Weather and Climate: Signal and Noise for Geodesy

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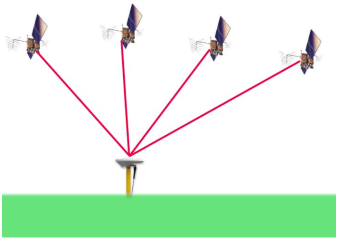
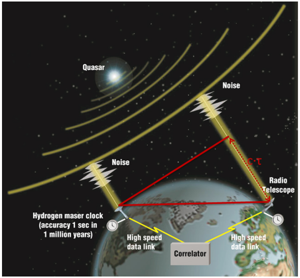
Space geodetic observations

Global Navigation Satellite Systems (GNSS)

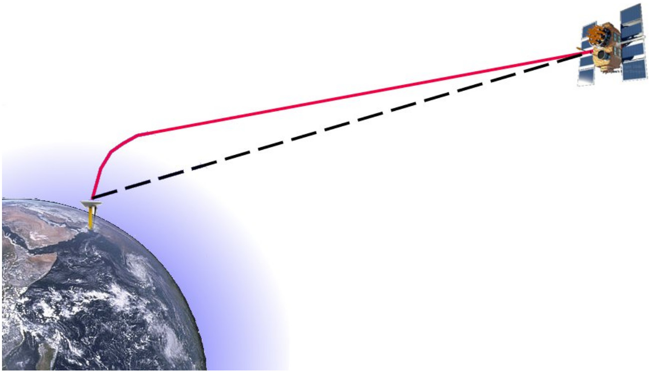


Very Long Baseline Interferometry (VLBI)



- Space geodetic techniques measure (differences of) travel times from radio sources like satellites or quasars
- These time measurements can be converted to distance measurements using the speed of light (299792458 m/s)
- Using these distances, the positions of the receiving antennas can be calculated
- Sub-cm position accuracy can be achieved , **Goal:** 1 mm accuracy

Atmospheric delays



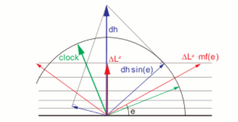
The signals in space geodetic techniques are delayed in the atmosphere due to:

- Propagation speed lower than speed of light in vacuum
- Bending

Total delay is several metres (depending on elevation angle)

Effect on estimated station positions

- If not corrected for, the atmospheric delay will cause an error in the estimated station position
- Error will be mostly in the vertical component, since both the effect of station height and the atmospheric delay are dependent on the elevation angle e:
  - Height $\propto \sin(e)$
  - Clock $\propto 1$
  - Atm. delay $\propto mf(e) \approx 1/\sin(e)$



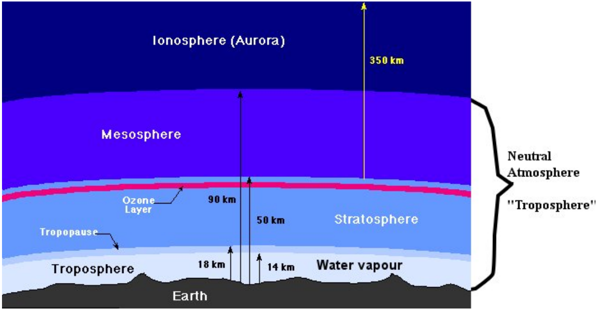
- The magnitude of the error depend on the observation geometry, the atmospheric delay as function of direction, . . .
- Rules of thumb for the vertical coordinate error:
  - Three times the error in the zenith atmospheric delay error
  - One fifth of the atmospheric delay error at the lowest elevation angle [MacMillan and Ma, 1994]

Handling atmospheric delays in space geodetic data analysis

There are two ways of handling the atmosphere in space geodetic data analysis:

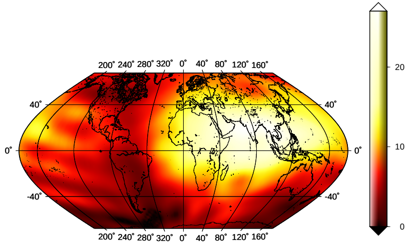
1. Use corrections from external sources:
   - Models
   - Ray-tracing though numerical weather models
   - Other instruments, e.g. water vapour radiometers
   - Requires high accuracy of corrections (mm level), difficult to achieve...
2. Estimate the atmospheric delay in the data analysis
3. A combination of both (1 + 2)

Atmospheric layers



- Atmosphere consists of several layers
- In space geodesy the atmosphere is normally divided into:
  - Neutral atmosphere
  - Ionosphere

Ionospheric delays



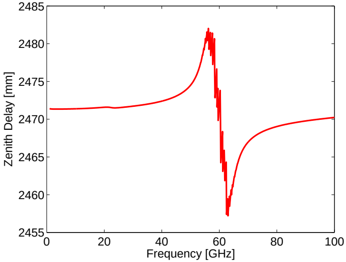
Example of ionospheric TEC (in TECU, 10^{16} e^-/m^2). From a combination of GPS, altimetry, and COSMIC data, 21/7 2007 9:00 UTC. From M. Alizadeh.

- Ionosphere: Ions and free electrons
- Ionospheric delay is frequency dependent ($L_i \tilde{\propto} \frac{1}{f^2}$), and proportional to the Total Electron Content (TEC)
- Can be removed using a combination of two frequencies (eq. (1))
- Models for removing also higher order effects ($\frac{1}{f^3}, \ldots$) exists

$$L_{if} = \frac{1}{f_1^2 - f_2^2} \left[f_1^2 \, L(f_1) - f_2^2 \, L(f_2) \right] \qquad (1)$$

Tropospheric delays

- In the neutral atmosphere the delay is practically frequency independent
- Must be corrected using external information, or estimated in the data analysis



The tropospheric delay L_t can be calculated by:

$$L_t = 10^{-6} \int_S N(s)\, ds \qquad (2)$$

Where the refractivity N is:

$$N = k_1 \frac{p}{T} + k_2' \frac{p_w}{T} + k_3 \frac{p_w}{T^2} \qquad (3)$$

p: total pressure, T: temperature, p_w: partial pressure due to water vapour.

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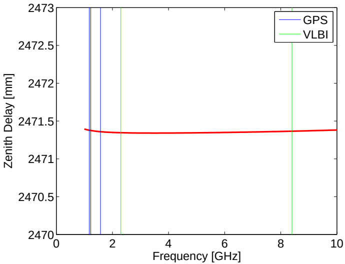

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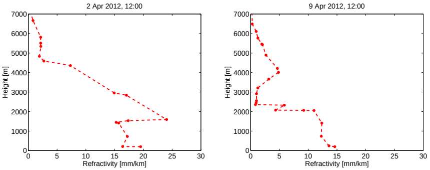
Hydrostatic and wet delays

The tropospheric delay can be divided into a hydrostatic part (L_h) and a wet part (L_w) :

$$L_t = \underbrace{\int_S k_1 \frac{p}{T}\, ds}_{L_h} + \underbrace{\int_S \left[k_2' \frac{p_w}{T} + k_3 \frac{p_w}{T^2}\right] ds}_{L_w} \qquad (4)$$

The hydrostatic delay is proportional to the surface pressure (hydrostatic equilibrium)

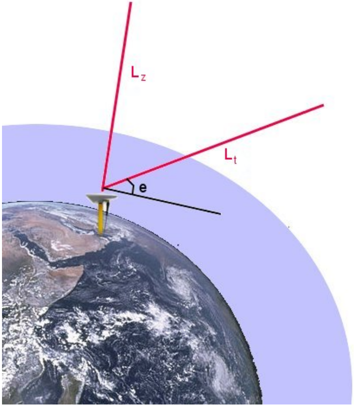
Wet delay cannot be predicted from surface meteorological data. Needs to be estimated in the data analysis.



Examples of vertical profiles of the wet refractivity. From Wien/Hohe Warte radiosonde data.

Modelling tropospheric delays in space geodetic data analysis

$$L_t = mf_h(e)\, L_h^z + mf_w(e)\, L_w^z + \text{Gradients} \qquad (5)$$

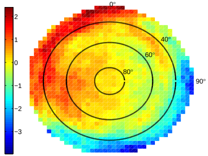


mf: Mapping function
$\mathbf{L_h^z}$: zenith hydrostatic delay (ZHD, 2.0–2.5 m)
$\mathbf{L_w^z}$: zenith wet delay (ZWD, 0–40 cm)
Gradients: model the linear horizontal variations in the refractivity

Normally ZHD is calculated from surface pressure measurements, while ZWD and gradients are estimated in the data analysis

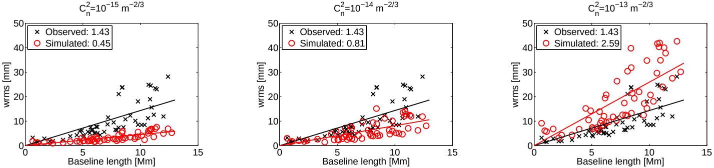
Limitations of the models

- Mapping functions need to be accurately known
  - Depends on the current atmospheric conditions
- It is assumed that the variations in the refractivity is linear
  - Small scale variations due to atmospheric turbulence cannot be modelled



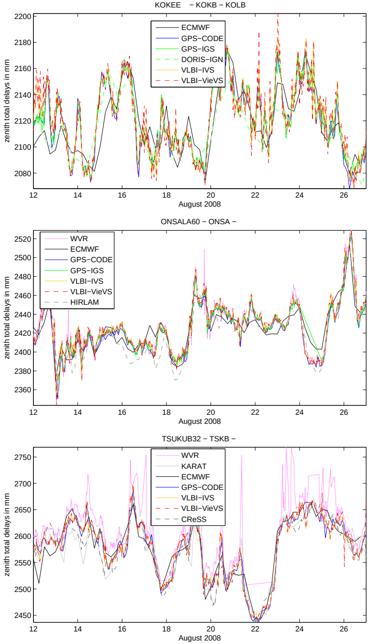
Wet tropospheric delays (mapped to zenith) simulated using a turbulence model

Error caused by turbulence in geodetic VLBI



- Continuous VLBI campaign CONT05 (12-27 September, 2005)
- Simulated VLBI observations
  - Tropospheric delays simulated using a turbulence model
  - Three different assumptions of the “strength” of turbulence
  - Clock errors and observation noise also simulated
- From Nilsson and Haas [2010]

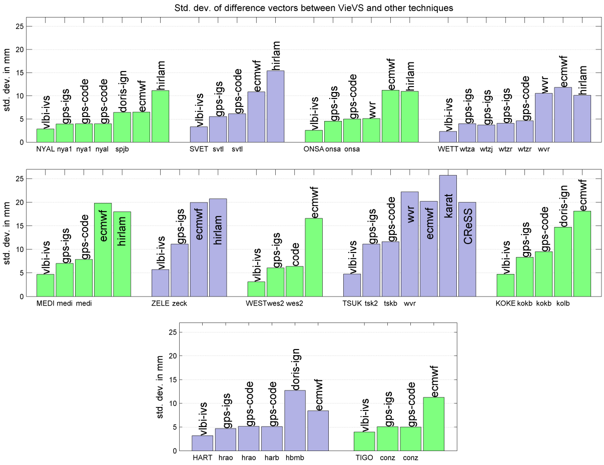
Comparison of tropospheric delays



Comparison of tropospheric delays estimated using different techniques during the CONT08 campaign (12-26 August, 2008); from Teke et al. [2011].

- VLBI (two solutions: VieVS and IVS)
- GPS (two solutions: CODE and IGS)
- DORIS
- Water Vapour Radiometry
- Numerical Weather models:
  - ECMWF (global)
  - HIRLAM (Europe)
  - JMA (KARAT) (Japan)
  - CReSS (Japan)

Comparison of tropospheric delays (II)

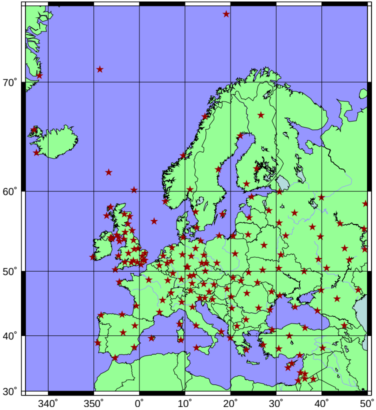


RMS differences between VLBI (VieVS) and other techniques

Applications of tropospheric delays from space geodesy

- The tropospheric delays estimated by GNSS and VLBI can be used for atmospheric studies
- The zenith wet delay is related to the integrated water vapour content (IWV): ZWD$\approx$ 6.5$\cdot$ IWV
- Interest of using ZTD (or ZWD) from space geodesy in:
  - Meteorology
  - Climatology

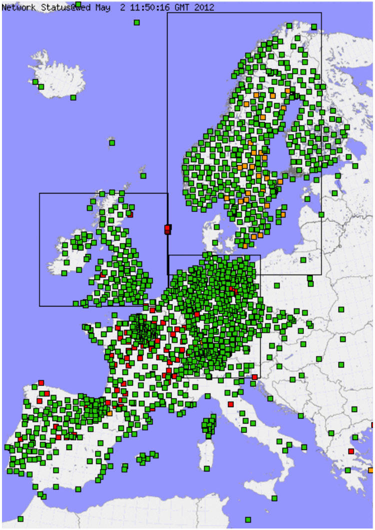
GNSS meteorology



Radiosonde launch sites in Europe
0–4 launches per day

- Water vapour is a very important parameter in meteorology
- It is very variable spatially and temporally
  - Requires continuous monitoring
- Most information about the vertical water vapour profile from radiosondes
  - Poor spatial and temporal resolution

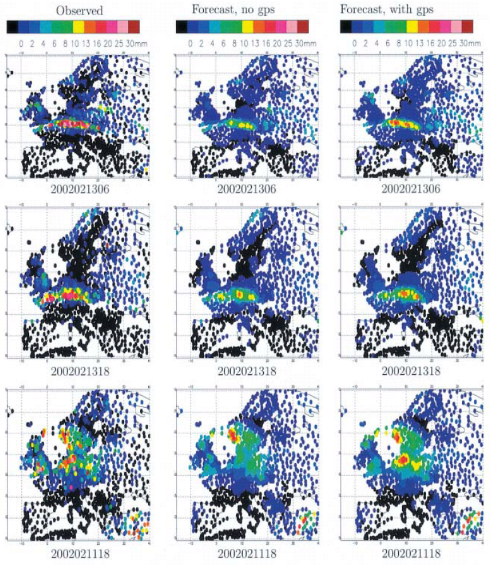
GNSS meteorology (II)



GNSS stations in Europe, used in the E-GVAP project

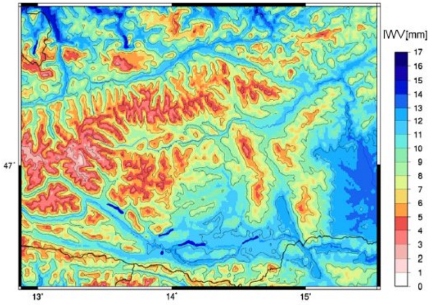
- Dense national GNSS networks exist
- All could be used for estimating ZTD
- Could be assimilated in numerical weather prediction models, when data is provided in (near) real time
- Projects:
  - NOAA GPS-IPW (USA)
  - COST716, TOUGH, E-GVAP (EU)
  - GNSSMET-Austria

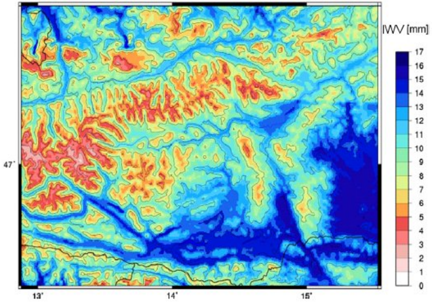
GNSS meteorology (III)



- Impact on precipitation forecasts when assimilating GPS data
- From Vedel and Huang [2004]
- GNSS data generally improves the weather forecast, especially in extreme weather conditions

GNSS meteorology (IV)

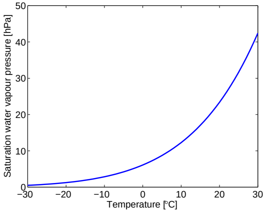




- Results from GNSS Met Austria
- IWV from a weather model (INCA) whitout (upper) and with (lower) assimilation of GPS IWV.
- Karabatić et al. [2011]

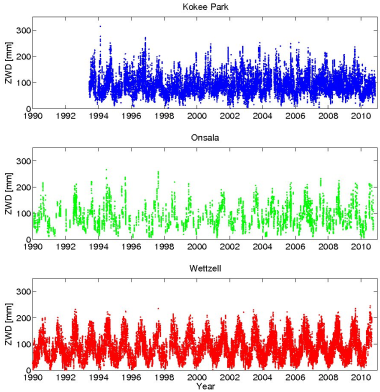
Climate studies

- Water vapour is the most important greenhouse gas
- Climate models predict that the average relative humidity is constant as temperature changes
- Saturation water vapour pressure increases (approx exponentially) with temperature
  - Absolute humidity increases as temperature increases
- 1 K temperature increase $\Rightarrow$ 5–7% increase in IWV (and ZWD)
- Thus, ZWD from VLBI and GNSS can be used for studying climate trends if the time series are long enough



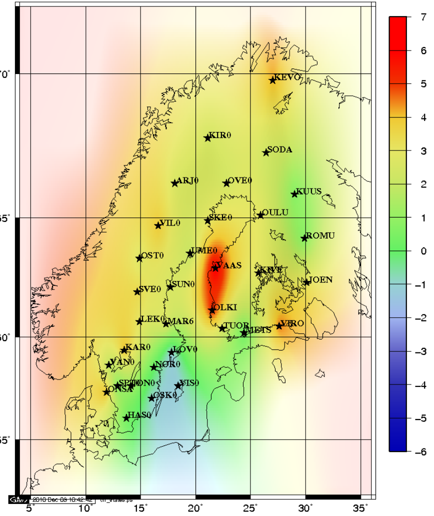
Saturation water vapour pressure as function of temperature

Climate trends from VLBI



- Time series of ZWD from VLBI
- Trends:
  - −0.11 mm/yr (Kokee)
  - 0.36 mm/yr (Onsala)
  - 0.51 mm/yr (Wettzell)
- Trends strongly dependent on the time period studied
- From Nilsson et al. [2011]

Climate trends from GNSS

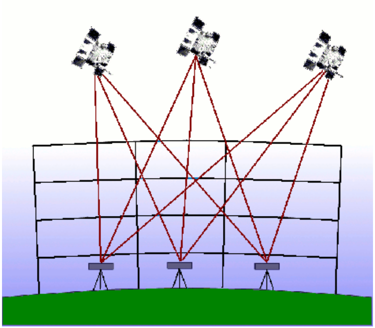


- ZWD trends over Sweden and Finland estimated from GPS data 1997–2006.
- From [Nilsson and Elgered, 2008]

GNSS tropospheric tomography

- The ZWD gives information only about the integrated amount of water vapour
- Would be interesting also to get the 3D (4D) structure of the water vapour content
- Tomography is a method for estimating 3D images from measurements of integrals along different paths
- **Idea:** apply tomographic methods to the observed GNSS slant wet delays (wet delays along the GNSS ray paths)

GNSS tropospheric tomography principle



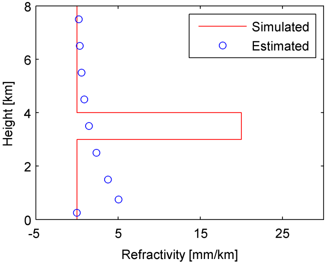
A slant wet delay L_s can be expressed as:

$$L_s = \sum_i N_i \, D_i \qquad (6)$$

N_i: refractivity of voxel i
D_i: distance of ray in voxel i

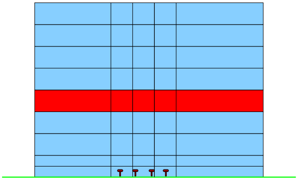
- Atmosphere divided into voxels (volume pixels)
- Refractivity of a voxel assumed constant
- The slant wet delays can be expressed as a linear combination of the voxel refractivities
- Inverting the obtained equation system gives the refractivities of the voxels
- Problems:
  - Obtaining the slant wet delays
  - Poor vertical sensitivity (no rays entering/exiting on the "sides")
  - Empty voxels

Simulation results



From Nilsson [2007]

- Performance of GNSS tomography from simulations
- 16 station network, station separation 6–7 km
- Refractivity 20 mm/km between 3–4 km, zero elsewhere
- GNSS tomography insensitive to the height of the refractivity layer



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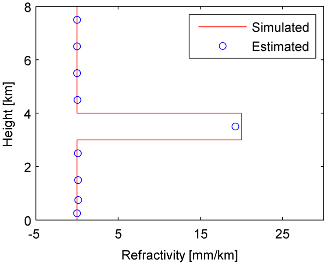
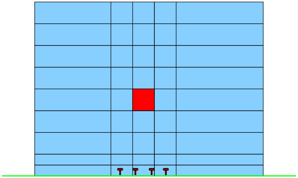
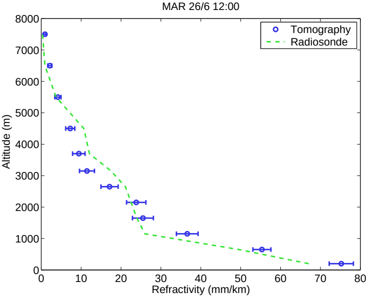


From Nilsson [2007]

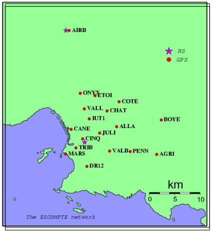
- Refractivity 20 mm/km only in middle voxel of the 3–4 km layer, zero elsewhere
- The refractivity profile is retrieved accurately
- Demonstrates that GNSS tomography is sensitive to horizontal variations in the refractivity field



Results using observed data



- Results from the ECOMPTE network, Marseille, France
- 18 Station network
- June, 2001
- From Nilsson et al. [2007]



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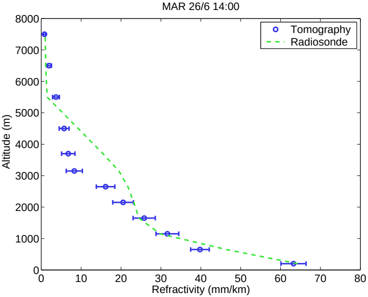

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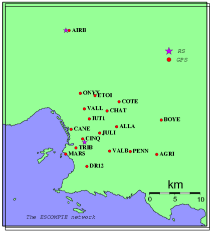

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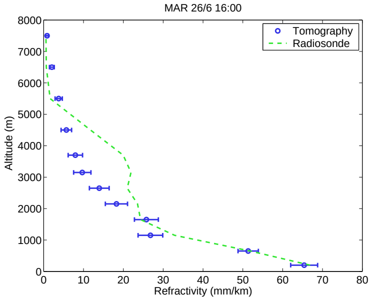

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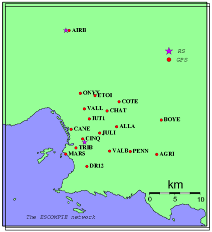
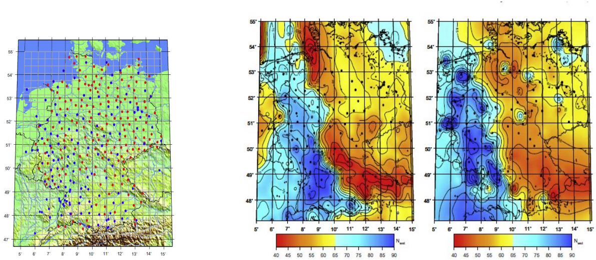
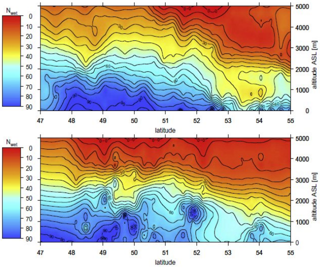


Results using observed data (II)



Wet refractivity at 676 m ASL. Left: NWP model (COSMO-DE), Right: Tomography. From Bender et al. [2011]



Vertical cut through the wet refractivity field at $\lambda = 7.52°E$.
Upper plot: COSMO-DE
Lower plot: tomography

Conclusions

- The atmosphere causes a delay of the signals used in space geodesy
- Normally the tropospheric delay is estimated in the data analysis
  - Not possible to model small scale fluctuations due to turbulence
- Tropospheric delays estimated by space geodetic techniques can be used in:
  - Meteorology (weather forecast)
  - Climatology

Danke schön

Herzlichen Dank zu:

- Meine Kollegen und Kolleginnen am HG TU WIEN
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- Föderung von:
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  - DFG
  - FWF
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