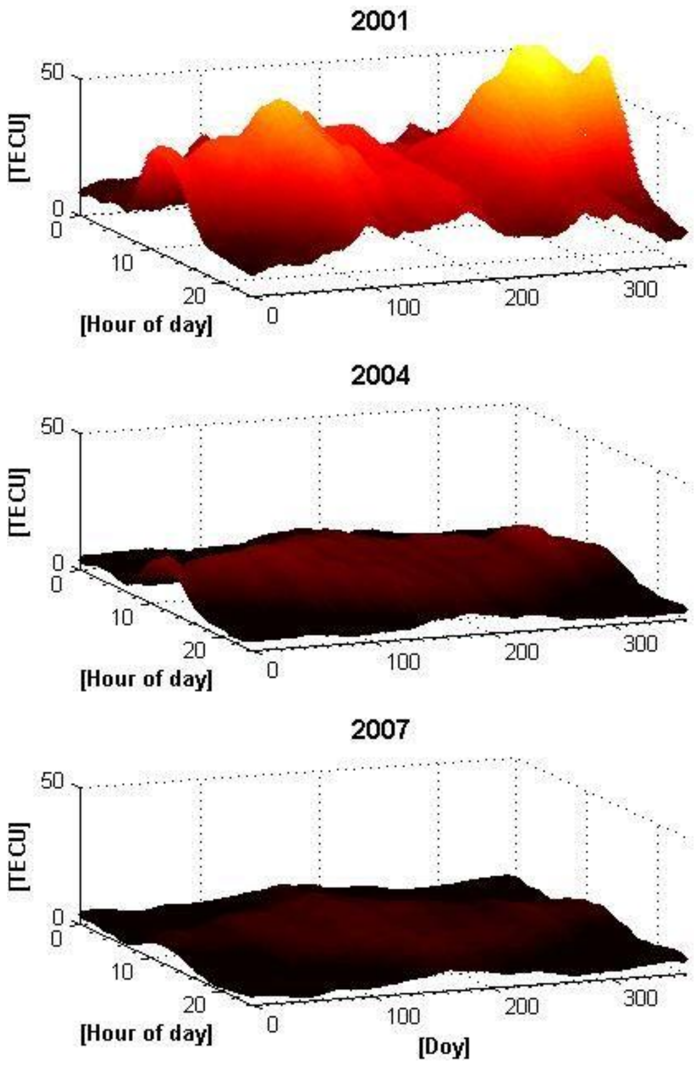
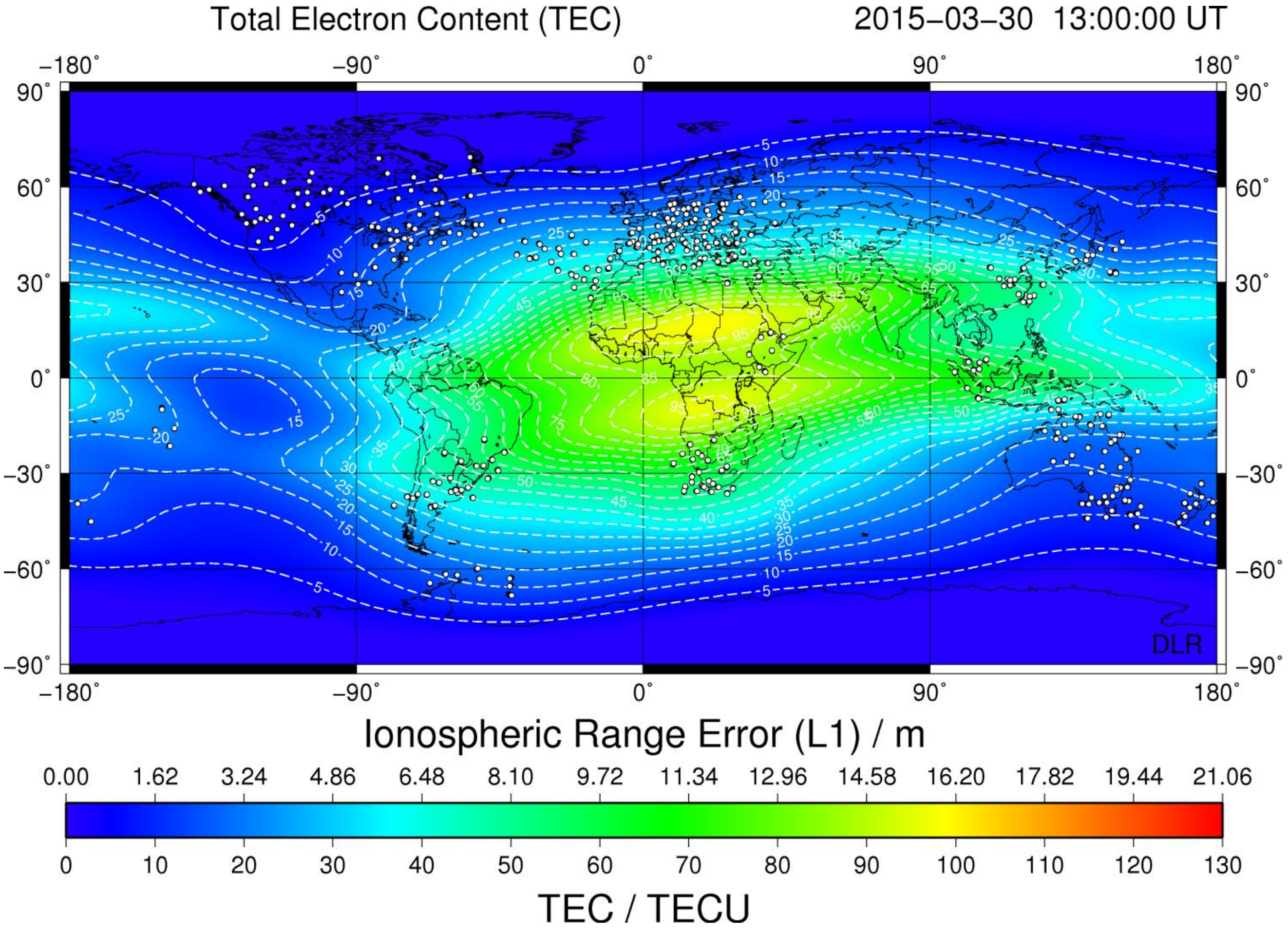


Figure from Jakob Jakobsen, DTU-Space

Geographic variation of TEC



Auroral activity

- Auroral activity causes disturbances to the general ionospheric activity

- Ionospheric models do not handle auroral activity well

⇒ GNSS positioning is less reliable in the auroral oval

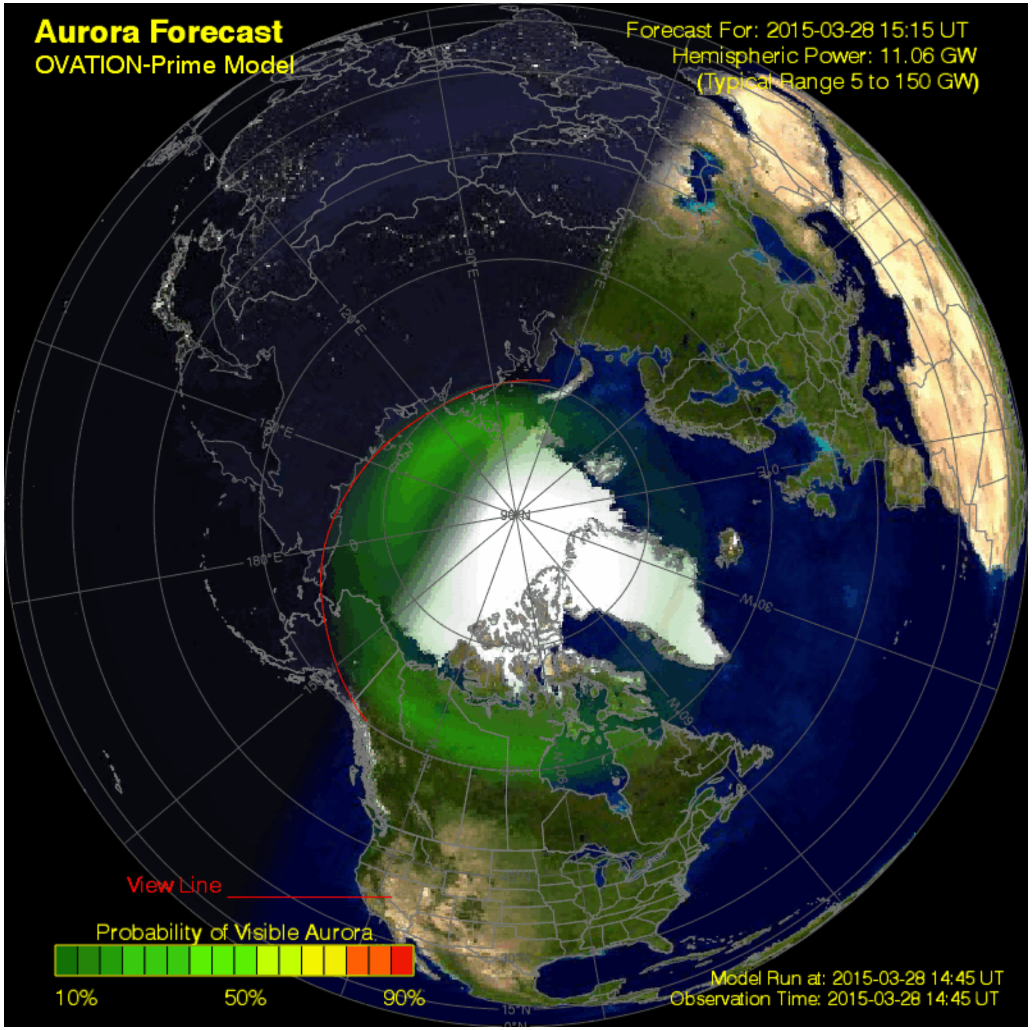


Figure from: http://www.swpc.noaa.gov/products/30-minute-aurora-forecast

The refractive index

- The refractive index, n is given by: $n = \frac{c}{v}$

where:

  - c is the speed of light in vacuum
  - v is the speed of the signal in the current medium

- The refractive index is not constant, it varies with the composition of the atmosphere

- The total refraction along the signal path is the integral of the refractive index along the path

Signal travel time

- The signal travel time, τ given in time units, can be determined as:

$$\tau = \int \frac{1}{v} ds$$

where the integration is carried out along the signal path, *ds*

Signal delay

- The signal delay, *d*, caused by the refraction, is determined by converting the transmission time to distance (pseudorange) and subtracting the geometric distance:

$$d = c \cdot \int \frac{1}{v} ds - \rho = \int n \, ds - \int ds = \int (n-1) \, ds$$

- *n* is a function of the signal frequency, and for a combined signal, like GNSS signals, *n* varies for the different parts of the signal (code and phase)

Group and phase refractive index

- The ionosphere is dispersive for radio waves, i.e. *v* (and *n*) is a function of signal frequency

- n_φ is the refractive index for the phase of a particular signal (L1 or L2) - the phase refractive index:

$$n_\varphi = \frac{c}{v_\varphi}$$

- n_g is the refractive index for a group of signals (the PRN codes) - the group refractive index:

$$n_g = \frac{c}{v_g}$$

Modeling the ionospheric effect

- The first order effect of the ionosphere on the phase refractive index is:

$$n_\varphi = 1 - \frac{40.3 \cdot N_e}{f^2}$$

where *f* is carrier frequency and N_e is electron density

- The first order effect of the group refractive index:

$$n_g = n_\varphi - f\,\frac{dn}{df} = 1 + \frac{40.3 \cdot N_e}{f^2} \qquad \frac{dn}{df} = 40.3 \cdot N_e \left(-2 \cdot \frac{1}{f^3} \right)$$

Group delay and phase advance

$$d_g = \int (n_g - 1)\, ds = \int \left(1 + \frac{40.3 \cdot N_e}{f^2} - 1 \right) ds = \frac{40.3}{f^2} TEC$$

- Similar for the phase delay:

$$d_\varphi = \frac{-40.3}{f^2} TEC$$

- dg and dφ are equal in size but with opposite sign; the code information experience a delay, and the carrier wave is advanced through the ionosphere

Size of ionospheric first order effect

- Typical sizes of first order ionospheric signal delay in the zenith direction:
  - 5-15 meter in the afternoon
  - 1-3 meter at night

- The numbers are valid for mid-latitudes. Higher “normal” values close to the Equator, and larger variability in auroral regions

- Largest value recorded: approximately 150 meter in Brazil

Broadcast model of ionospheric delay

- Broadcast model of ionospheric delay in the zenith, Iz:

$$\frac{I_z}{c} = \begin{cases} A_1 + A_2 \cos\left(\dfrac{2\pi(t - A_3)}{A_4}\right) \\ \qquad\qquad A_1 \end{cases}$$

- *A1, A2, A3,* and *A4* are polynomial functions, and their coefficients are estimated by the GPS control center, and transmitted with the navigation message. *t* is current time, and *c* is the speed of light

- Models in general about 50% of the ionospheric effect

The obliquity factor

- The ionospheric effect is also dependent on signal elevation angle, and the broadcast expression for the obliquity factor, *OF*, is:

$$OF_{\zeta} = \left[1 - \left(\frac{R_E \sin(\zeta)}{R_E + h_I} \right)^2 \right]^{-1/2}$$

- where:
  - h_I is the mean ionospheric height, 350 km
  - R_E is Earth mean radius, 6371 km
  - ξ = 90 - elevation angle

The broadcast ionosphere model, also called the Klobuchar model

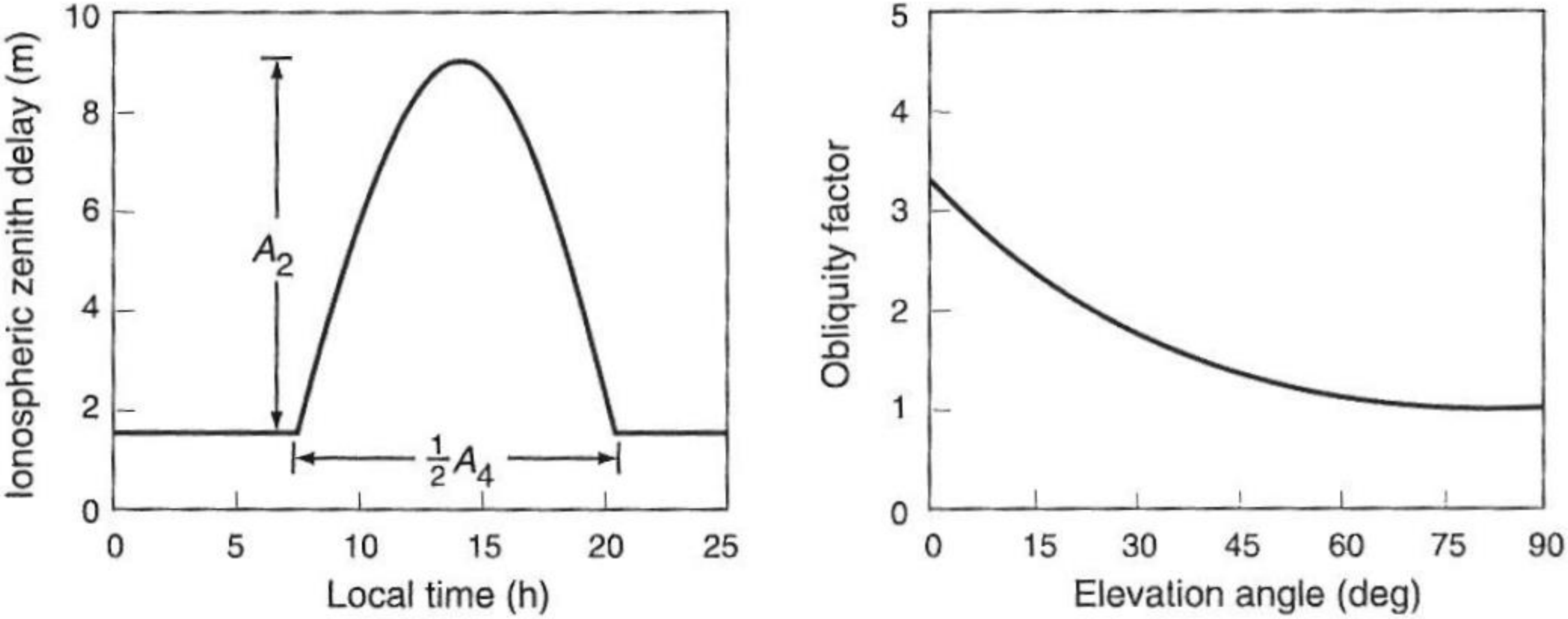


Figure:

Global Positioning System, Signals, Measurements and Performance. By Misra and Enge, 2006

The ionosphere free linear combination

- Can be used with both code observations (P for pseudorange) and phase observations (φ)

$$P_{IF} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} P_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2} P_{L2}$$

- Noise is increased with a factor of about 3

- For phase observations, the IF combination models the first order ionospheric effect within 3 cm for elevation angles > 15°

Other ionospheric effects

- Significant higher order ionospheric effects can be encountered during:
  - Auroral activity (Northern light)
  - Ionospheric storms (1-5 days after a solar flare or a coronal mass ejection)

- Scintillation
  - Changes in phase and amplitude of the signal => loss of signal lock
  - Caused by small “lumps” of electrons aligned along the geomagnetic field lines. Is often correlated with increased ionospheric activity

Principal regions of scintillation

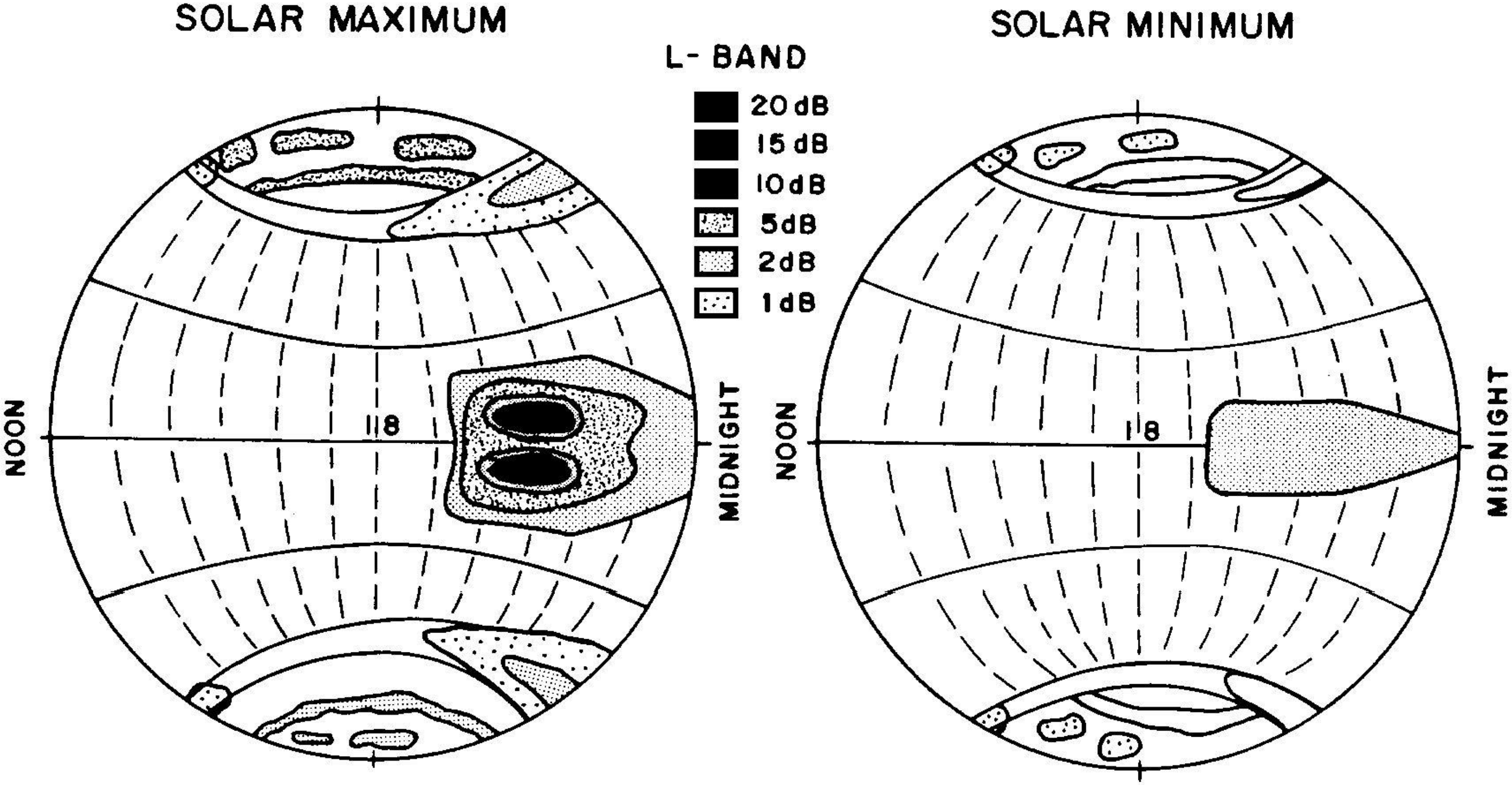
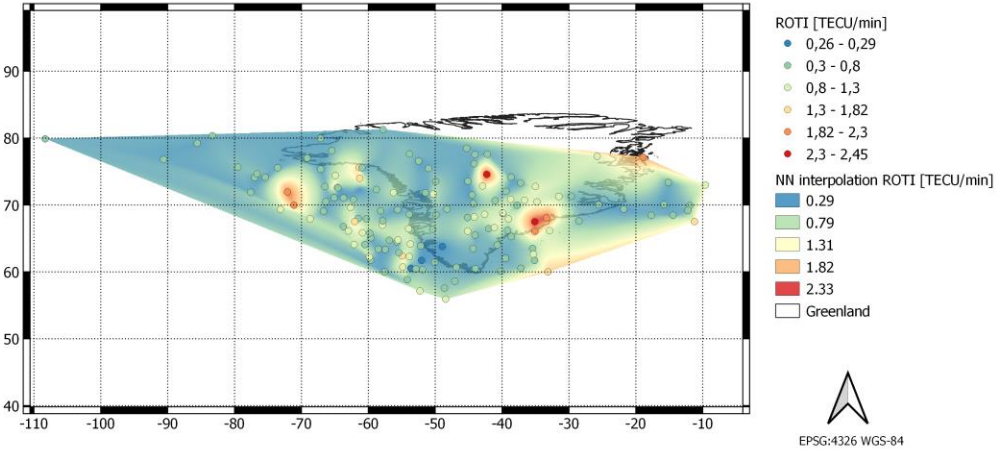


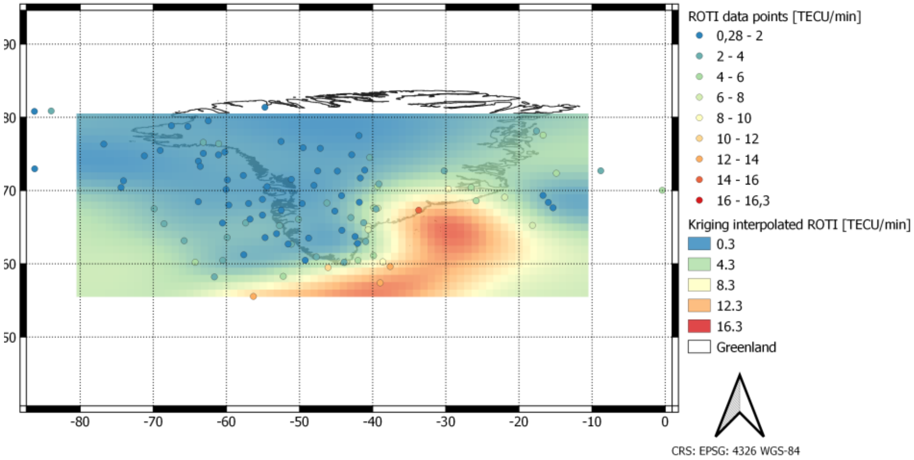
Figure from: Hunsucker, R.D. and Hargreaves, J.K., ”The High Latitude Ionosphere and its Effects on Radio Propagation”, Cambridge University Press, 2003

Scintillation at geomagnetically active and quiet day

Natural neighbour interpolated ROTI map above Greenland on day 30 2014 at 05:51:25 UTC



Kriging Interpolated map of ROTI above Greenland on day 50 2014 at 05:51:25 UTC, with range = 10 deg.



Indices of ionospheric activity

- The planetary Kp index, 3-hour index, logarithmic scale from 0 (low) to 9 (high)
  - http://www.swpc.noaa.gov/products/planetary-k-index
- The Geomagnetic Storm Scale, G1 (minor) to G5 (extreme)
  - https://www.swpc.noaa.gov/noaa-scales-explanation
- Other indices are also available e.g. the A index, the Polar Cap (PC) index, the Disturbed Storm Time (DST) index, and the Auroral Activity (AE) index

Indicies of ionospheric scintillation

- Rate of TEC index (ROTI)

$$ROT_m = \frac{TEC_m^i - TEC_{m-1}^i}{t_m - t_{m-1}}$$

$$ROTI = \sqrt{\frac{1}{N-1}\sum_{m=n}^{m+N-1}(ROT_m - \langle ROT\rangle)^2}$$

i=satellite, m=ROT time index, n=ROTI time index, N=nr. of ROT values used for one ROTI value (usually 60)

- σ_φ – Phase scintillation index

$$\sigma_\varphi = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\varphi_i - \langle\varphi\rangle)^2}$$

φ=signal phase, N=number of observations the index is averaged over

- S_4 - Amplitude scintillation index

$$S_4 = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}}$$

I=signal intensity

More information on ionospheric activity

- Web site of Space Environment Center of NOAA:
  - http://www.sec.noaa.gov/

- Web site of the European Space Agency:
  - http://swe.ssa.esa.int/

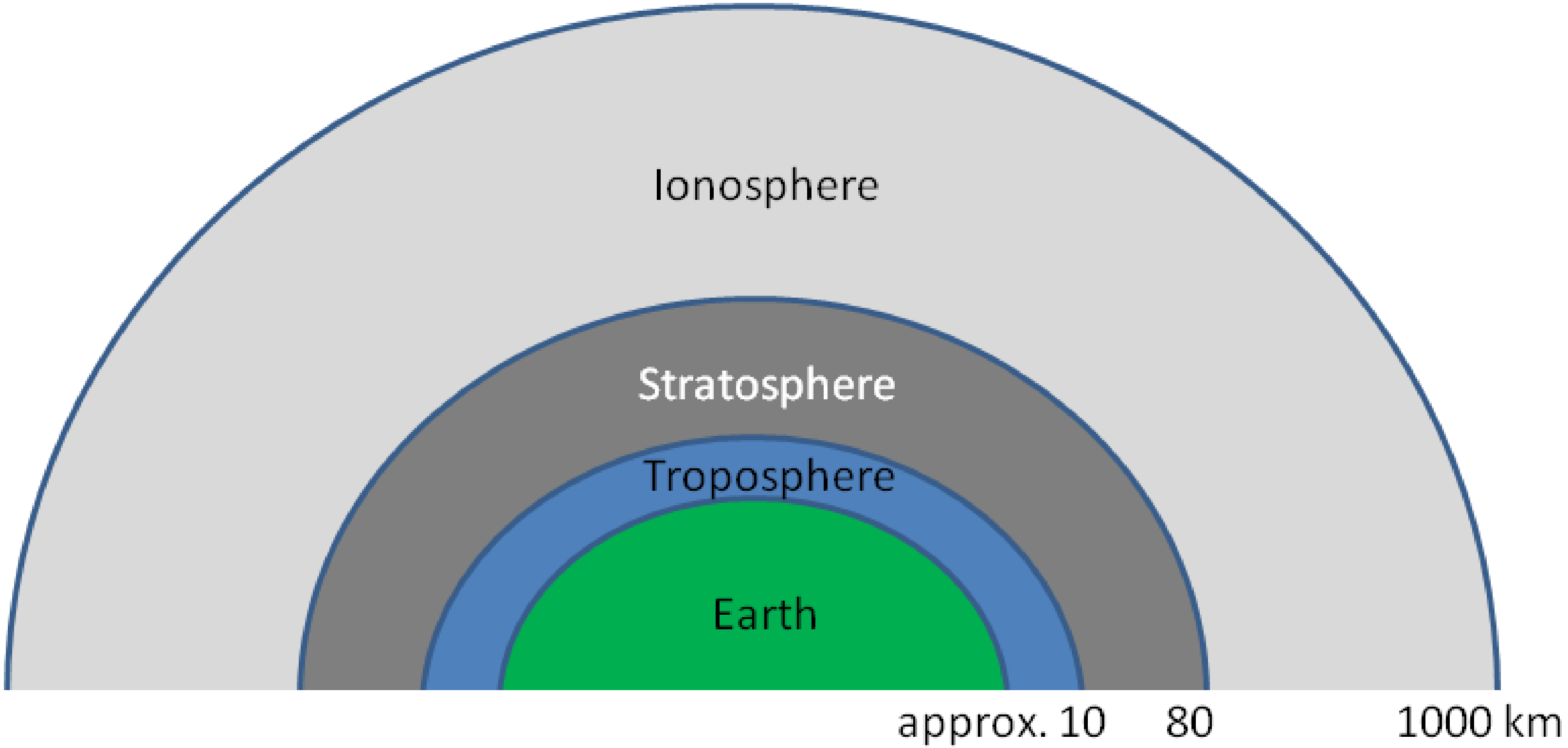
- Web site of German Aerospace Center:
  - http://swaciweb.dlr.de/index.php?id=19&L=1

Content

- ✓ The ionosphere
- ✓ Space weather, solar activity and variation in electron content
- ✓ Modelling of the ionospheric effect

- The neutral atmosphere
- Refractivity
- Modelling of the tropospheric effect

Earth’s atmosphere



The Neutral Atmosphere (1)

- Is the part of the atmosphere that is electrically neutral to radio waves
  - ⇒ refractive index is still frequency dependent, but in the neutral atmosphere the refractive index is identical for all radio frequencies

- Consists of:
  - **Troposphere**, altitude up to about 10 km
    - Where the "weather" is located. It is a very active part of the atmosphere
  - **Tropospause**, point where the temperature lapse rate is zero

Atmosphere temperature profiles

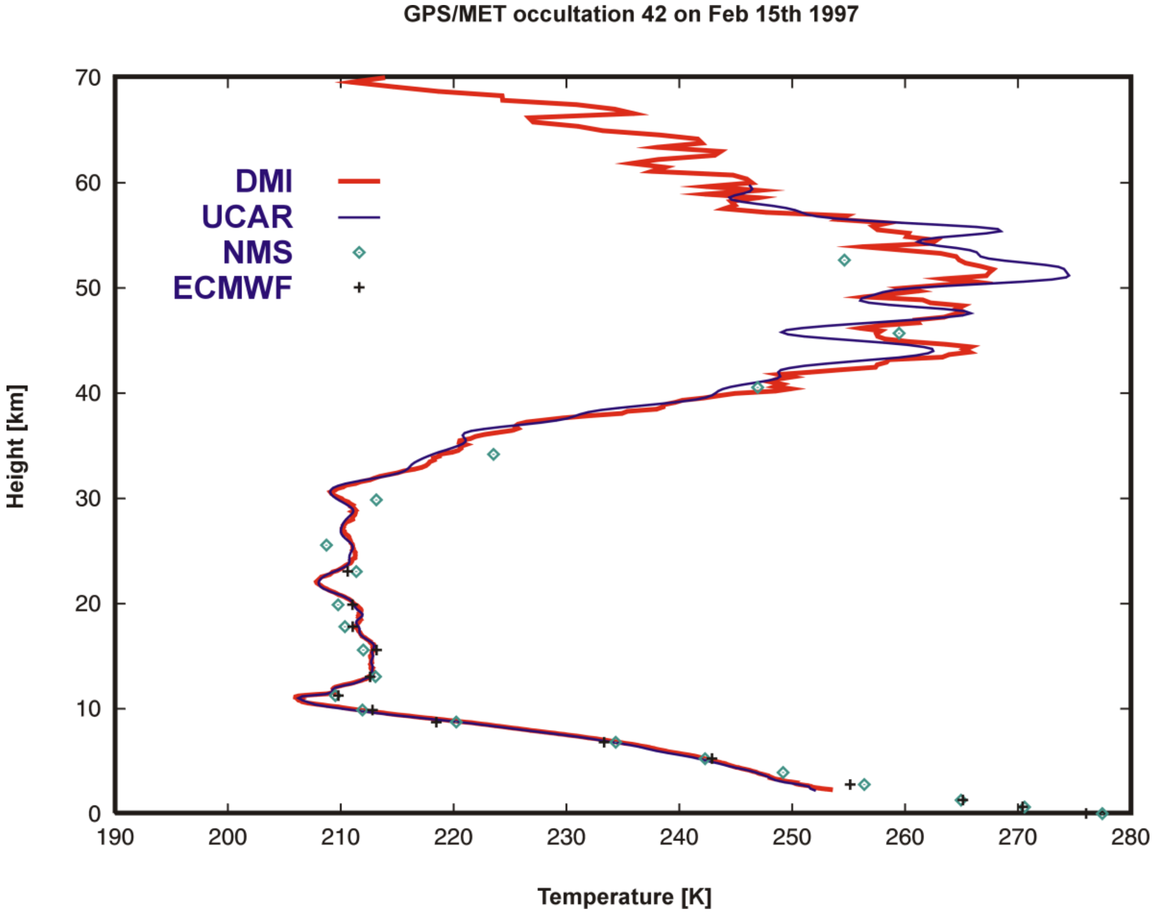


Figure from DMI

The Neutral Atmosphere (2)

- Consists of:
  - **Stratosphere**, altitudes between approx. 10 and 50 km
    - The temperature is basically constant in the lowest part of the stratosphere, and increases from about 20 km and upwards because of increasing amount of ozone that absorbs ultraviolet radiation from the sun

The Neutral Atmosphere (3)

- The effect of the neutral atmosphere on GNSS satellite signals is often called the *tropospheric delay*, because most of the effect is caused by the troposphere

- The density of the atmosphere is highest close to the surface of the Earth
  - =>The refractive index is highest close to the Earth and is decreasing with altitude

The Neutral Atmosphere (4)

- Refraction in the neutral atmosphere is a function of meteorological conditions:
  - Pressure, temperature and humidity (amount of water vapor)
- Refraction is larger in hot and humid areas, and smaller in cold and dry conditions

Refractivity (1)

- Refractivity, N is now introduced as a new variable because it is easier to work with than the refractive index, n:

$$N = (n - 1) \cdot 10^6$$

- For example:
  - –Close to sea level; n = 1.0003 and N = 300

Refractivity (2)

- Assuming an ideal gas behaviour, the refractivity can be expressed as:

$$N = k_1 \underbrace{\left(\frac{P_d}{T} \right)}_{\text{dry}} + \underbrace{\left(k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \right)}_{\text{wet}}$$

- where:
    - Pd is partial pressure of dry air
    - T is temperature
    - e is partial pressure of water vapor
    - k1, k2, and k3 are empirical constants

Tropospheric delay

- The tropospheric signal delay can now be given as:

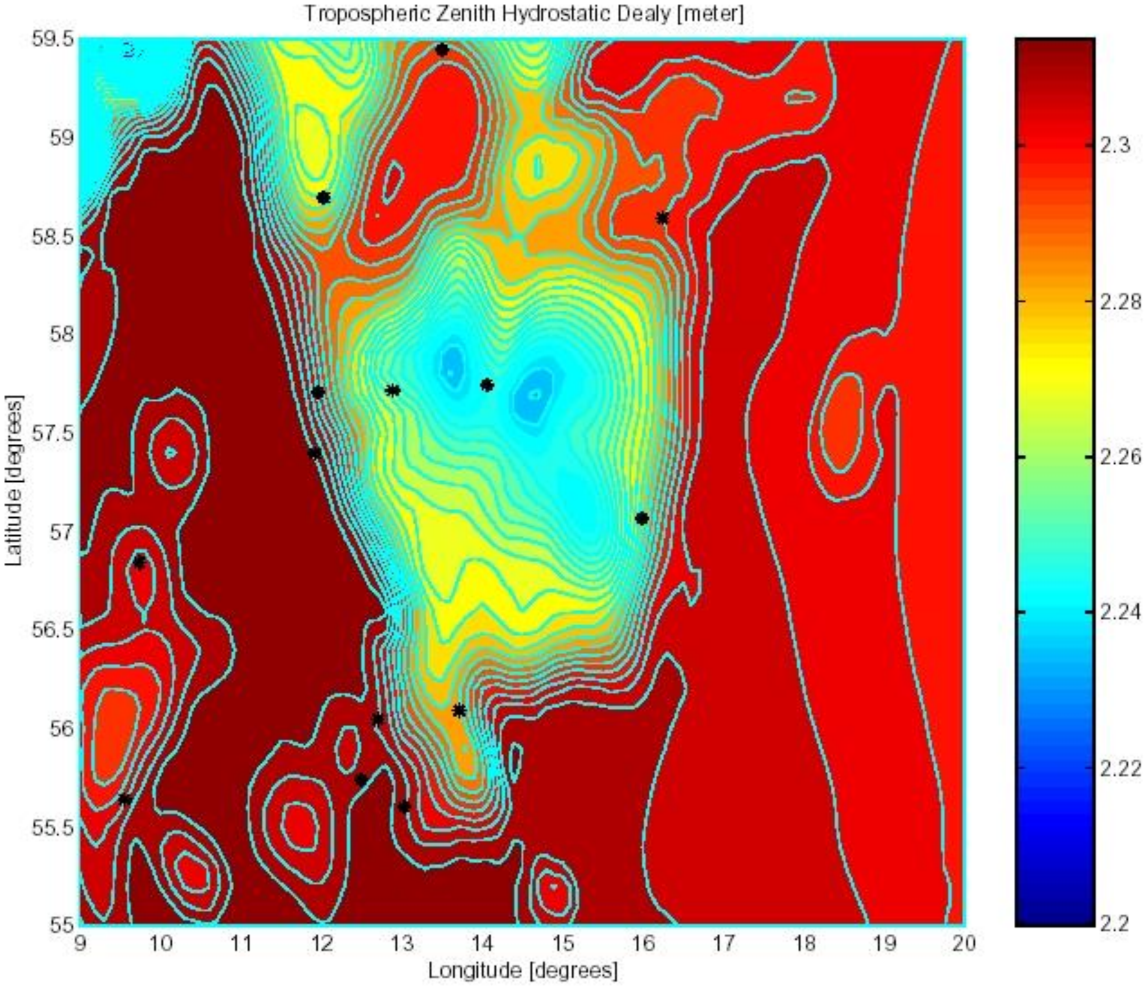
$$d_{trop} = 10^{-6} \int N\, ds = 10^{-6} \int \left[N_d + N_w \right] ds$$

where:

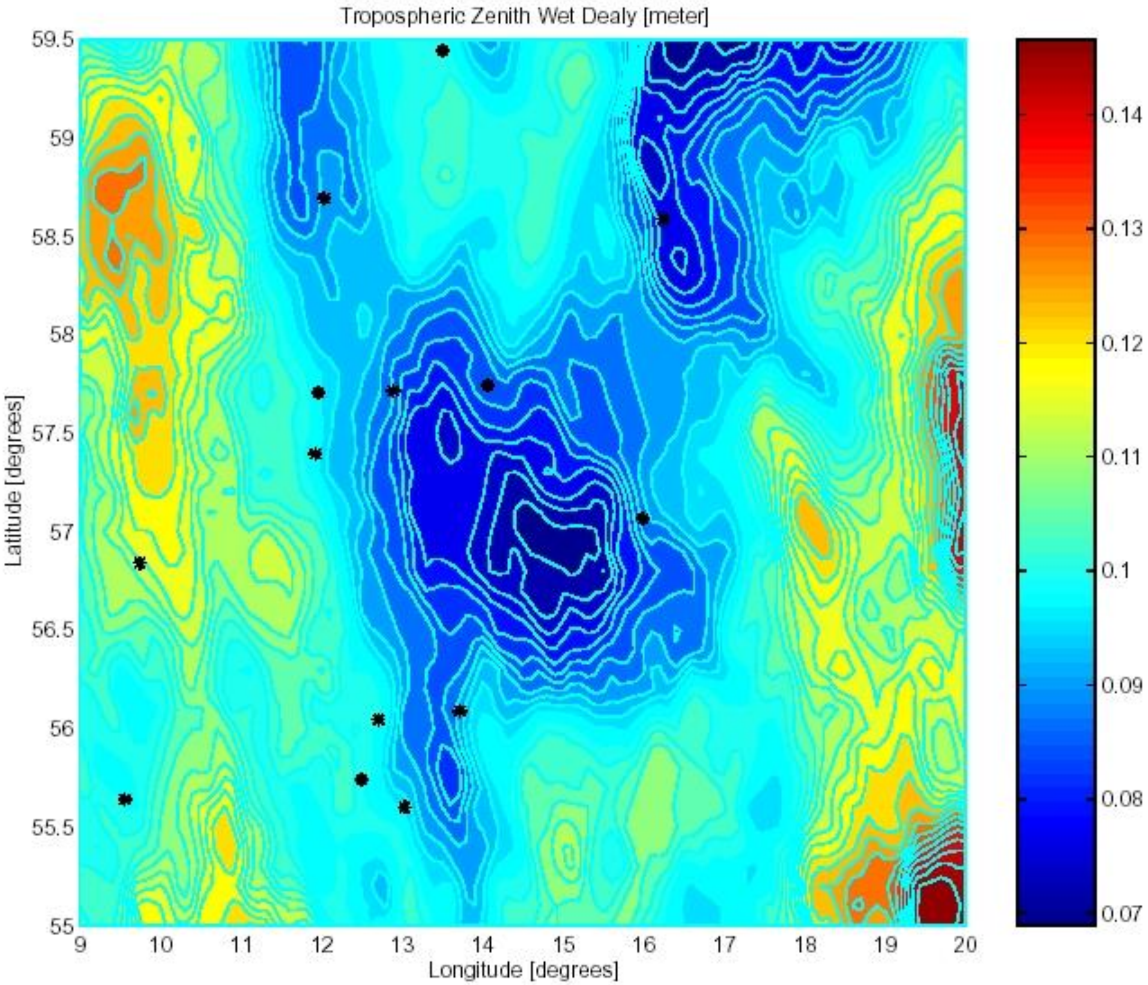
N_d is the dry part of the refractivity, and N_w is the wet (or humid) part of the refractivity

- If we know *P*, *T*, and *e* along the signal path, the delay can be determined by numerical integration
  - But, we don't know *P*, *T*, and *e* => modelling!

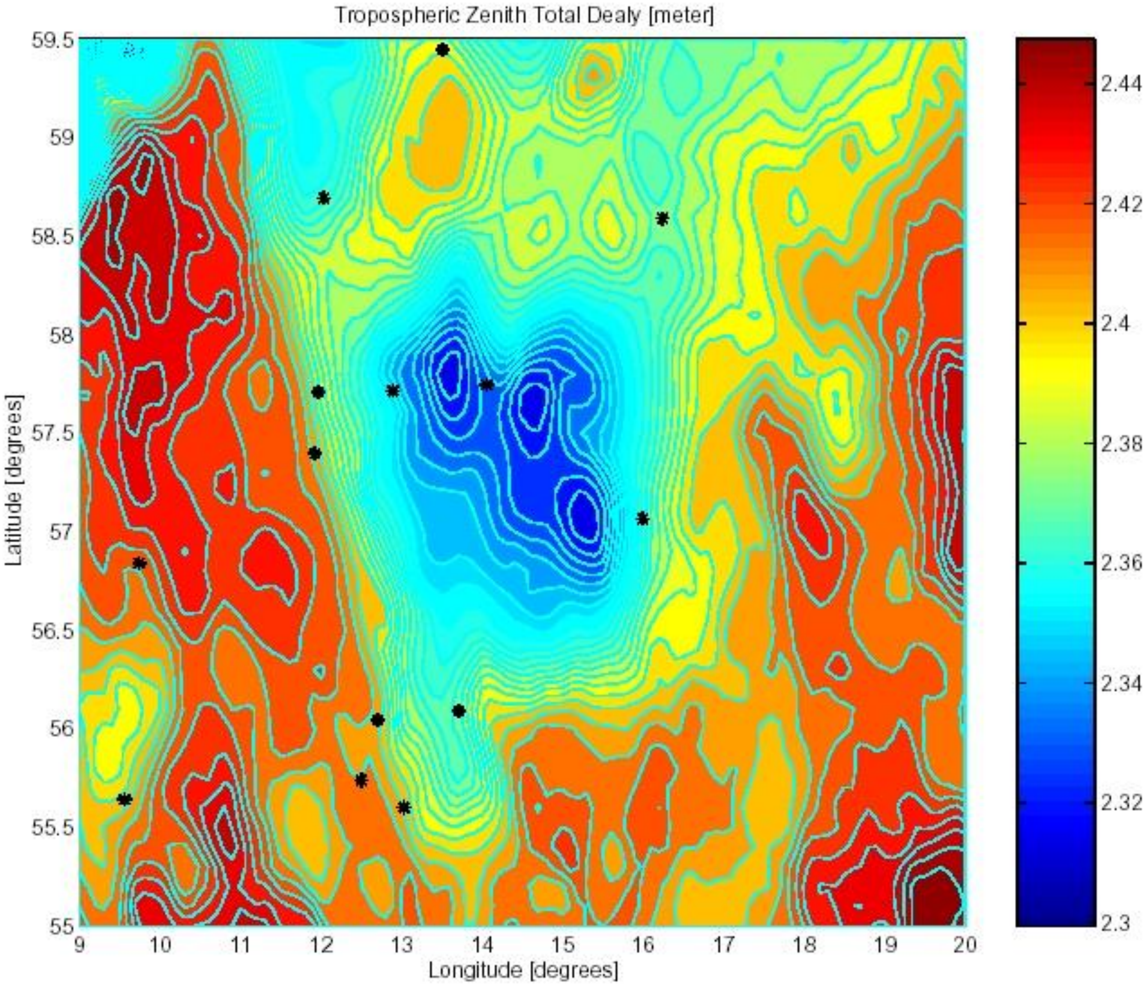
Tropospheric zenith dry delay



Tropospheric zenith wet delay



Tropospheric zenith delay



Tropospheric delay modelling

- Several models for the zenith tropospheric signal delay of satellite signals have been developed

- Performance of the models vary greatly, mainly because the spatial and temporal distribution of water vapor is very difficult to model
  - There is room for improvement => research area

- Examples of a few commonly used models:

The Hopfield model

$$d_{trop} = \frac{1}{5}10^{-6}\left(\left(77.6\frac{P_s \cdot (H_d - h_{ant})}{T_s}\right) + \left(3.73 \cdot 10^5 \frac{e_s (H_w - h_{ant})}{T_s^2}\right)\right)$$

$$H_d = 43.130 - 5.206 \sin^2(\phi_{ant})$$

- P_s is pressure at surface (hPa)
- T_s is temperature at surface (K)
- e_s is water vapor pressure at surface (hPa)
- H_d is equivalent dry height (km), where N_d is zero
- H_w is equivalent wet height (km), where N_w is zero
- h_{ant} is MSL height of antenna (km)
- φ_{ant} is latitude of antenna

The Saastamoinen model

$$d_{trop} = 0.002277 \cdot D \cdot \left(P_s + \left(\frac{1255}{T_s} + 0.05 \right) \cdot e_s \right)$$

$$D = 1 + 0.0026 \cos\left(2\phi_{ant}\right) + 0.00028 \cdot h_{ant}$$

- P_s is pressure at surface (hPa)
- T_s is temperature at surface (K)
- e_s is water vapor pressure at surface (hPa)
- h_{ant} is MSL height of antenna (km)
- φ_{ant} is latitude of antenna

Ifadis' model for zenith wet delay

$$d_{wet-trop} = 0.00554 - 0.880 \cdot 10^{-4}\left(P_s - 1000\right) + 0.272 \cdot 10^{-4} e_s + 2.771\left(\frac{e_s}{T_s}\right)$$

- P_s is pressure at surface (hPa)
- T_s is temperature at surface (K)
- e_s is water vapor pressure at surface (hPa)

- Ifadis' model can be used with the dry part of the Saastamoinen model for estimating the total tropospheric delay in the zenith direction

Modelling accuracy

- At sea level approximate size of zenith delay is:
  - 2.3 meter for dry delay
  - 0.05 - 0.2 meter for wet delay
- Generally the dry part is about 90% and the wet part is about 10% of the total zenith delay
- The dry part is modelled well; std. dev. < 5 mm for most models
- The wet part is more difficult to model; std. dev. 3-4 cm for the best models (e.g. Saastamoinen)

Mapping functions (1)

- The previous models are used for estimating tropospheric signal delay in the zenith direction
- The delay, however, increases for signals received at lower elevation angles

$$d_{trop}(elv) = m(elv) * d_{trop}\ (zenith)$$

- m(elv) is called a mapping function, and it is used for mapping, or scaling, of the zenith delay to lower elevations

Mapping functions (2)

- Several mapping functions have been developed, and the performance vary, especially for the low elevation angles (< 10°)

- The most simple mapping function is:

  m(elv) = 1/sin(elv)

- The Niell mapping function is currently considered to be the best

The Niell mapping function (NMF)

- Presently known as the best mapping function. Does not take meteorological parameters as input:

$$m(\varepsilon)=\frac{1+\dfrac{a}{1+\dfrac{b}{1+c}}}{\sin(\varepsilon)+\dfrac{a}{\sin(\varepsilon)+\dfrac{b}{\sin(\varepsilon)+c}}}+H*10^{-3}\left(\frac{1}{\sin(\varepsilon)}-\frac{1+\dfrac{a_{ht}}{1+\dfrac{b_{ht}}{1+c_{ht}}}}{\sin(\varepsilon)+\dfrac{a_{ht}}{\sin(\varepsilon)+\dfrac{b_{ht}}{\sin(\varepsilon)+c_{ht}}}}\right)$$

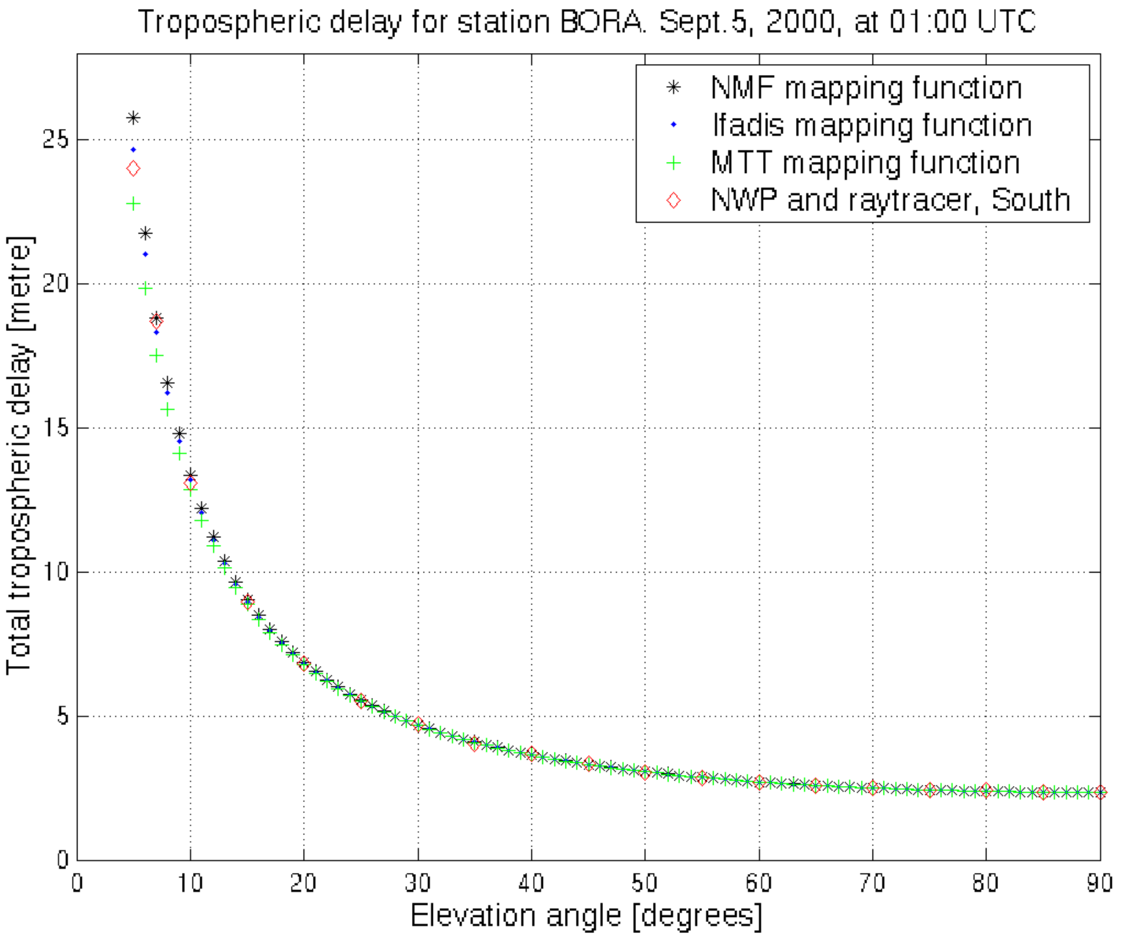
Where :

H is altitude, ε is elevation angle of satellite signal

a, b, c are functions of latitude, altitude and time of year

- Many other functions exist

Mapping functions (3)



Mapping functions (5)

- Limitations in mapping functions:
  - Assume isotropic atmosphere
  - Limited accuracy for low elevation angles, below 10°
  - Generally not valid below 5°

- Solution: Estimation of residual tropospheric effects and/or tropospheric gradients in positioning process

  => Reduced degrees of freedom in adjustment process

- Room for improvement; better mapping functions are requested by high accuracy GNSS users

Size of total tropospheric delay

- Zenith tropospheric delay:
  - Approx. 2.4 meter at sea level
  - Decreasing with higher altitude (~1 m at Mount Everest)
- Slant tropospheric delay:
  - Approx. 24 meter at 5° elevation
  - Elevation mask can limit residual effect for low elevations
- Residual (unmodelled) tropospheric delay affects the height component of the position more than the horizontal