GNSS and the Troposphere

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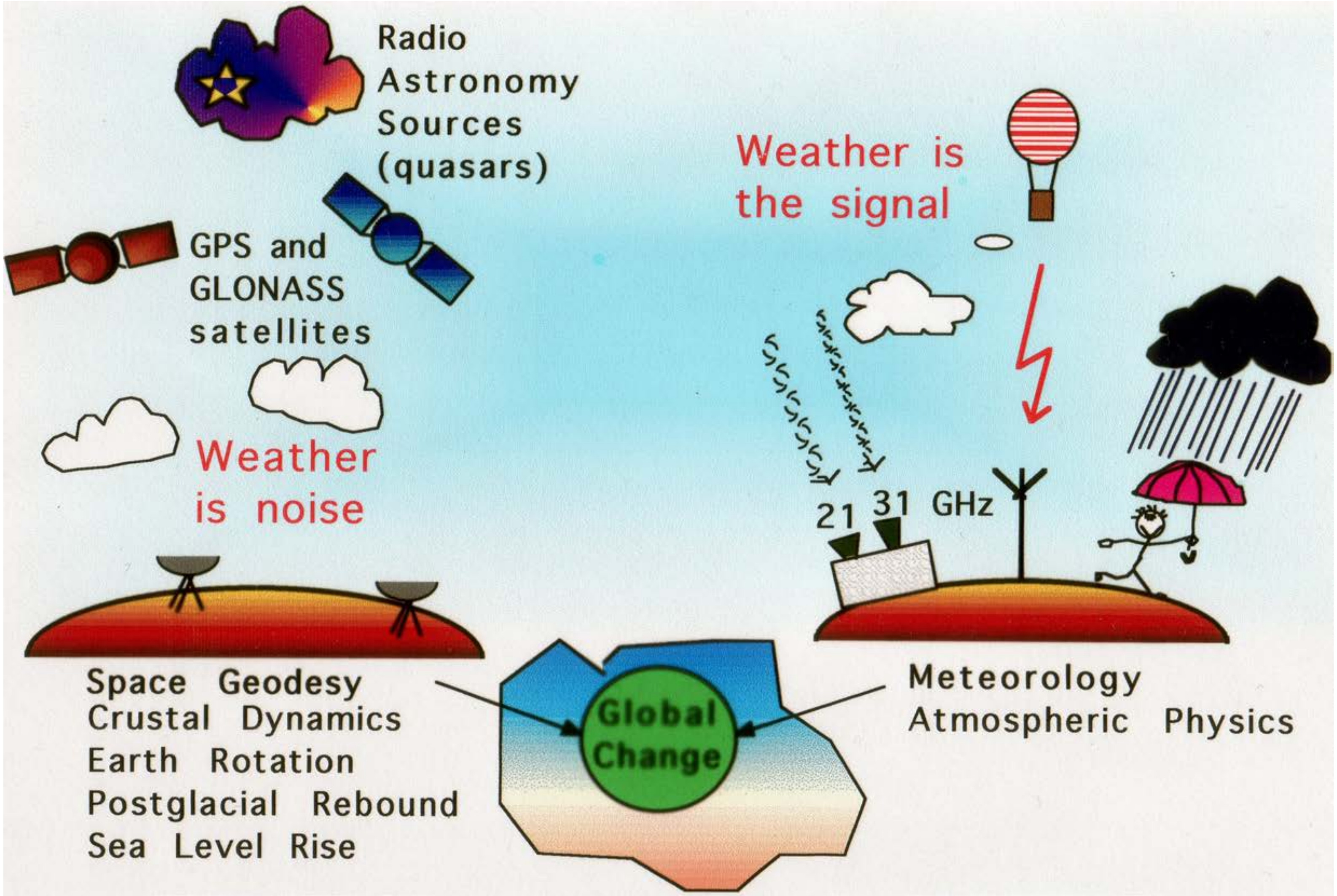
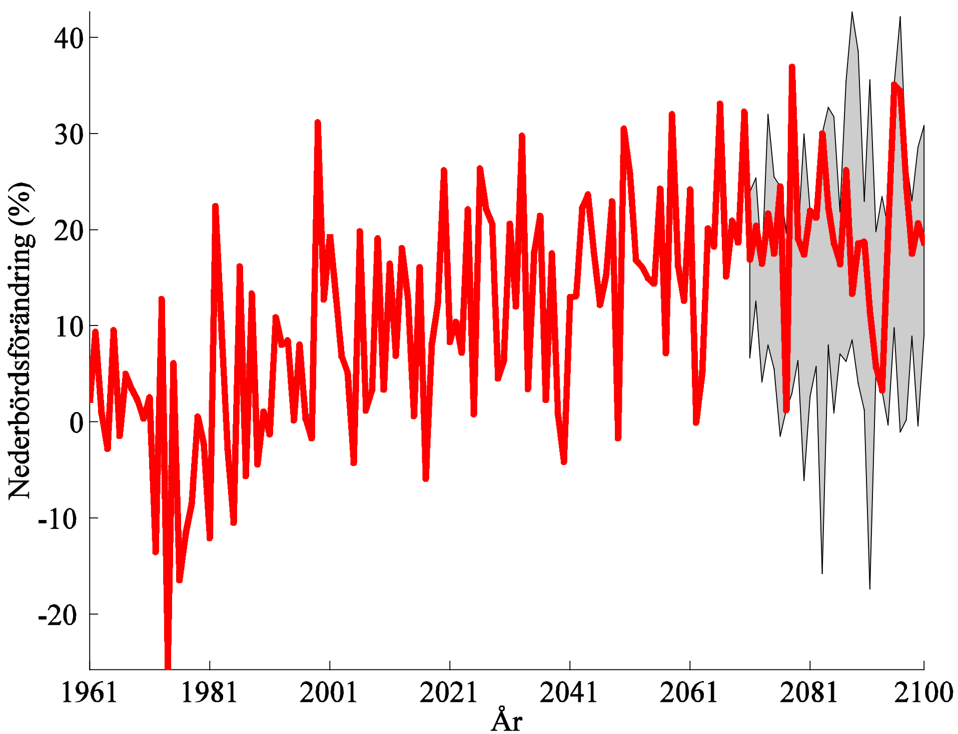
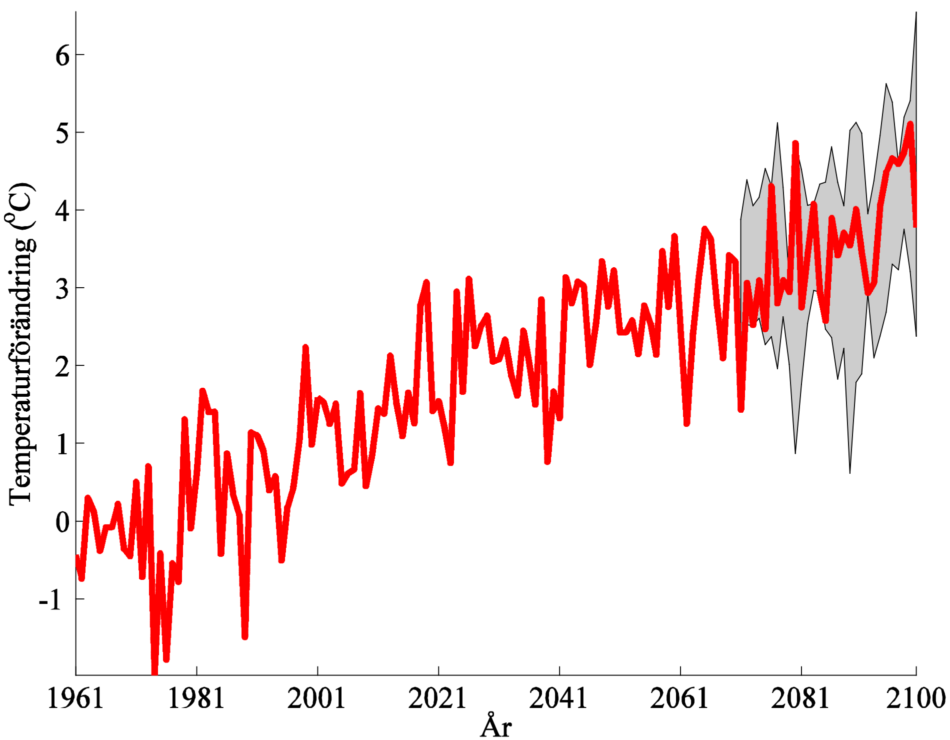

Radio
Astronomy
Sources
(quasars)
Weather is
the signal
GPS and
GLONASS
satellites
Weather
is noise
21
31
GHz
Space Geodesy
Crustal Dynamics
Earth Rotation
Postglacial Rebound
Sea Level Rise
Global
Change
Meteorology
Atmospheric Physics

Estimated ”climate change” in Sweden relative to the period 1961-1990

Annual precipitation



Annual mean temperature

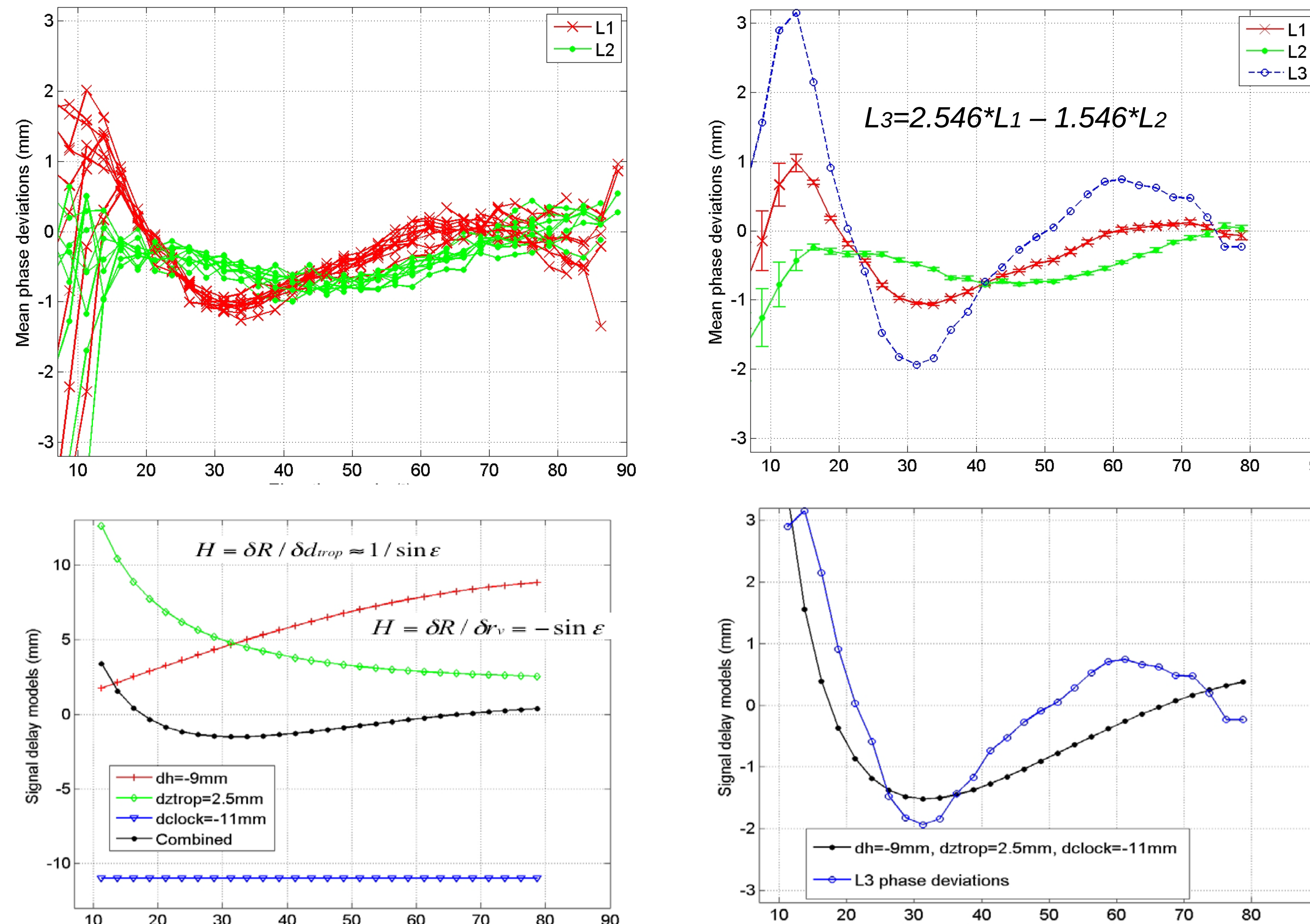


Red line shows Rossby Centres most recent simulation of ”climate change”.
Grey indicates results from 4 earlier simulations.

SMHI

GPS observations 30 years ago

”Weather observations”



Mean phase deviations (mm)
L1
L2
L3
$L_3 = 2.546 * L_1 - 1.546 * L_2$
Signal delay models (mm)
$H = \delta R / \delta d_{trop} \approx 1 / \sin \varepsilon$
$H = \delta R / \delta r_v = -\sin \varepsilon$
dh=-9mm
dztrop=2.5mm
dclock=-11mm
Combined
dh=-9mm, dztrop=2.5mm, dclock=-11mm
L3 phase deviations

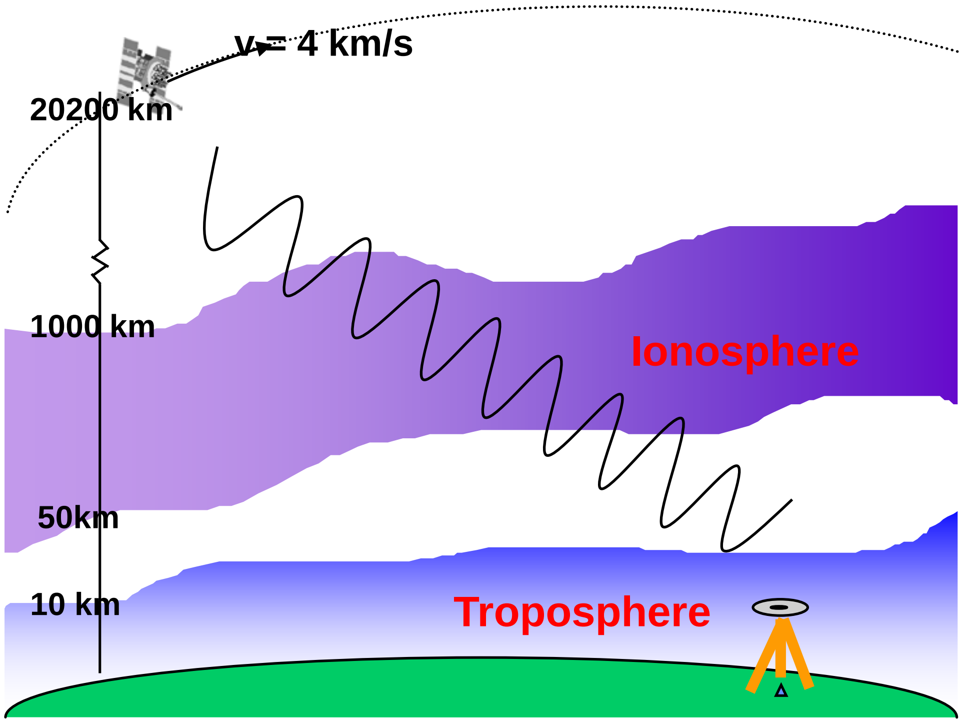
Outline

- Introduction
- General about the troposphere
- Propagation path delay
- How to handle troposphere in GNSS
- Development e.g. Mapping Functions
- Other “atmospheric issues”
- Measuring atmospheric water vapour using GPS
  - Uncertainty of GPS-derived water vapour
  - Long-term trends estimation
  - Evaluation of climate models
- Conclusions

Code & Phase Observations

$$R = \rho + c_0\left(d\tau - dt\right) + d_{ion} + d_{trop} + v_R$$

$$\phi = \rho / \lambda + v\left(d\tau - dt\right) - \varphi_{ion} + \varphi_{trop} + N + v_\phi$$



R = observed time delay from SV signal transmit to station A signal reception

ρ = delay due to geometry, distance

t = apparent delay due to user clock offset

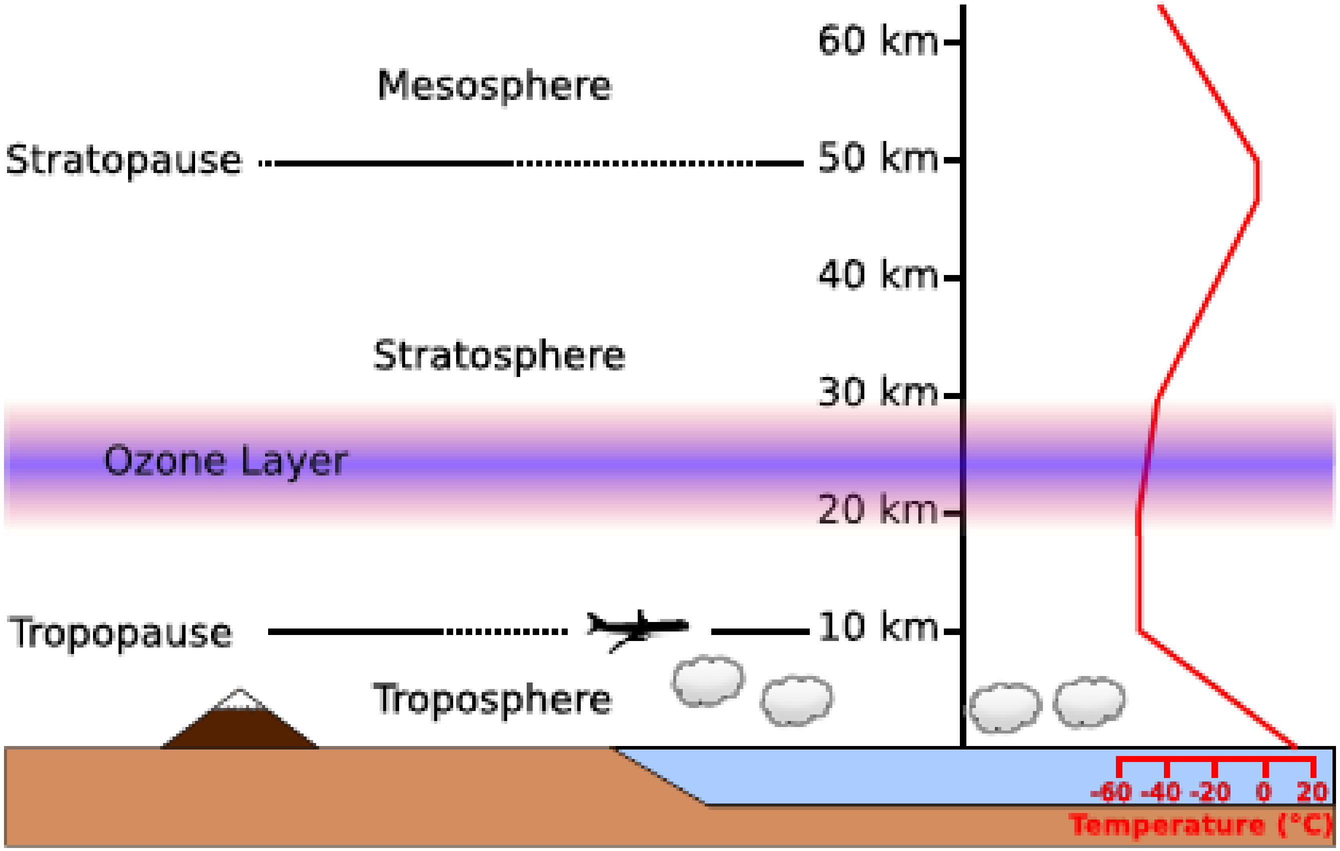
τ = apparent delay due to satellite clock offset

d_{iono} = dispersive delay due to ionosphere

$d_{atm(wet/dry)}$ = delay due to troposphere

v_R = delay due to multipath, signal reflection, noise

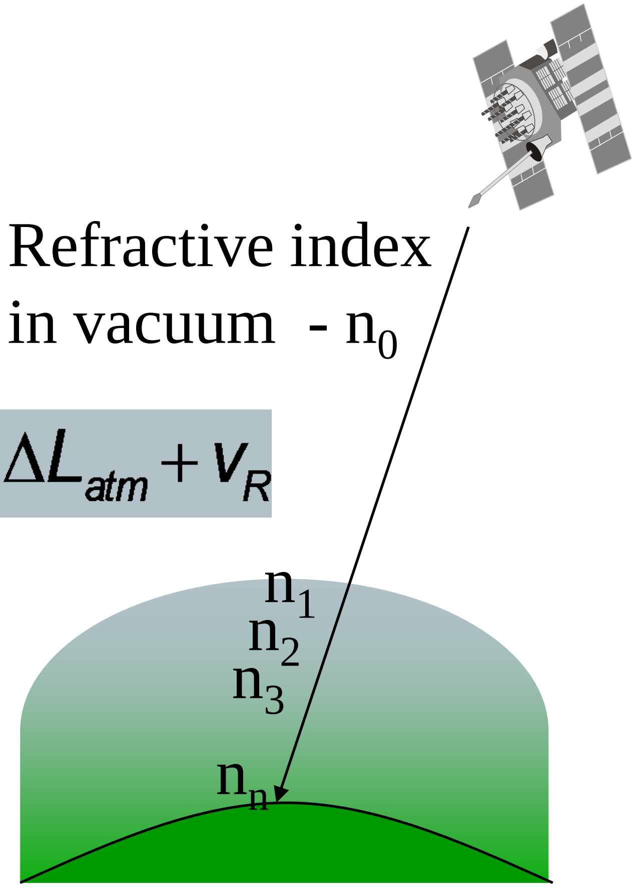
Basic atmospheric structure



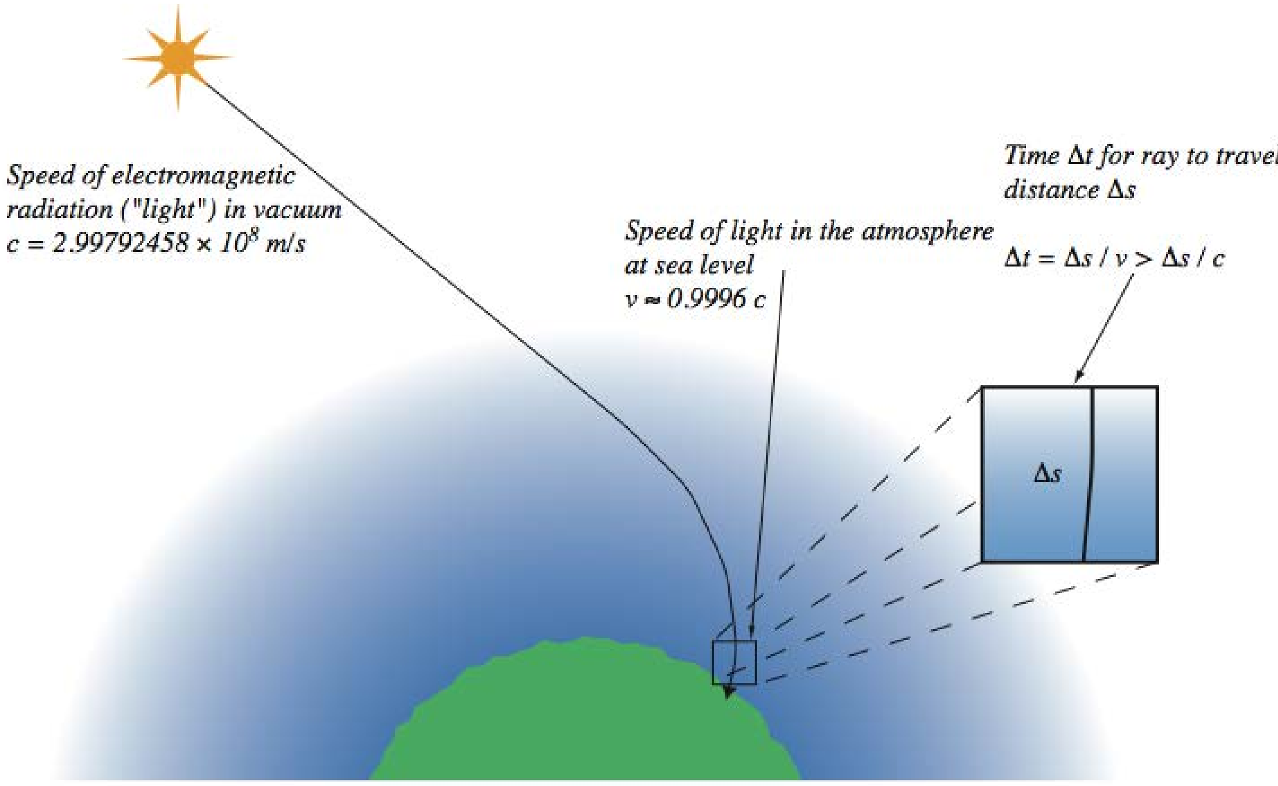
Troposphere is where the temperature stops decreasing in the atmosphere (~10 km altitude)

Atmosphere and Observation Equation

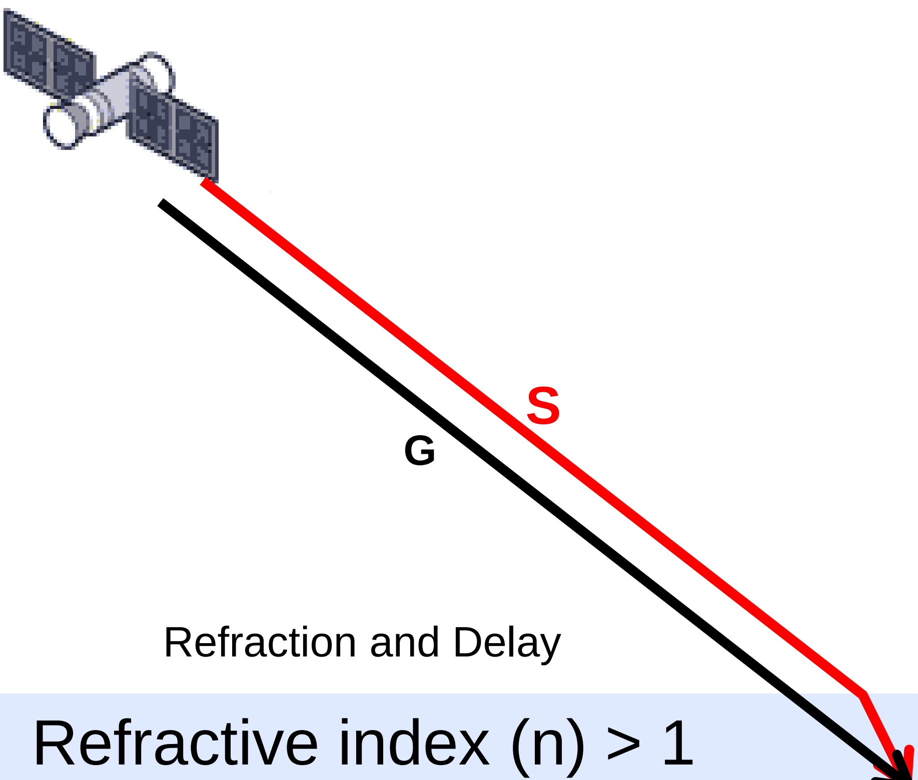
$$R = \rho + c_0 \left(d\tau - dt \right) + \Delta L_{atm} + v_R$$



Speed of the GNSS signals



Delay through the neutral atmosphere



Refraction and Delay

Refractive index (n) > 1

neutral atmosphere

Path delay:

$$\Delta L = \int_S n(s)ds - G$$

Definition of the excess propagation path (1)

Assume a refractive index, **n**, in the atmosphere. The electrical path length **L** of a signal propagating along **S** is defined as

$$\mathbf{L} = \int_{s} \mathbf{n} \; \mathbf{ds}$$

The path **S** is determined from the index of refraction in the atmosphere using Fermat's Principle, to wit: the signal will propagate along the path that gives the minimum value of **L**.

The geometrical straight line distance, **G**, through the atmosphere is always shorter than the path **S** of the propagated signal.

The electrical path length of the signal propagating along **G** is longer than that for the signal propagating along **S**.

Definition of the excess propagation path (2)

The difference between the electrical path length and the geometrical straight line distance is called *excess propagation path*, *path delay*, or simply *delay*:

$$\mathbf{\Delta L = \int_s n \; ds - G}$$

We may rewrite this expression as $\mathbf{\Delta L = \int_s (n-1)\, ds + S - G}$

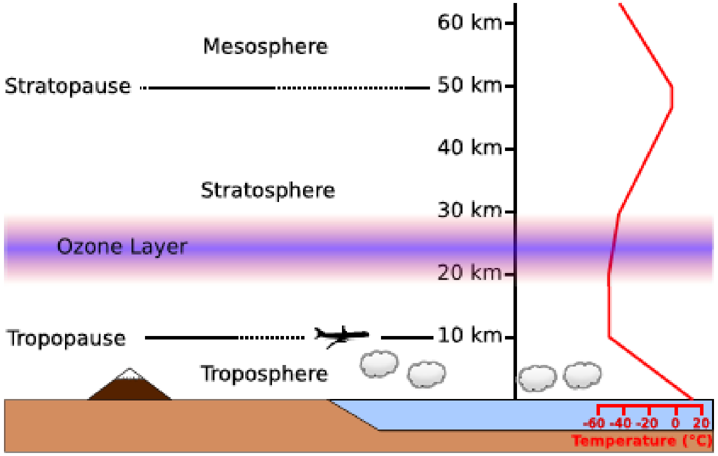
where $\mathbf{S = \int_s ds}$. The **(S-G)** term is often referred to as the *geometric delay* or the delay due to bending, denoted $\mathbf{\Delta L_g}$:

$$\mathbf{\Delta L_g \equiv S - G}$$

If the atmosphere is horizontally stratified, **S** and **G** are identical in the zenith direction and hence the *geometric delay* becomes equal to zero at this angle. (typically 3 cm at an elevation angle of 10°and 10 cm at 5°).

The Neutral Atmosphere (1)

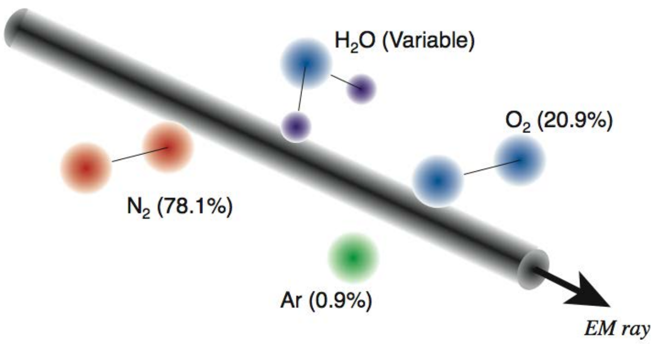
- Main components of dry air (N_2, O_2, Ar, CO_2)
- Composition constant up to about 100 km
- Above 100 km these gases appear as separate gases
- Other important constituents are Ozone and Water vapor
- Stratospheric Ozone important for absorption of UV-radiation and X-ray radiation from the sun (only 0.0001 % of volume)
- Below 30 GHz not dispersive (e.g. GPS and GLONASS identically influenced)

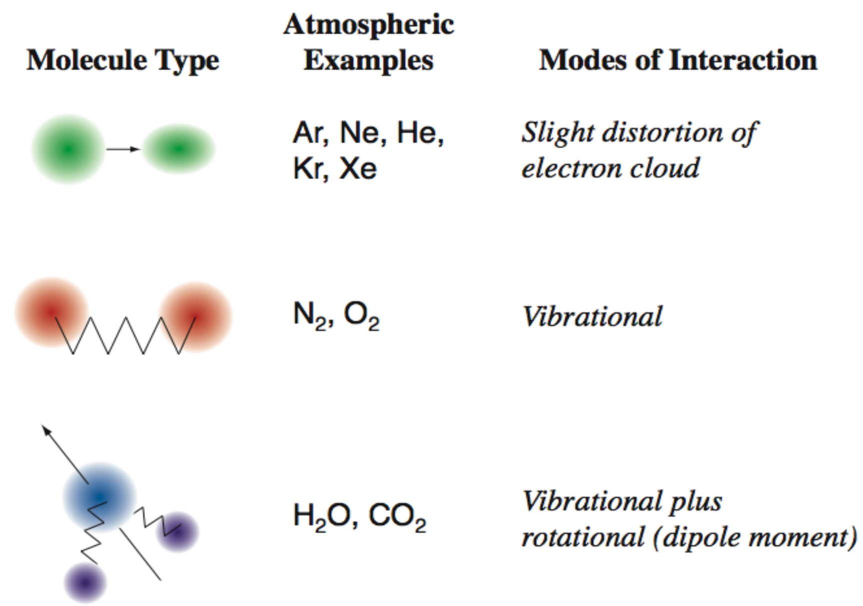


Refractivity of air

- Air is made up of specific combination of gases, the most important ones being oxygen and nitrogen.
- Each gas has its own refractive index that depends on pressure and temperature.
- For the main air constituents, the mixing ratio of the constituents is constant and so the refractivity of a packet of air at a specific pressure and temperature can be defined.
- The one exception to this is water vapor which has a very variable mixing ratio.
- Water vapor refractivity also depends on density/temperature due to dipole component.

Refractivity of air - continued





Refractivity of air - continued

- The refractivity of moist air is given by:

$$N = k_1 \underbrace{\frac{P_d}{T} Z_d^{-1}}_{\substack{\text{Density of} \\ \text{dry air}}} + k_2 \underbrace{\frac{P_w}{T} Z_d^{-1}}_{\substack{\text{Density of} \\ \text{water vapor}}} + k_3 \underbrace{\frac{P_w}{T^2} Z_d^{-1}}_{\substack{\text{Dipole component} \\ \text{of water vapor } \rho/\text{T}}}$$

$$k_1 = 77.60 \pm 0.05 \ \text{K/mbar}$$

$$k_2 = 70.4 \pm 2.2 \ \text{K/mbar}$$

$$k_3 = (3.730 \pm 0.012) \times 10^5 \ \text{K}^2\text{/mbar}$$

$$\text{N} = 10^6 (\text{n - 1}) \text{; where n is the refractive index}$$

- For most constituents, refractivity depends on density (i.e., number of air molecules). Water vapor dipole terms depends on temperature as well as density

Refractivity in terms of density

- We can write the refractivity in terms of density:

$$N = k_1 \frac{R}{M_d} \rho + \left(\frac{k'_2}{T} + \frac{k_3}{T^2} \right) P_w Z_w^{-1}$$

$$k'_2 = k_2 - k_1 M_w / M_d = 22.1 \pm 2.2 \quad \text{K/mbar}$$

- Density ρ is the density of the air parcel including water vapor. R is universal gas constant, M_d and M_w are molecular weights. Z_w is compressibility (deviation from ideal gas law)

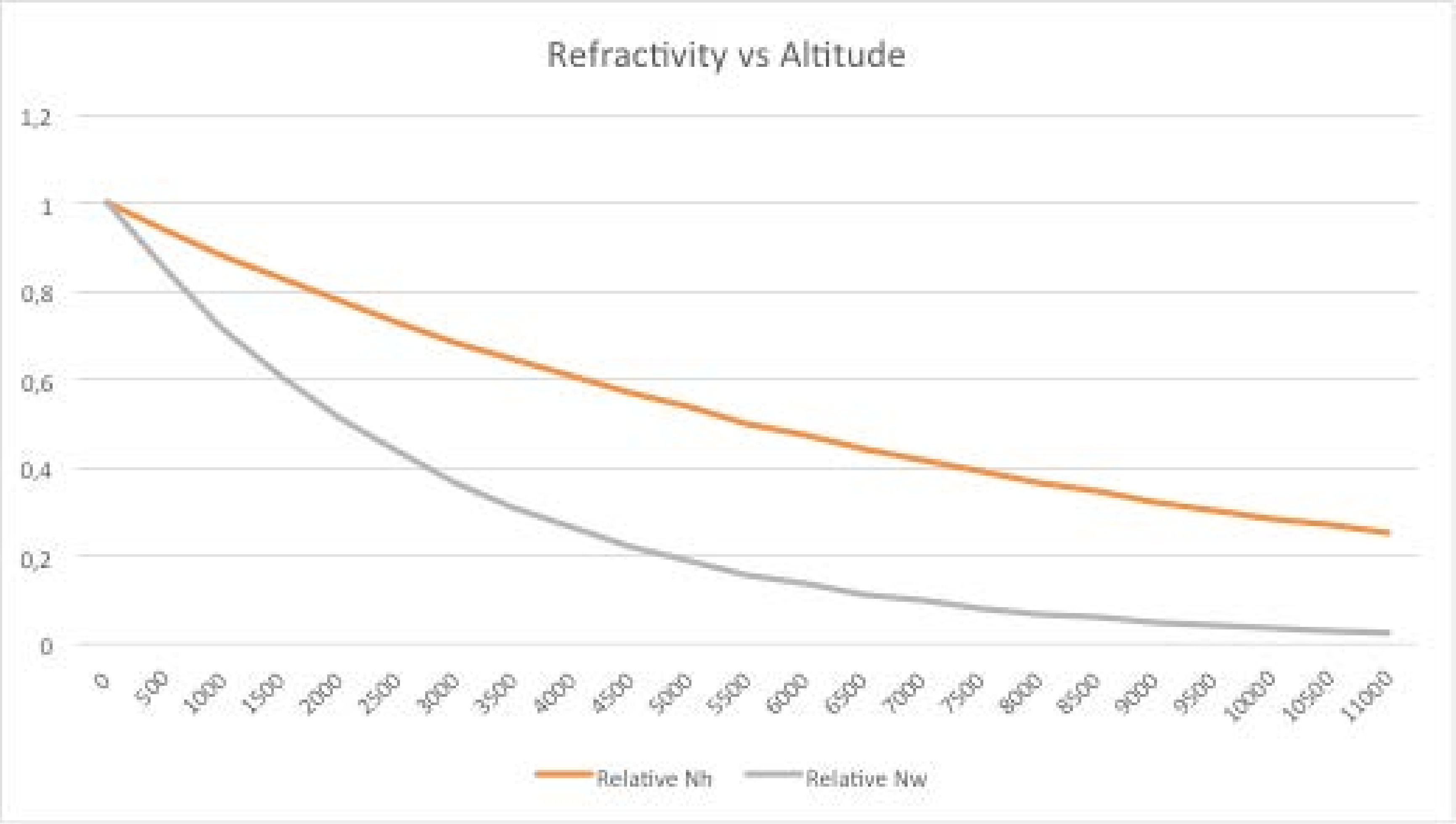
Refractivity

$$N = k_1 \frac{R}{M_d} \rho + \left(\frac{k'_2}{T} + \frac{k_3}{T^2} \right) P_w Z_w^{-1}$$

$$k'_2 = k_2 - k_1 M_w / M_d = 22.1 \pm 2.2 \quad \text{K/mbar}$$

$$\mathrm{N} = \mathrm{N}_{dry} + N_{wet}$$

Relative changes of refractivity



Integration of Refractivity

- To model the atmospheric delay, we express the atmospheric delay as:

$$\Delta L = \int_{atm} n(s)ds - \int_{vac} ds \approx m(\varepsilon)\int_{Z}^{\infty}(n(z)-1)dz = m(\varepsilon)\int_{Z}^{\infty} N(z)\times 10^{-6} dz$$

- Where the *atm* path is along the curved propagation path; *vac* is straight vacuum path, *z* is height for station height and *m(ε)* is a mapping function. (Extended later for non-azimuthally symmetric atmosphere)
- The final integral is referred to as the "zenith delay"

Integration of Refractivity

$$\Delta L = \int_{atm} n(s)ds - \int_{vac} ds \approx m(\varepsilon)\int_Z^{\infty} N(z)\times 10^{-6}\,dz =$$

$$m_{dry}(\varepsilon)\int_Z^{\infty} N_{dry}(z)\times 10^{-6}\,dz + m_{wet}(\varepsilon)\int_Z^{\infty} N_{wet}(z)\times 10^{-6}\,dz =$$

$$m_{dry}(\varepsilon)\Delta L_{dry} + m_{wet}(\varepsilon)\Delta L_{wet}$$

$$\Delta L_{dry} = \mathrm{ZHD}$$

$$\Delta L_{wet} = \mathrm{ZWD}$$

Zenith hydrostatic delay

- The Zenith hydrostatic delay is given by:

$$ZHD = 10^{-6} k_1 \frac{R}{M_d} g_m^{-1} P_s \approx 0.00228 \text{ m/mbar}$$

- Where g_m is mean value of gravity in column of air (Davis et al. 1991)
  g_m=9.8062(1-0.00265cos(2ϕ)-3.1x10^{-7}(0.9Z+7300)) ms^{-2}
- P_s is total surface pressure (again water vapor contribution included)
- Since P_s is 1013 mbar (hPa) at mean sea level; typical ZHD =2.3 meters

Zenith wet delay

- In meteorology, the term "Precipitable water" (PW) is used. This is the integral of water vapor density with height and equals the depth of water if all the water vapor precipitated as rain (amount measured on rain gauge).
- If the mean temperature of atmosphere is known, PW can be related to Zenith Wet Delay (ZWD) (See next page)

PW and ZWD

- Relationship:

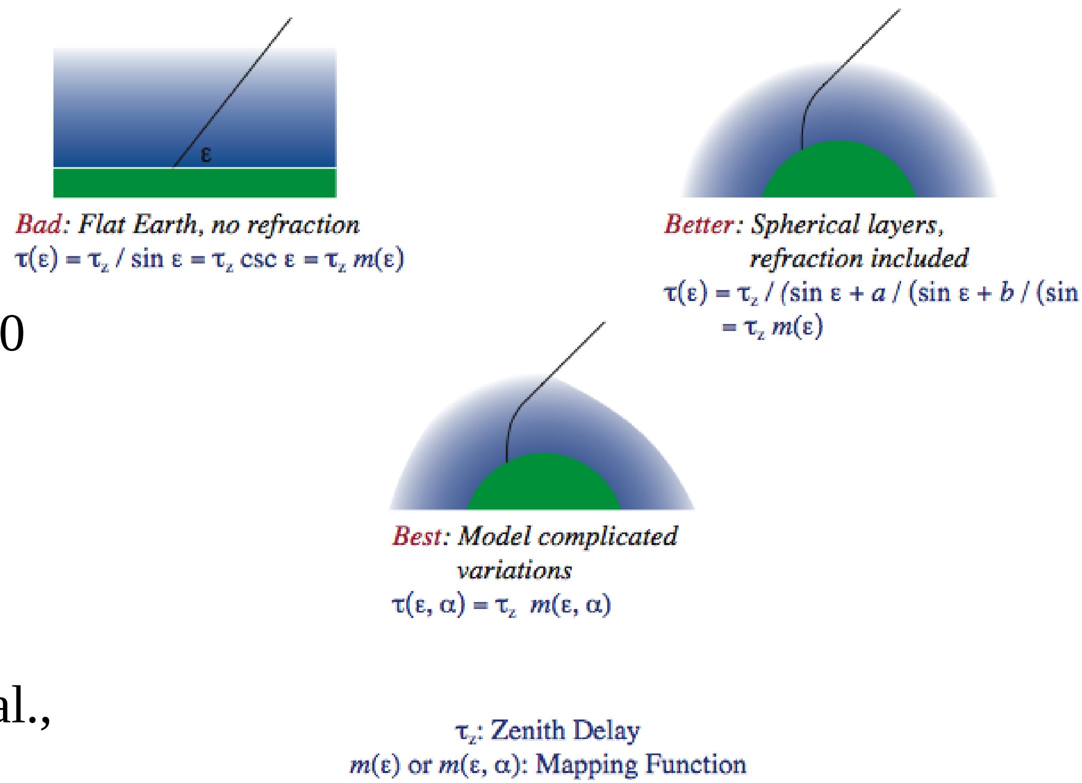
$$ZWD = 10^{-6} \frac{R}{M_w} (k'_2 + k_3 / T_m) PW$$

$$T_m = \frac{\int P_w / T dz}{\int P_w / T^2 dz}$$

- The factor for conversion is ~6.7 mm delay/mm PW
- This relationship was the basis of ground based GPS meteorology where GPS data are used to determine water vapor content of atmosphere.
- ZWD is usually between 0-40cm.

Mapping functions

- Zenith delays discussed so far; how to relate to measurements not at zenith
- Problem has been studied since 1970's.
- In simplest form, for a plain atmosphere, elevation angle dependence would behave as 1/sin(elev). (At the horizon, elev=0 and this form goes to infinity.
- For a spherically symmetric atmosphere, the 1/sin(elev) term is "tempered" by curvature effects.
- Most complete form is "continued fraction representation" (Davis et al., 1991).



Tropospheric Mapping Functions

The total tropospheric delay, ΔL , at any elevation angle, ε, is often modeled as a function of the elevation angle

$$\Delta L(\varepsilon) = ZHD * m_h(\varepsilon) + ZWD * m_w(\varepsilon)$$

where m_h and m_w are the hydrostatic and and wet ***mapping functions***.

A simple example of such a mapping function could look like

$$m(\varepsilon) = 1/\sin(\varepsilon)$$

For any elevation down to 15° we can often use the same mapping function for both the hydrostatic and the wet delay (better than 5 mm)

Continued fraction mapping function

- Basic form of mapping function was deduced by Marini (1972) and matches the behavior of the atmosphere at near-zenith and low elevation angles. Form is:

$$m(\varepsilon) = \cfrac{1}{\sin(\varepsilon) + \cfrac{a}{\sin(\varepsilon) + \cfrac{b}{\sin(\varepsilon) + \cfrac{c}{\sin(\varepsilon) + \cdots}}}}$$

Truncated version

- When the mapping function is truncated to the finite number of terms then the form is:

$$m(\varepsilon)=\frac{1+\dfrac{a}{1+\dfrac{b}{1+c}}}{\sin(\varepsilon)+\dfrac{a}{\sin(\varepsilon)+\dfrac{b}{\sin(\varepsilon)+c}}}$$

$$\text{when } \varepsilon=90; \quad m(e)=1$$

•Basic problem with forming a mapping function is determining the coefficient a,b, c etc for specific weather conditions. Different “solutions” available.

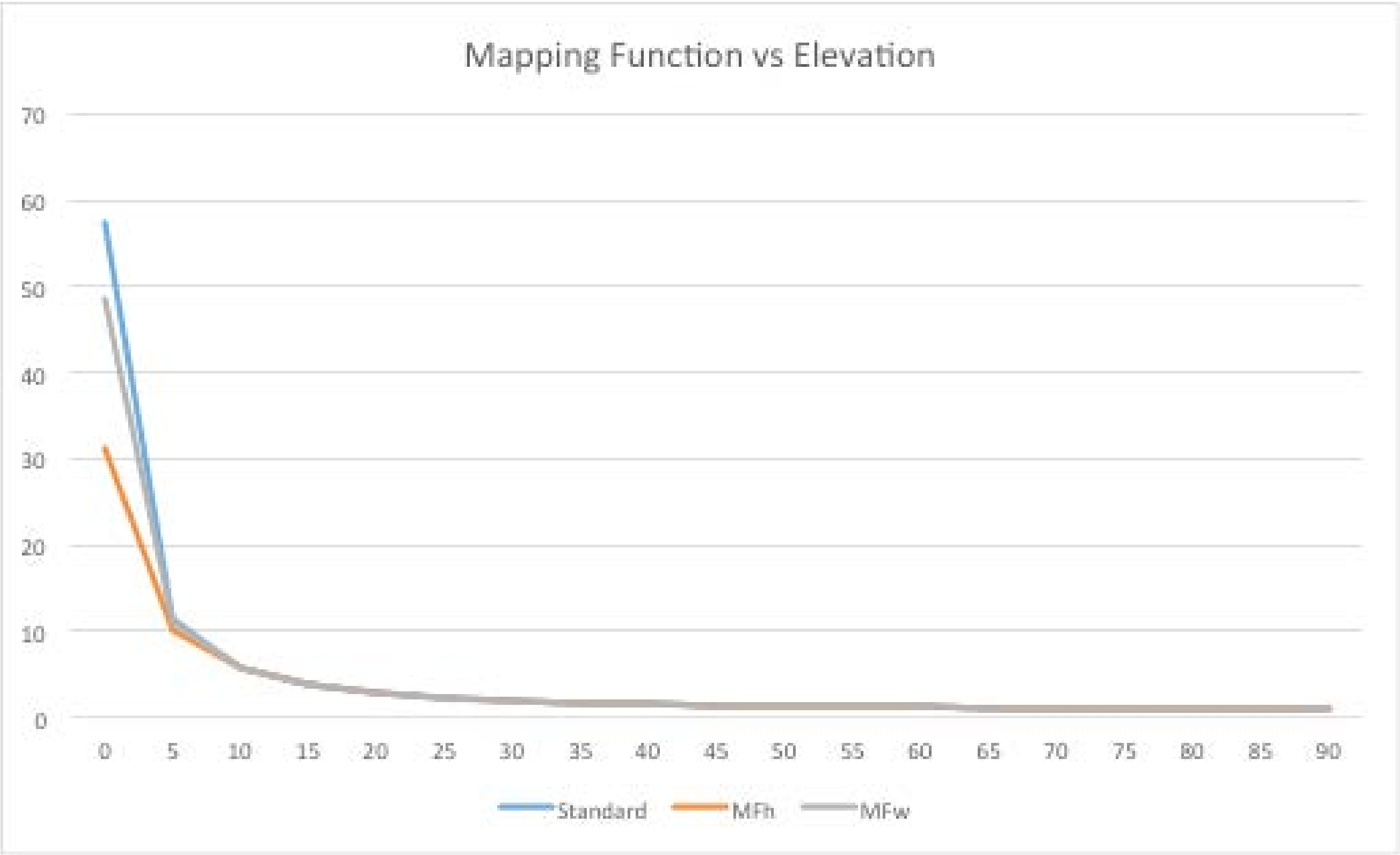
Coefficients in mapping function

The typical values for the coefficients are

- Hydrostatic:
  - a=1.232e-3, b=3.16e-3; c=71.2e-3
- Wet delay
  - a =0.583e-3; b=1.402e-3; c=45.85e-3

- Since coefficients are smaller for wet delay, this mapping function increases more rapidly at low elevation angles.
- At 0 degrees, hydrostatic mapping function is ~36. Total delay ~82 meter

Comparison of "Dry" and "Wet" MF



Mapping functions

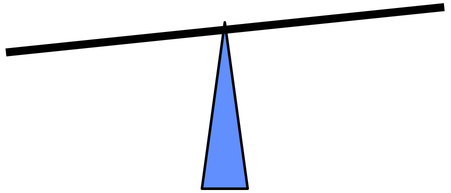
- The basic form of the continued fraction fit raytracing through radiosonde temperature, pressure and humidity profiles to a few millimeters at 3 degree elevation angle.
- Basic problem is parameterizing a,b,c in terms of observable meteorological parameters.
- a, b, and c depend on ground surface temperature, station latitude and height of the station

Mapping function

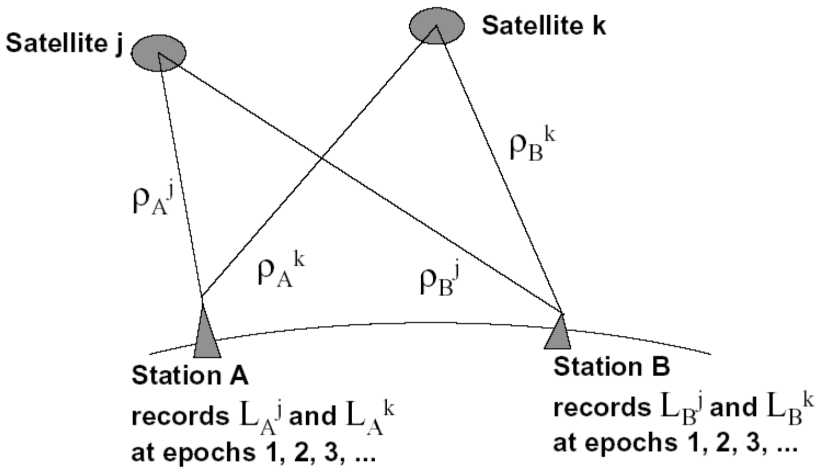
- Cfa, MTT, Ifadis
  - Ray-tracing of Radiosondes and surface met-data used
- NMF - Niell Mapping Function
  - Ray-tracing of Radiosonde profiles and Climatological model based on time-of-year, latitude and altitude
- VMF – Vienna Mapping Function
  - Ray-tracing of real NW-model (4 per day) from the ECMWF
- GMF, GPT2 – Global Mapping Function, Global Pressure an Temperature model
  - Ray-tracing of periodic averages from global models e.g. from ECMWF

Horizontal gradients

- In recent years; more emphasis put on deviation of atmospheric delays from azimuthal symmetry.
- These effects are much smaller (usually <30mm) but do effect modern GNSS measurements.
- There is a mean NS gradient that is latitude dependent and probably due to equator to pole temperature gradient.
- Parameterized as cos(azimuth) and sin(azimuth) terms with a "tilted" atmosphere model



Double Differencing



$$\Delta L^j_{AB} = \Delta\rho^j_{AB} + c\Delta\tau_{AB} + \Delta Z^j_{AB} - \Delta I^j_{AB} + \Delta B^j_{AB}$$
$$\Delta L^k_{AB} = \Delta\rho^k_{AB} + c\Delta\tau_{AB} + \Delta Z^k_{AB} - \Delta I^k_{AB} + \Delta B^k_{AB}$$

$$\begin{aligned}
\nabla\Delta L^{jk}_{AB} &\equiv \Delta L^j_{AB} - \Delta L^k_{AB} \\
&= \left(\Delta\rho^j_{AB} + c\Delta\tau_{AB} + \Delta Z^j_{AB} - \Delta I^j_{AB} + \Delta B^j_{AB}\right) - \left(\Delta\rho^k_{AB} + c\Delta\tau_{AB} + \Delta Z^k_{AB} - \Delta I^k_{AB} + \Delta B^k_{AB}\right) \\
&= \left(\Delta\rho^j_{AB} - \Delta\rho^k_{AB}\right) + \left(c\Delta\tau_{AB} - c\Delta\tau_{AB}\right) + \left(\Delta Z^j_{AB} - \Delta Z^k_{AB}\right) - \left(\Delta I^j_{AB} - \Delta I^k_{AB}\right) - \left(\Delta B^j_{AB} - \Delta B^k_{AB}\right) \\
&= \nabla\Delta\rho^{jk}_{AB} + \nabla\Delta Z^{jk}_{AB} - \nabla\Delta I^{jk}_{AB} + \nabla\Delta B^{jk}_{AB}
\end{aligned}$$

$$\nabla\Delta L^{jk}_{AB} = \nabla\Delta\rho^{jk}_{AB} + \nabla\Delta Z^{jk}_{AB} - \nabla\Delta I^{jk}_{AB} - \lambda_0 \nabla\Delta N^{jk}_{AB}$$

Effects of atmospheric delays

- Effects of the atmospheric delay can be approximately assessed using a simple model of the form:

$$y = \begin{bmatrix} 1 & \sin(\varepsilon) & m(e) \end{bmatrix} \begin{bmatrix} \Delta clk \\ \Delta H \\ \Delta ZTD \end{bmatrix}$$

- Simulated data y (e.g. error in mapping function) can be used to see effects on clock estimate (*Δclk*), Height (*ΔH*), and atmospheric delay (*ΔZTD*)
- If atmospheric zenith delay not estimated, then when data is used to 10 degree elevation angle, error in height is ~6 times zenith atmospheric delay error

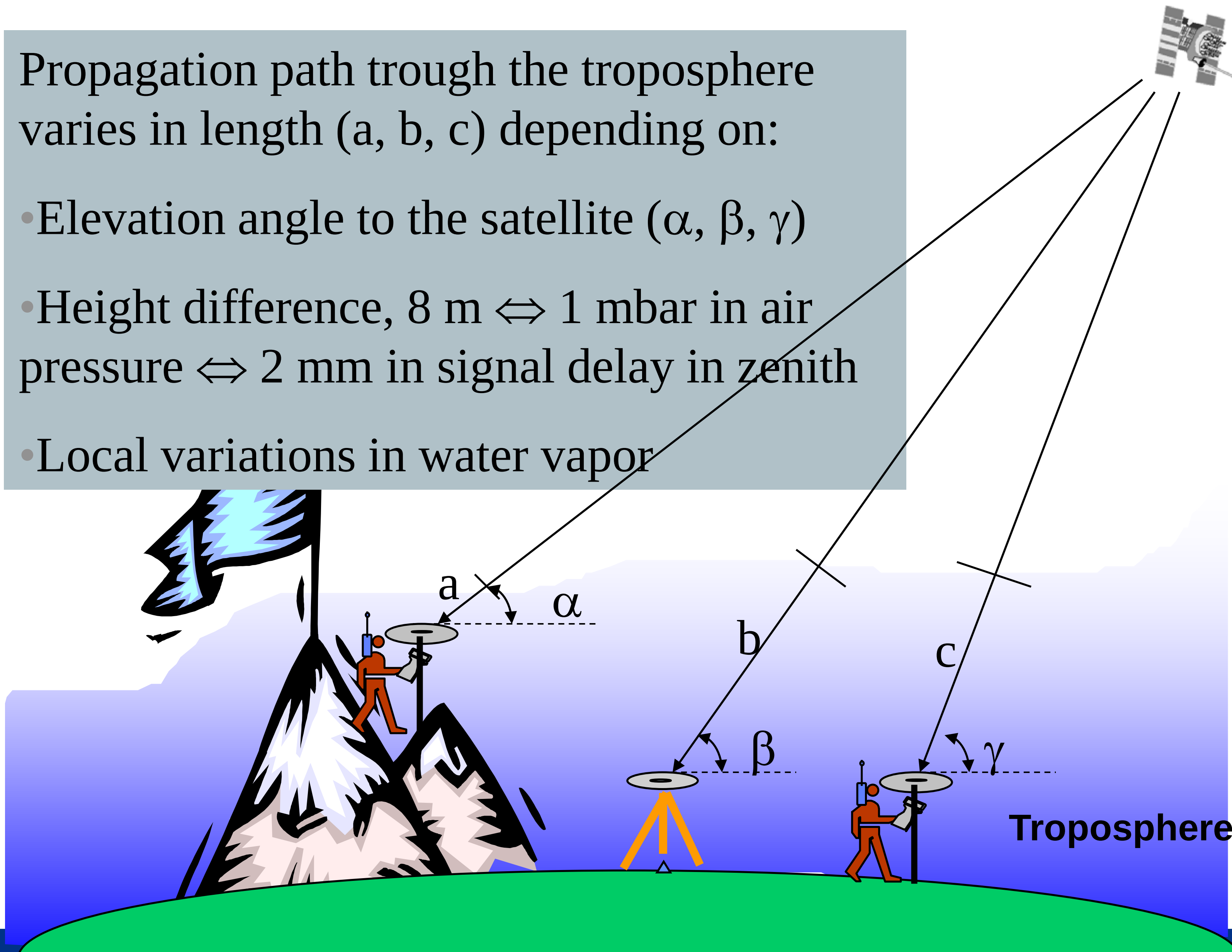
Parameterization of atmospheric delay

- Atmospheric delays are one the limiting error sources in GPS
- Parameterization is either Kalman filter or coefficients of piece-wise linear functions
- Delays are nearly always estimated:
  - At low elevation angles can be problems with mapping functions
  - Spatial inhomogenity of atmospheric delay still unsolved problem even with gradient estimates.
  - Estimated delays are being used for weather forecasting if latency <2 hrs.

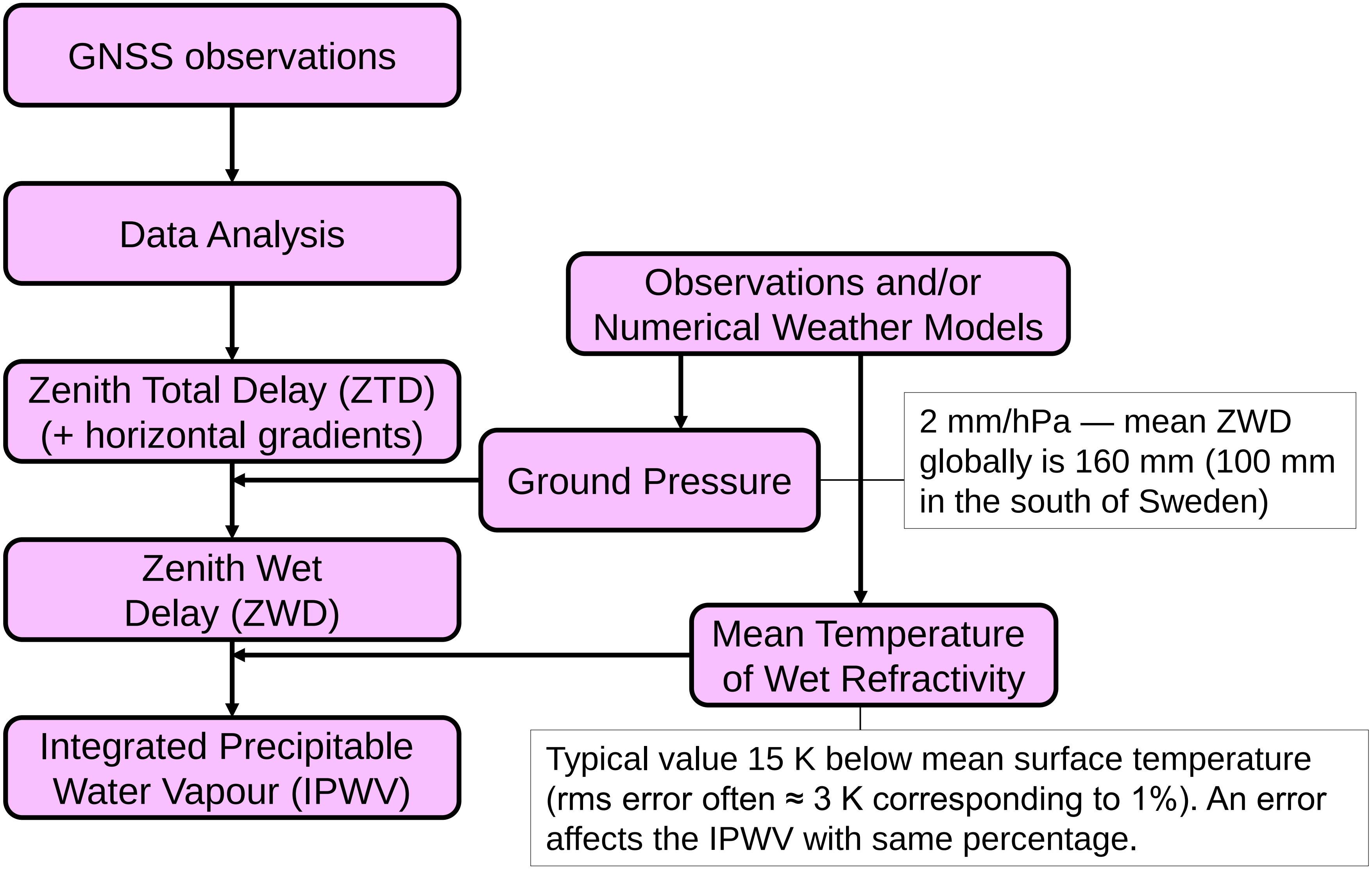
Influence of the Troposphere

Propagation path trough the troposphere varies in length (a, b, c) depending on:

- Elevation angle to the satellite (α, β, γ)
- Height difference, 8 m ⇔ 1 mbar in air pressure ⇔ 2 mm in signal delay in zenith
- Local variations in water vapor

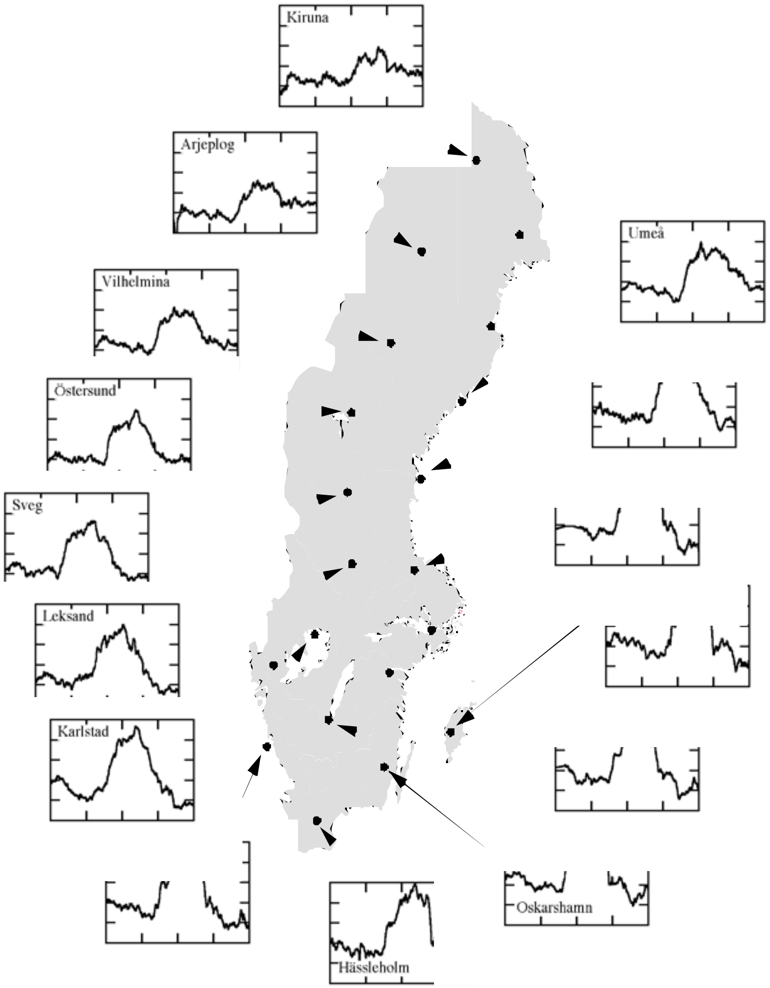


Water vapour time series from GNSS observations

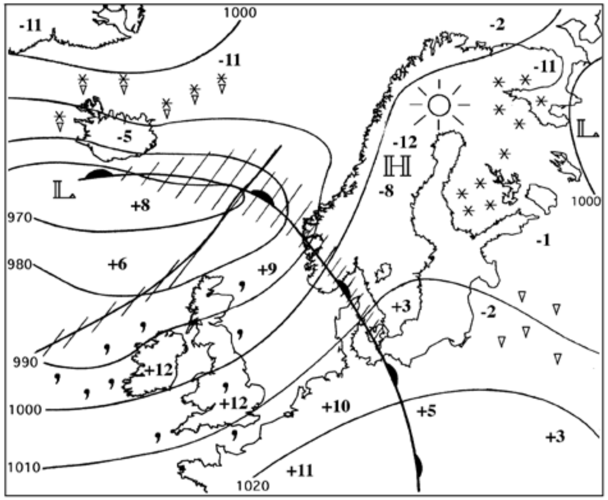


Observing Moving Air Masses with a GPS Network

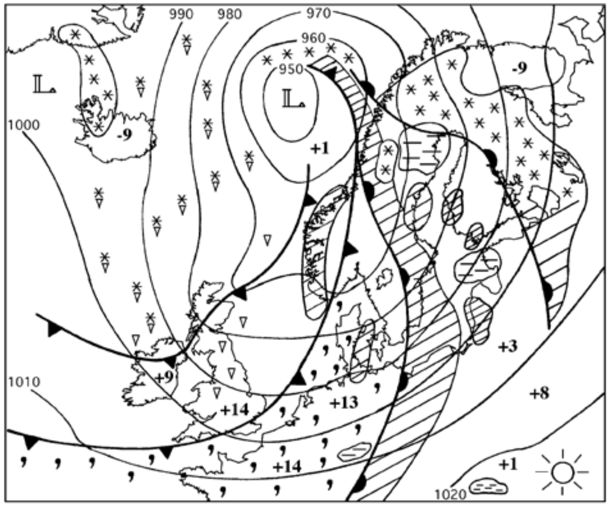
Elgered et al., Geophys. Res. Lett., vol.24, pp.2663-2666, 1997.



12 UT December 18



12 UT December 19



Y-axis: Integrated Water Vapor, 0 - 30 mm,
X-axis: 00 UT Dec 17 - 00 UT Dec 21, 1993

Observing Moving Air Masses with a GPS Network

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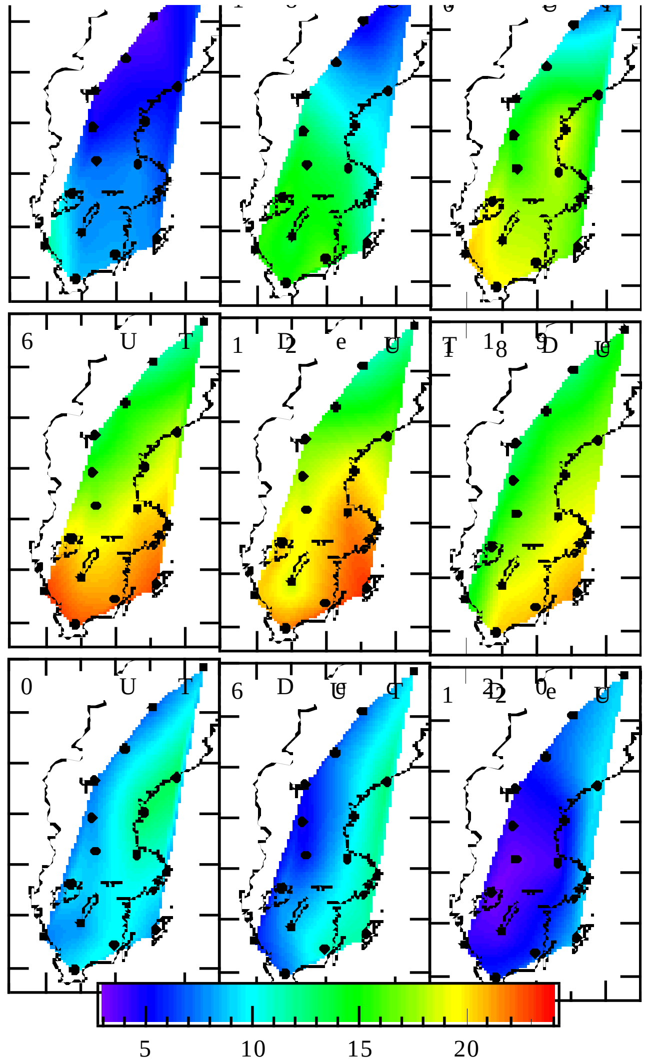
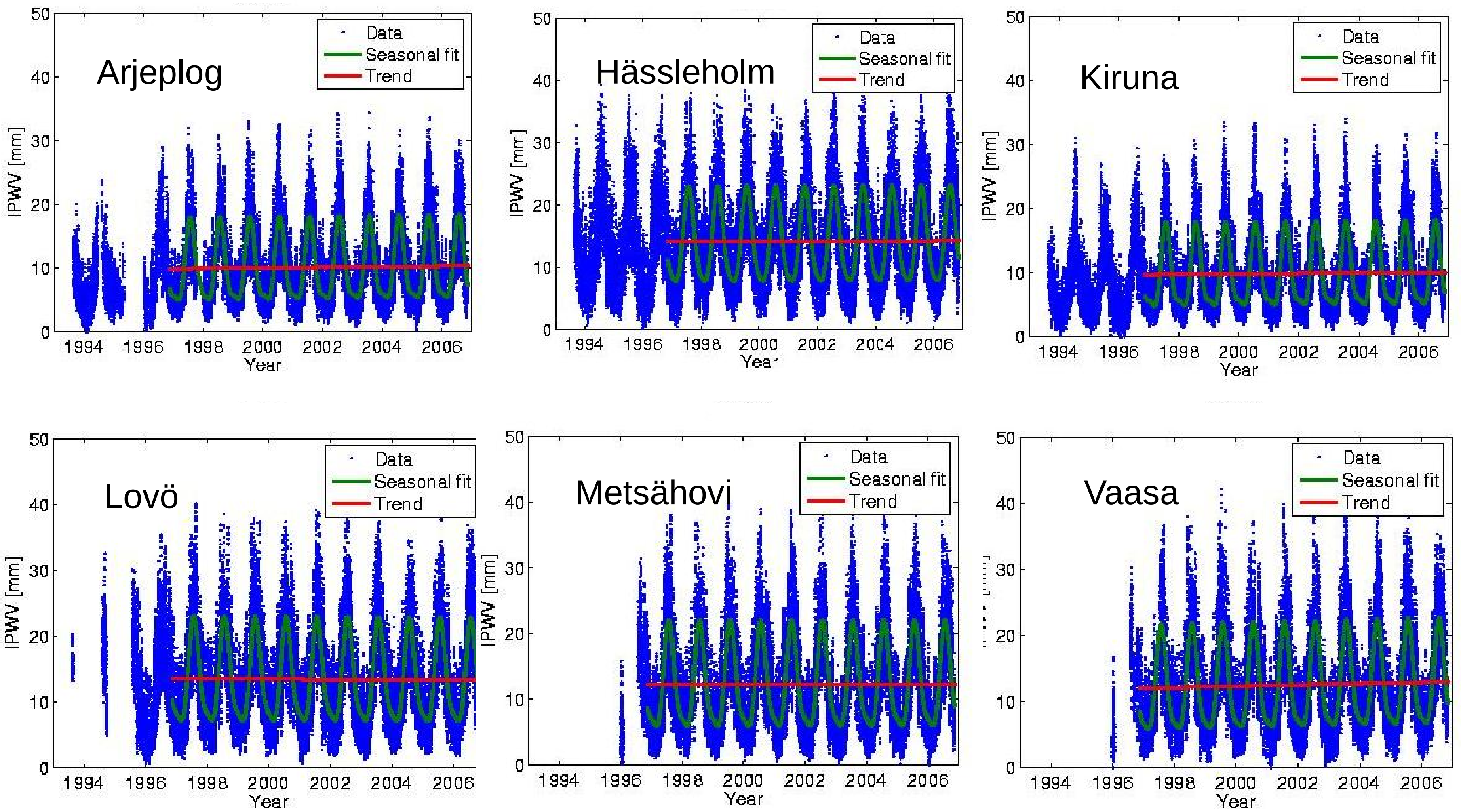
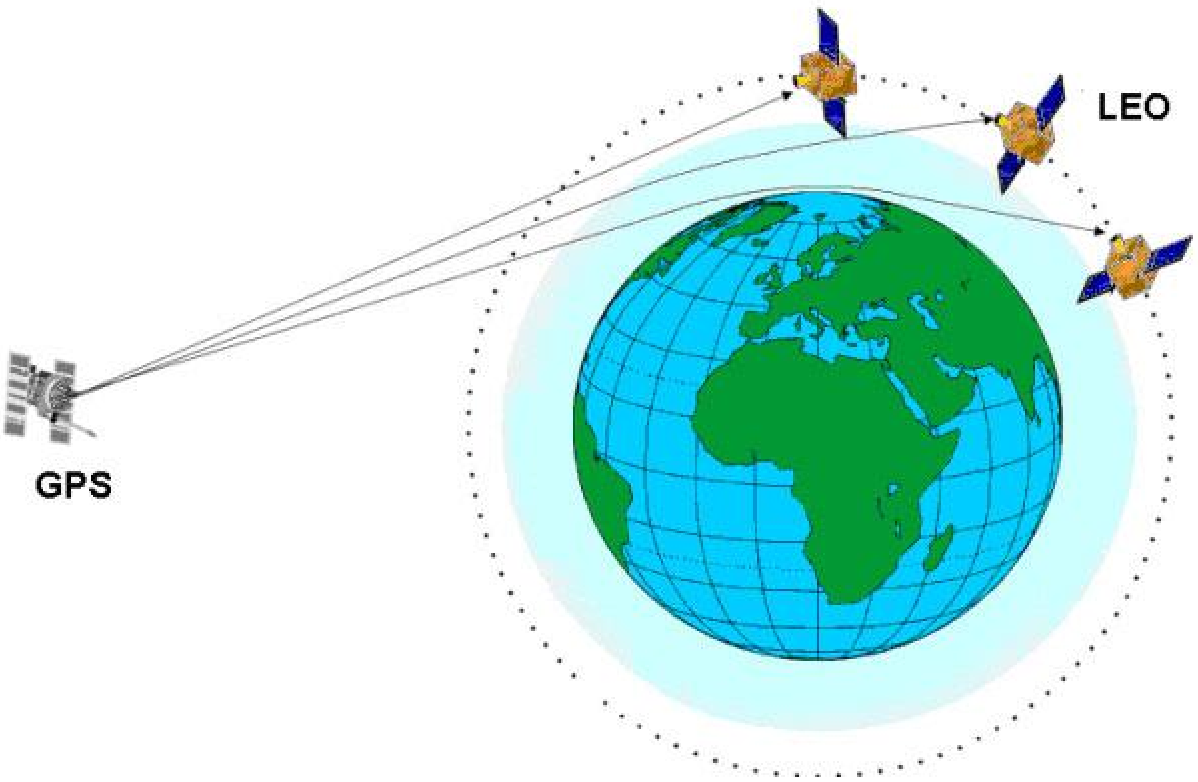


Integrated Water Vapor, mm

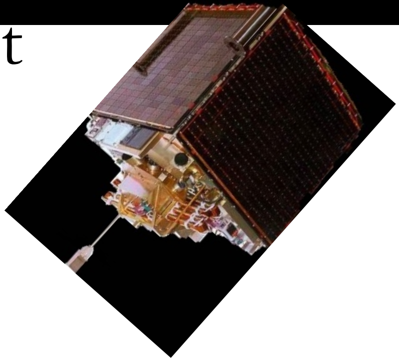
IPWV trends for some stations in Sweden and Finland



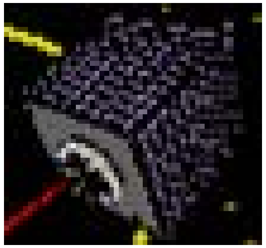
GPS/GNSS Occultation

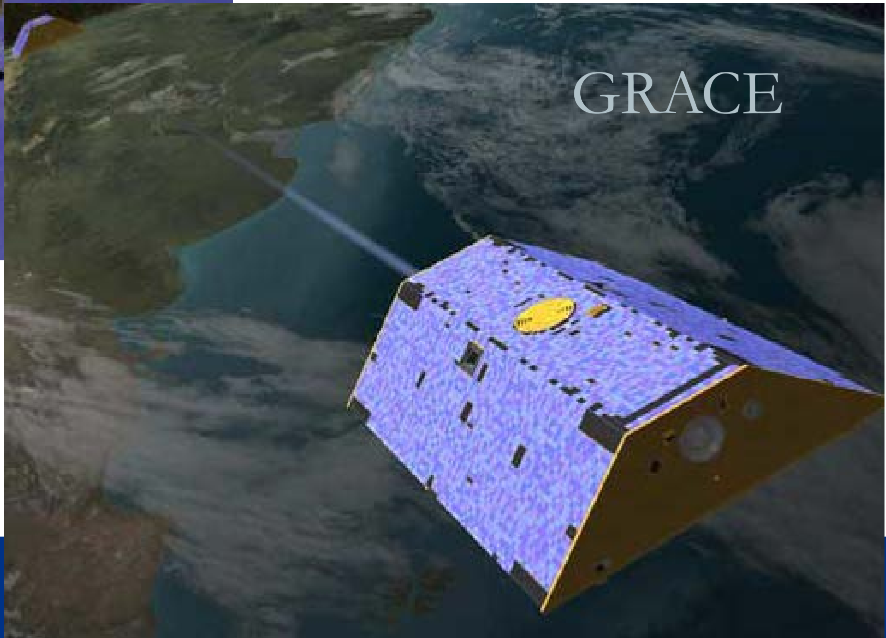


Sunsat



IOX



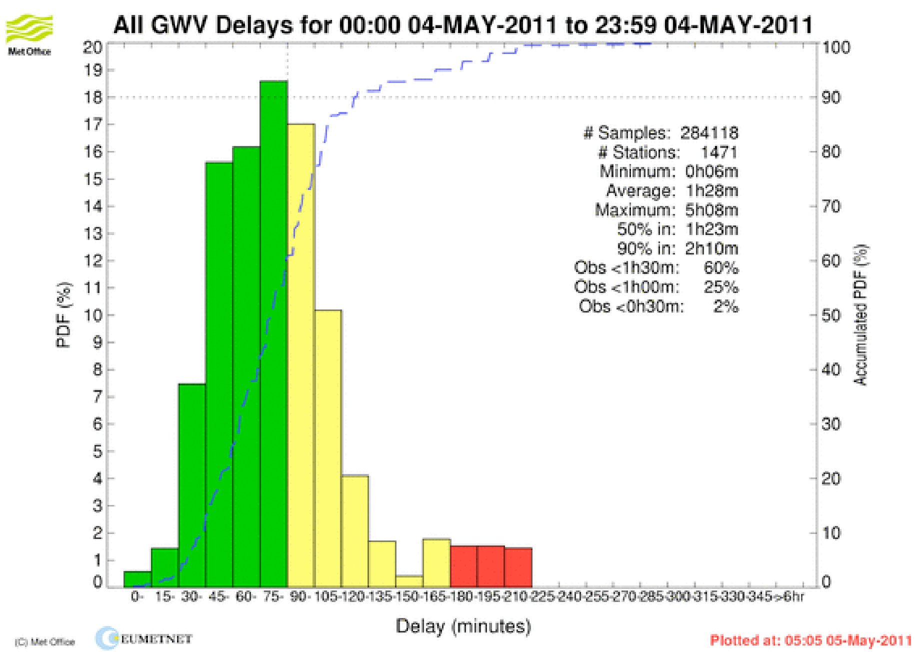


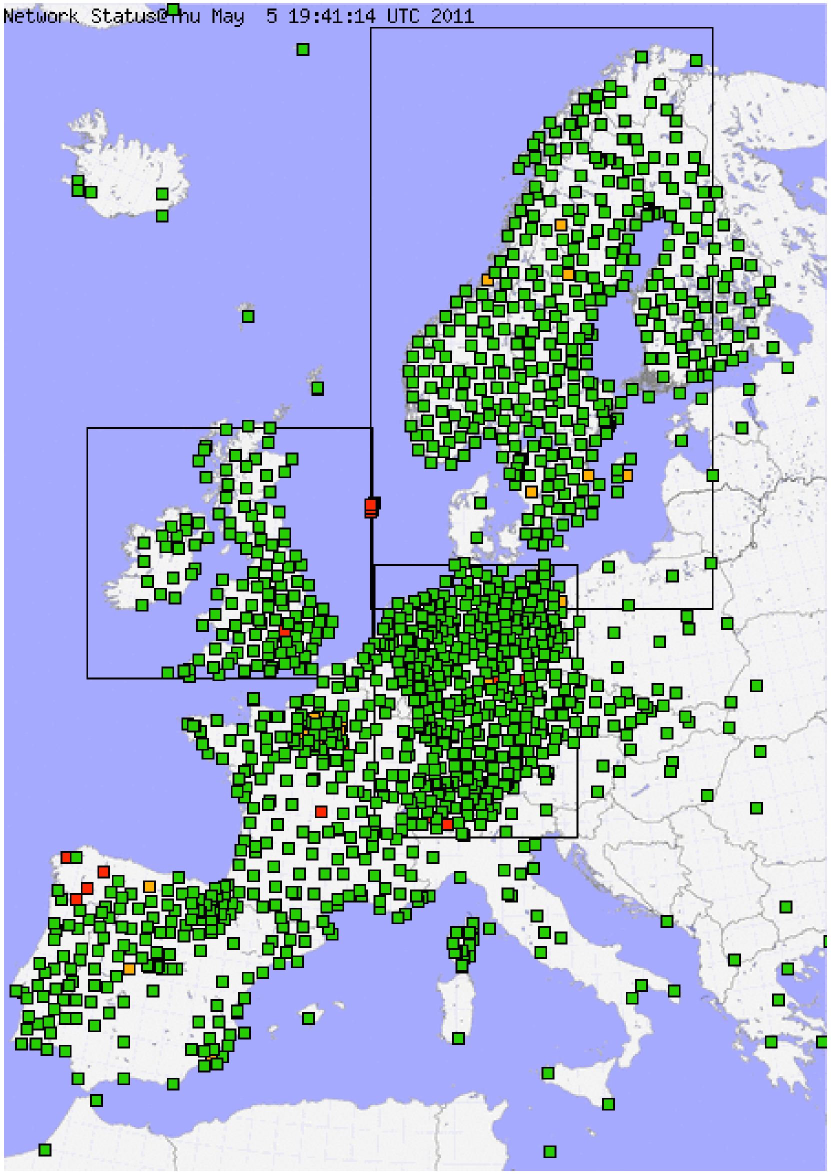
Weather Forecasts vs. Climate Models

- Both are based on similar models
- Forecasts starts at a given situation and calculates weather parameters for later time epochs
- The dynamics of the atmosphere implies that reliable forecasts cannot be made for time periods approaching ten days or longer
- Neither a weather forecast model nor a climate model can predict the weather at a specific time in the future
- However, the models can be applied to long time scales
- Climate models simulate and describe the statistics of the weather (parameters)

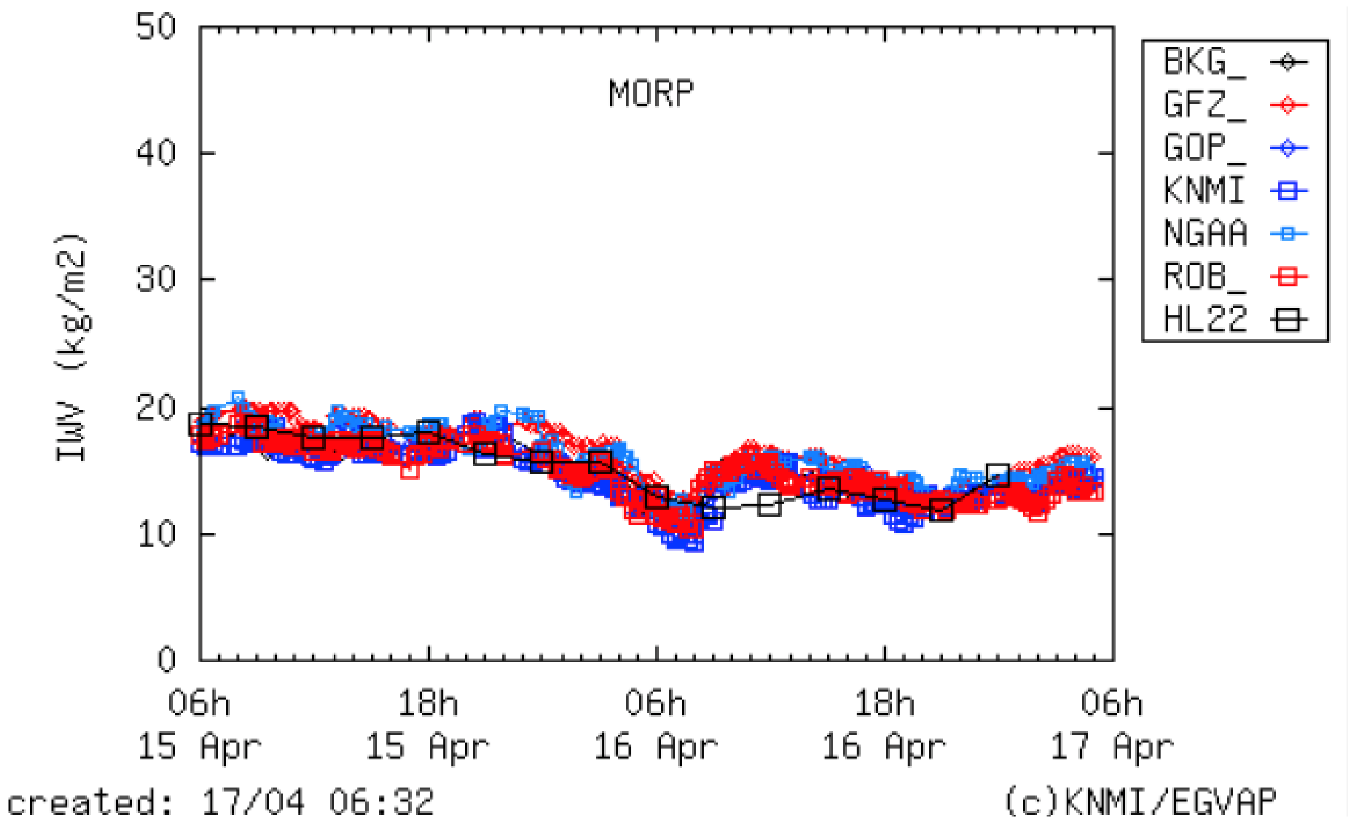
EUMETNET operates the E-GVAP project:

http://egvap.dmi.dk/

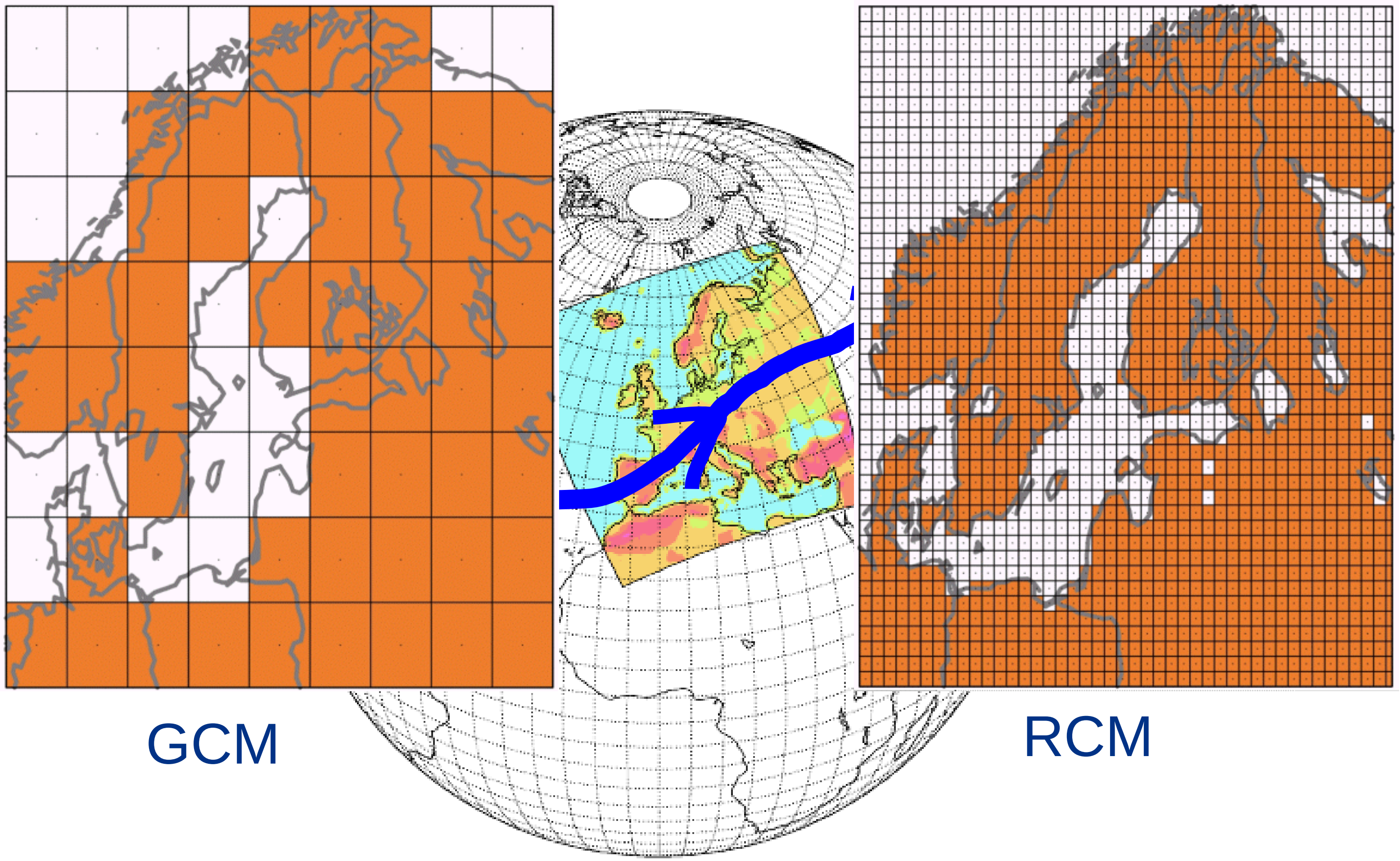




Several data processing centres analyze sites in different regions + some common reference sites



Regional Climate Modelling



Motivation

- Water vapour is a very efficient greenhouse gas
- Water vapour is one of the most important parameters in the climate feedback process
- Long-term trends in the atmospheric water vapour content can be used as an independent data source to detect climate changes
- Accurate observations with long-term stability is crucial for trend estimations
- A high spatial density of measurements is desired for a global monitoring

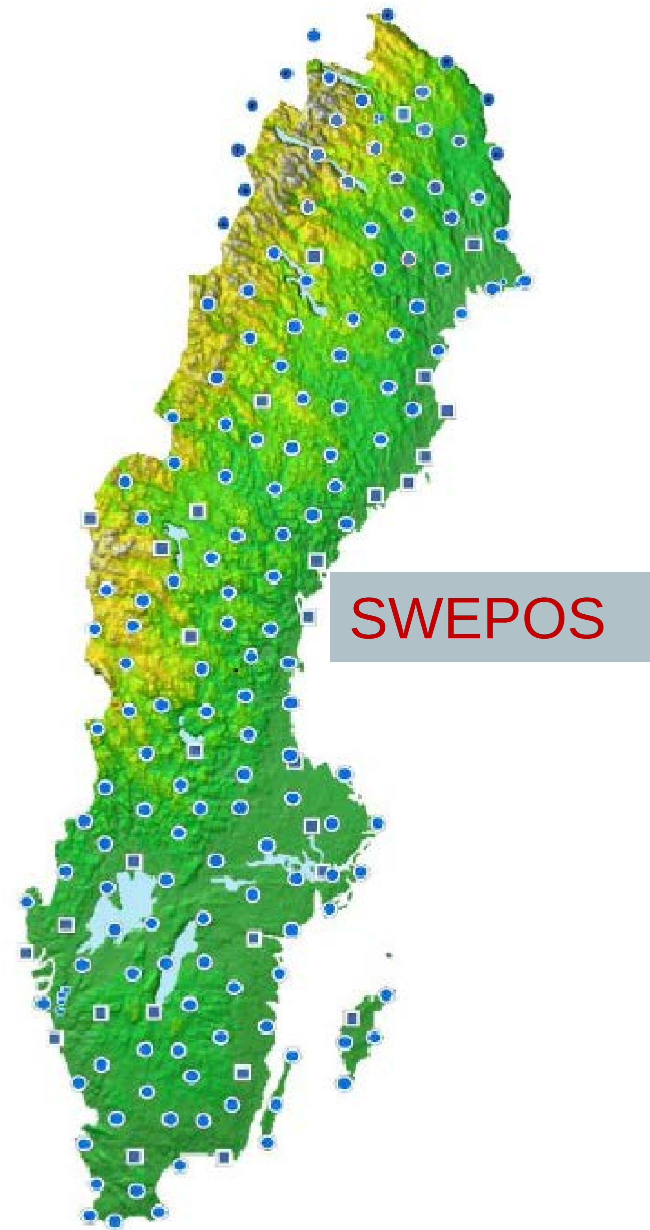
Tong Ning, PhD Thesis, Chalmers University of Technology, 2012

Why GPS?

- GPS can work in principle under all weather conditions
- High temporal resolution (a few minutes)
- Continuously improving spatial resolution

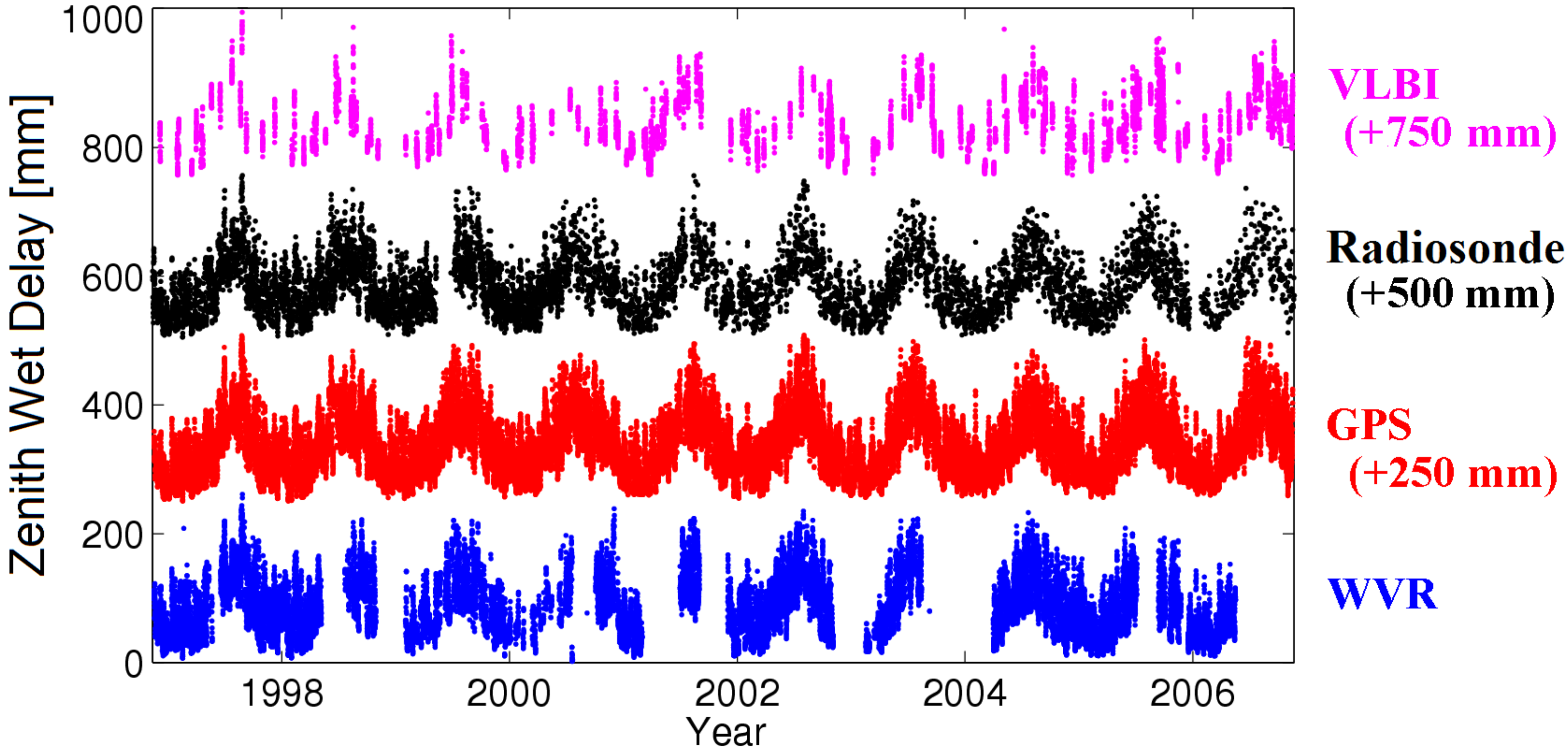
Global: The number of stations from the permanent International Global Navigation Satellite Systems (GNSS) Service (IGS) is now (June 2011) globally over 370.

Local network from Sweden: More than 200 stations, with a separation of ~35 km for most parts of Sweden.



The uncertainty of GPS-derived water vapour is evaluated by other independent data sources

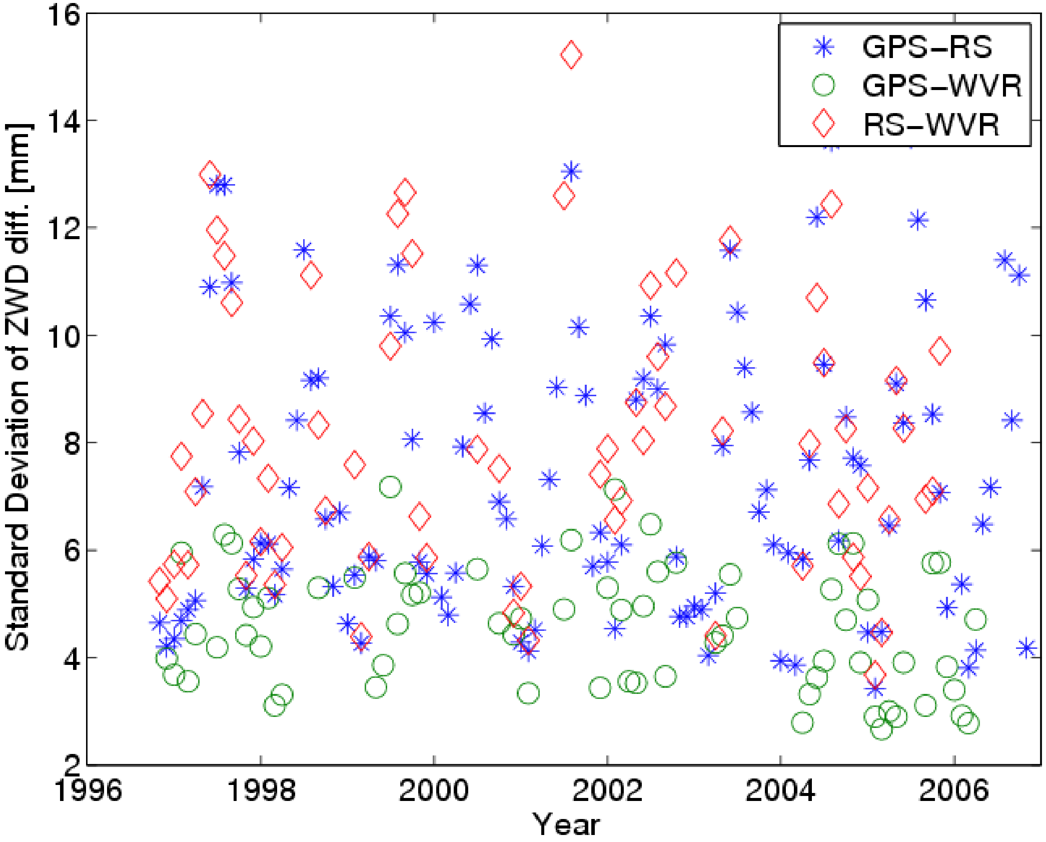
Comparing different techniques



RMS differences:
- VLBI – GPS: 6.2 mm
- VLBI – WVR: 7.4 mm
- VLBI – Radiosonde: 10.2 mm

Corresponding IWV differences:
- VLBI – GPS: 0.95 kg/m²
- VLBI – WVR: 1.14 kg/m²
- VLBI – Radiosonde: 1.57 kg/m²

Comparing GPS, WVR and Radiosondes



- The standard deviation of the ZWD difference including the radiosonde (RS) data varies with the season, which is not clear for GPS-WVR
- The result indicates that the uncertainties in ZWD estimates from GPS and WVR have only a small dependence on weather

The figure depicts the monthly standard deviations of the ZWD differences from the comparisons between the GPS data to the radiosonde and the WVR data

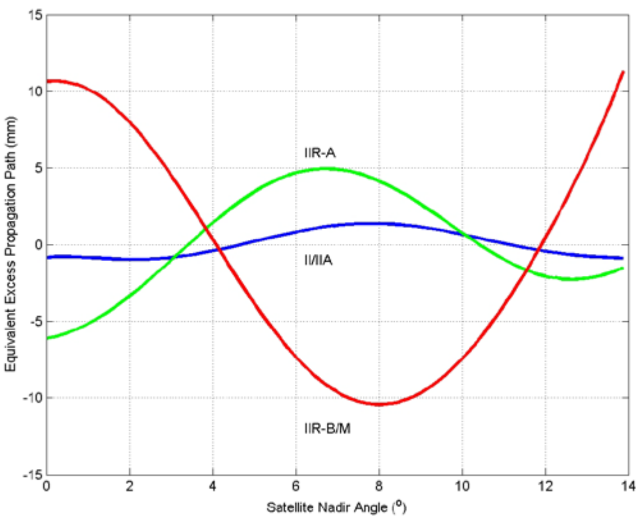
GNSS Error Sources

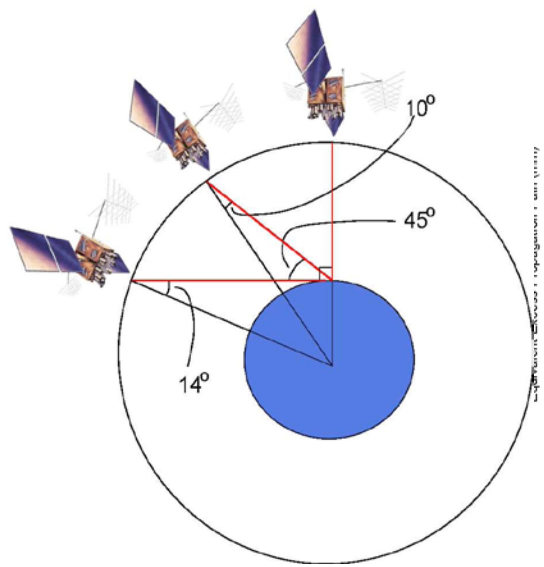
- Ionospheric effects (< 0.04 kg/m^2)
- Effects due to phase centre variations (PCVs) of the transmitting antennas as well as ground antennas

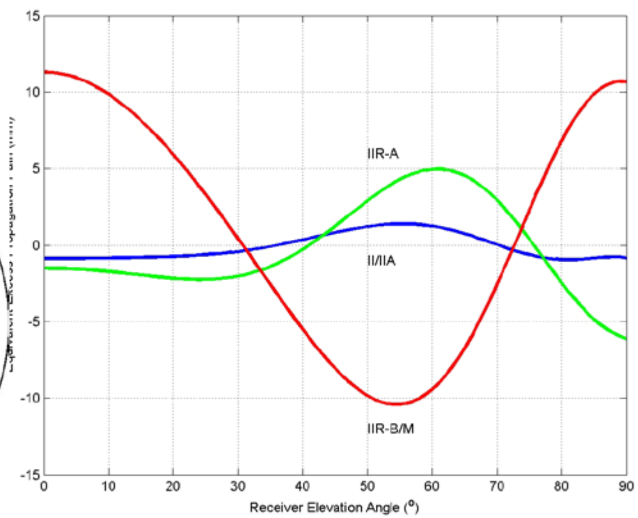
Effects due to antenna phase centre variations (PCVs)

PCVs as a function of the satellite nadir angle

PCVs as a function of the receiver elevation angle



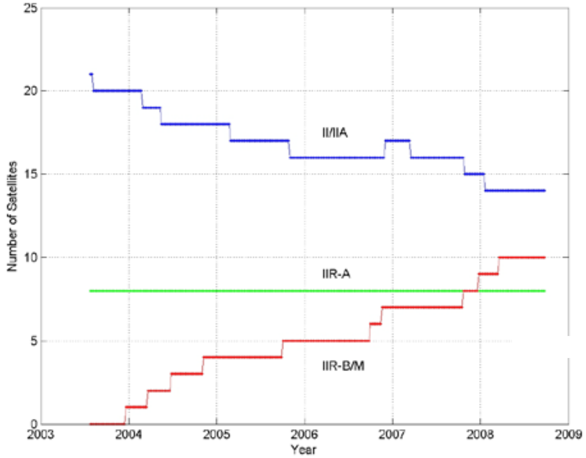




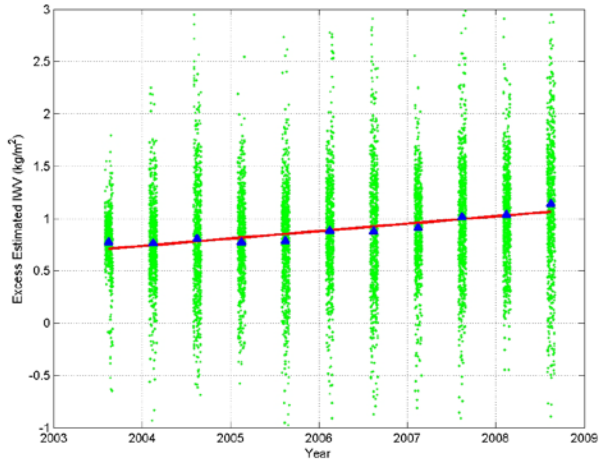
Jarlemark et al., Ground-Based GPS for Validation of Climate Models: the Impact of Satellite Antenna Phase Center Variations, IEEE Trans. Geosci. Rem. Sens., in press, 2010.

Effects due to antenna phase centre variations (cont.)

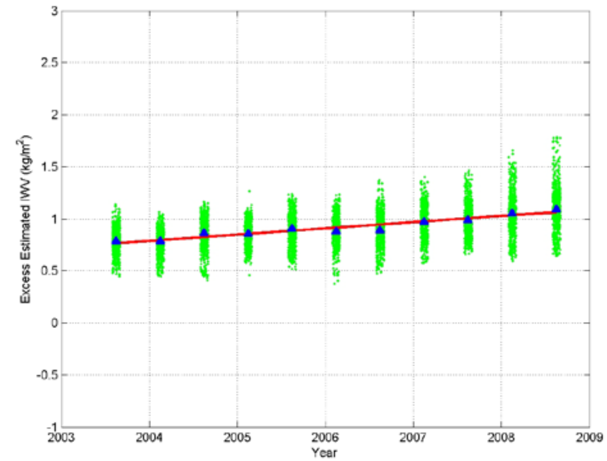
During the period mid 2003 to mid 2008 the satellite type IIR-B/M is replacing type II/IIA



Real data:
elev. cutoff 10°
Trend: 0.07 kg/m^2/year



Simulated data:
elev. cutoff 10°
Trend: 0.06 kg/m^2/year

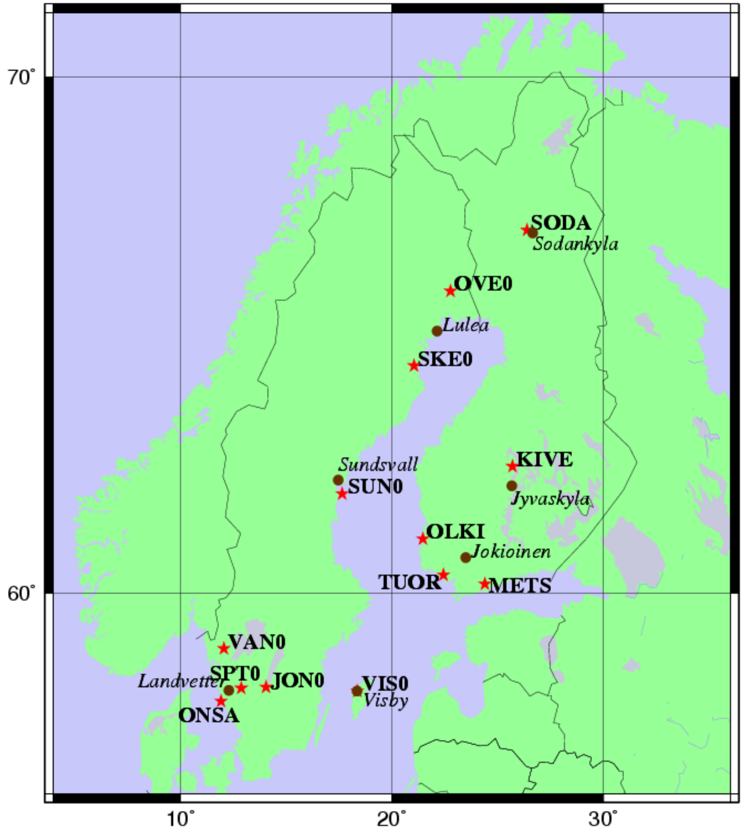


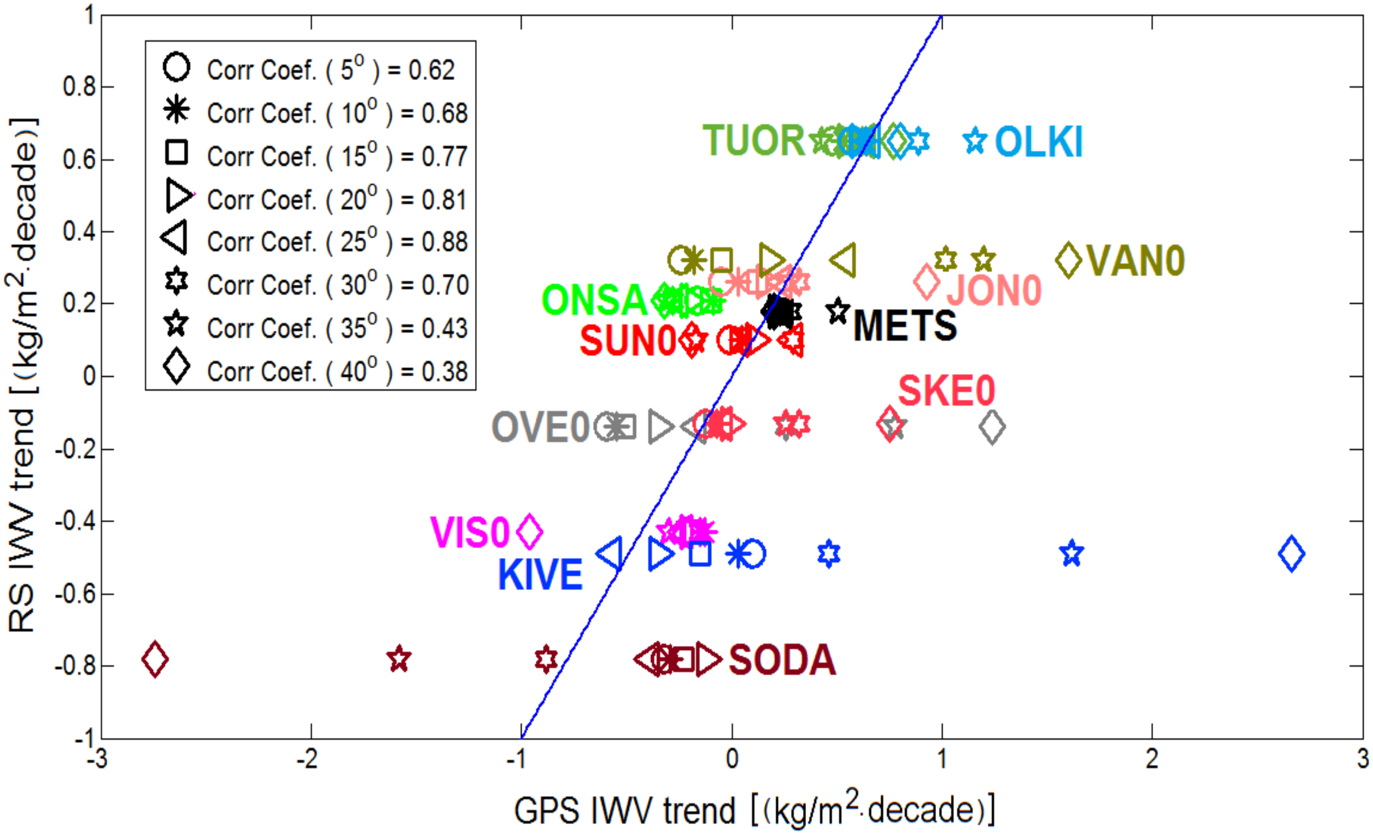
Using sites at different latitudes and different elevation cut-off angles, simulations show that ignoring APC variations in the satellite can lead to an additional IWV trend of up to 0.15 kg/m^2/year for regular GPS processing for the time period 2003–2008

Long-term trend estimation

Trends in the atmospheric water vapor content from ground-based GPS: the impact of the elevation cutoff angle

- Using 8 different elevation cutoff angles (from 5^o to 40^o) for the GPS data processing
- GPS-derived IWV trend from 13 sites for each cutoff angle solution were compared to the ones obtained from 7 nearby radiosonde sites (see map)
- Correlation between the GPS and the radiosonde IWV trends were performed for each cutoff solution





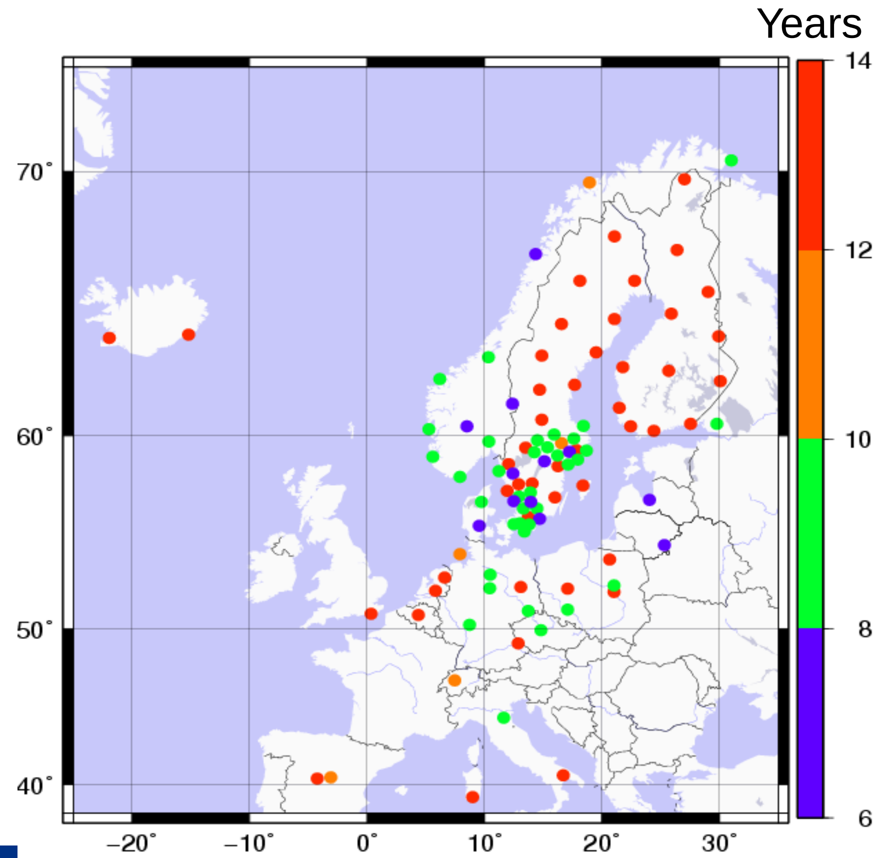
The best fit in trends is seen for the 25° cutoff angle solution

(corr. coef. = 0.88)

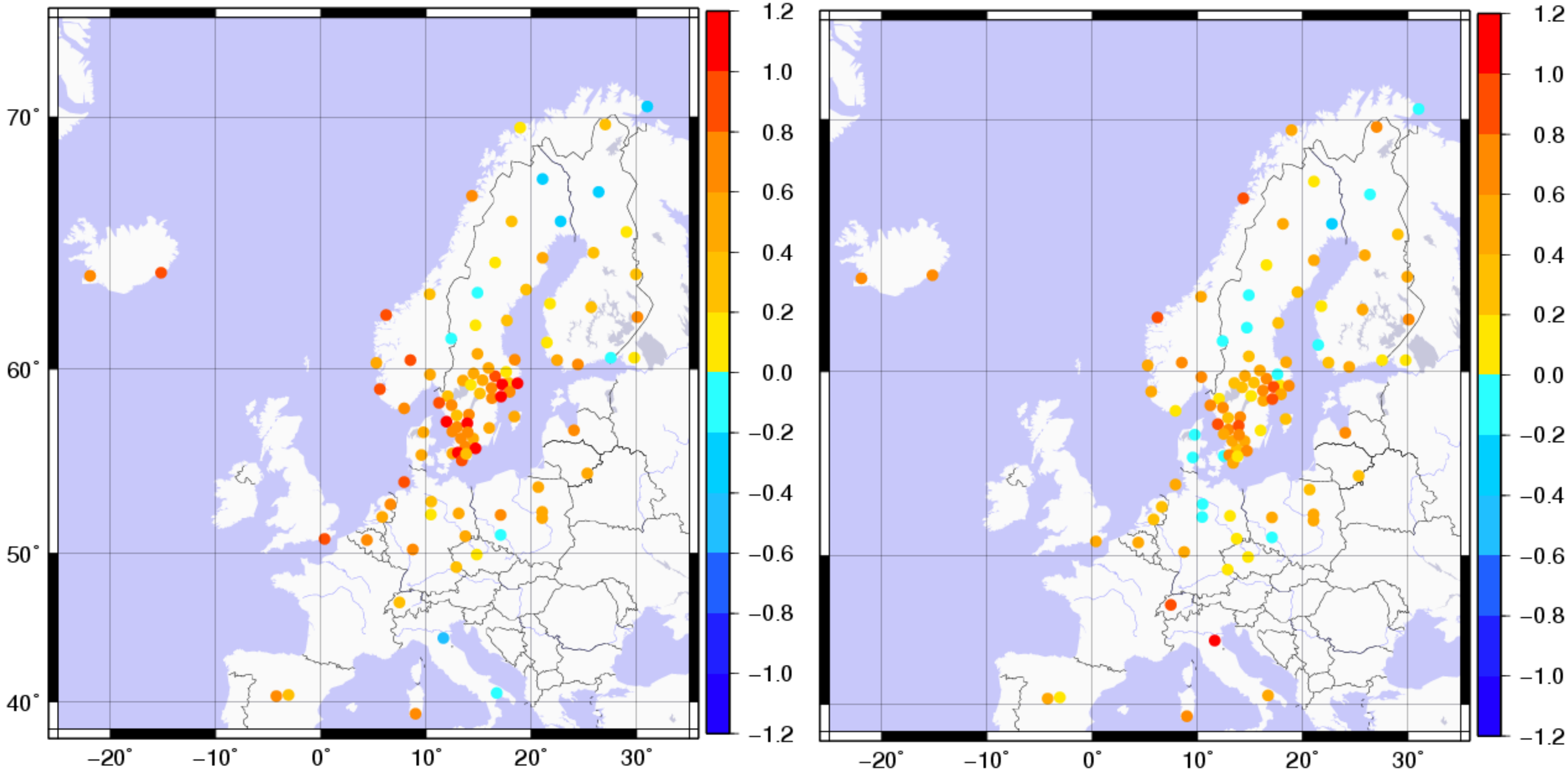
Evaluation of climate models

Evaluation of the atmospheric water vapor content in a regional climate model using ground-based GPS measurements

- Process the GPS data from 99 European sites with a maximum time period of 14 years (January 1997 to December 2010).
- Evaluate the IWV simulated by the Regional Rossby Centre Atmospheric (RCA) model, which is developed by Swedish Meteorological Hydrological Institute (SMHI)

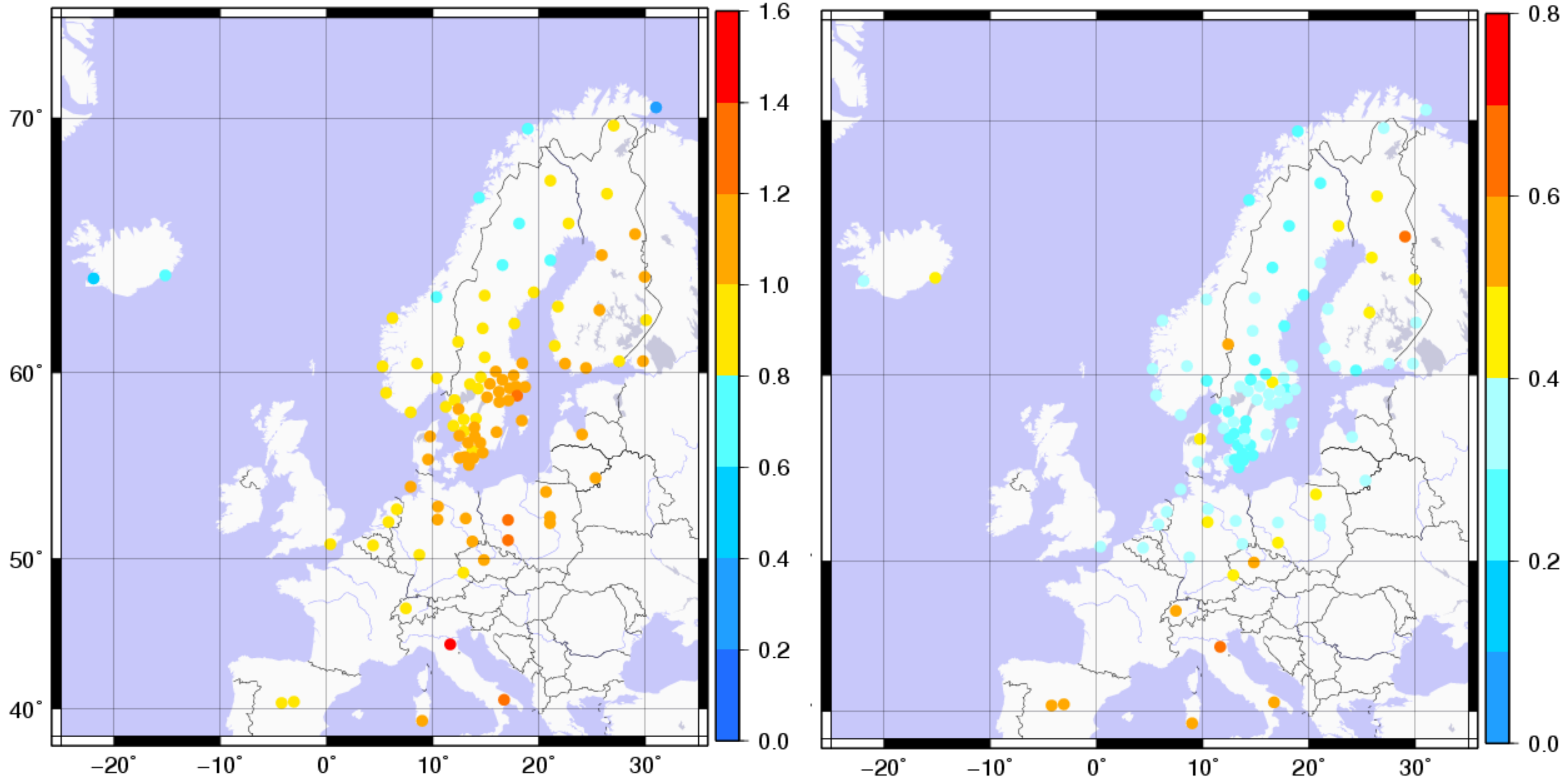


Comparing GPS and Climate Models



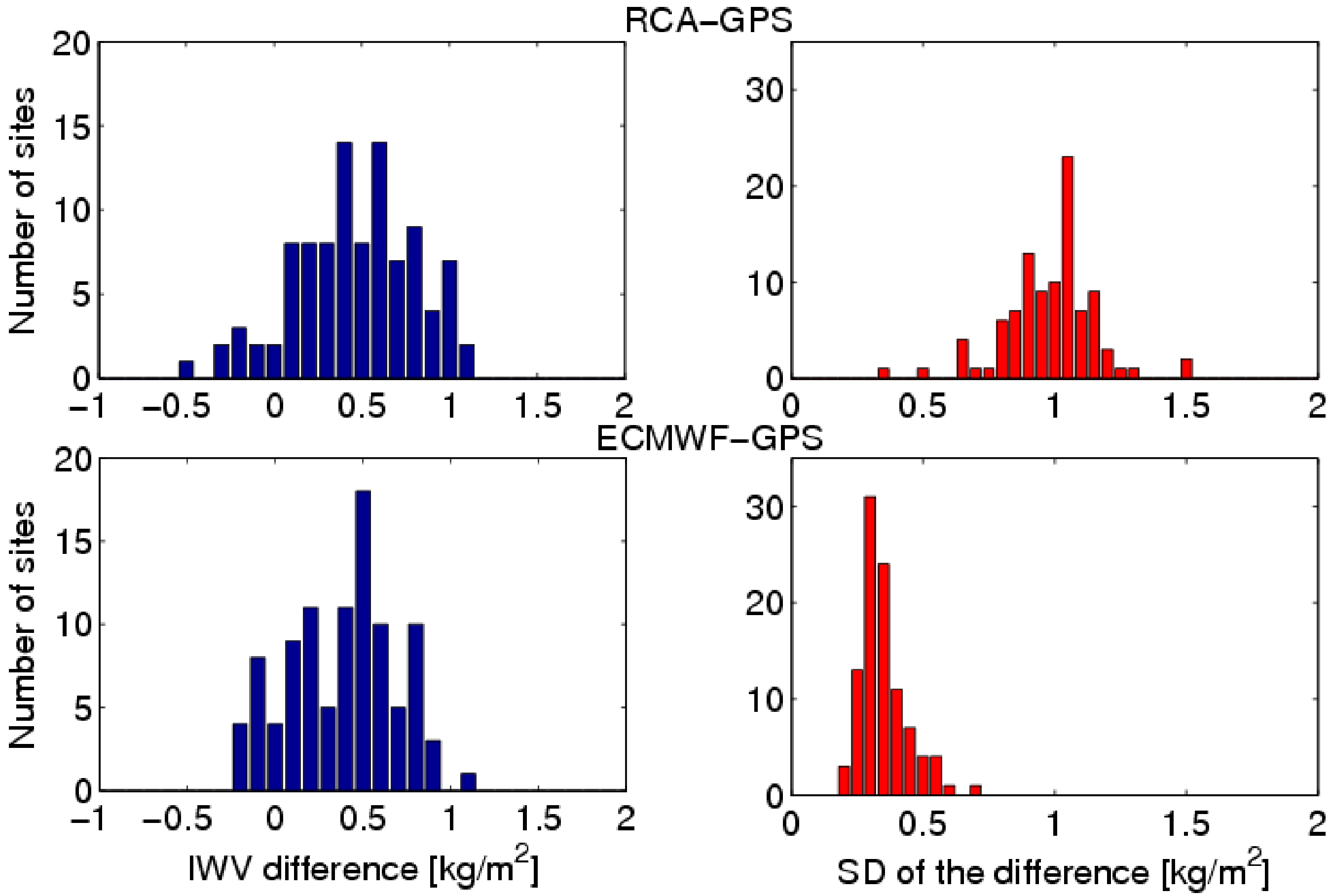
The mean IWV difference (kg/m²) for RCA-GPS (left) and ECMWF-GPS (right)

Comparing GPS and Climate Models



The standard deviation of the IWV difference (kg/m²) for RCA-GPS (left) and ECMWF-GPS (right)

Comparing GPS and Climate Models



Histograms of the mean IWV difference and the standard deviation between models and GPS for all sites

Conclusions

- GPS is capable of monitoring atmospheric water vapour with high accuracy over long time scales, which is confirmed by a high correlation (0.88) between trends from GPS and radiosondes. However, systematic errors (e.g. signal multipath) cannot be ignored
- As GPS time series are getting longer, the accuracy of the trends of GPS-estimated IWV are also improved and more valuable contributions from GPS data to climate research are expected

More reading

- Thomas Hobiger and Norbert Jakowski (2017). Atmospheric Signal Propagation, in Springer Handbook of Global Navigation Satellite Systems, eds. P.J.G. Teunissen and O. Montenbruck, ISBN 978-3-319-42926-7.