POSITIONING AND APPLICATIONS

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     4.0           ANNOUNCEMENT                          RINEX VERSION / TYPE
POSITIONING AND APPLICATION SYMPOSIUM      IAG COM. 4    EVENT NAME / AGENCY
WUELS           WROCLAW         POLAND                   LOCATION / CITY / COUNTRY
  2016    09    04            2016    09    07           TIME START / END
51.11283  17.063761  3835751.626  1177249.744  4941605.054  APPROX POSITION B / L / XYZ
1 Emerging Positioning Technologies                      SESSION NO / TOPIC
2 Geospatial Mapping and Engineering Applications        SESSION NO / TOPIC
3 Atmosphere Remote Sensing                              SESSION NO / TOPIC
4 Multi-Constellation GNSS                               SESSION NO / TOPIC
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About the new Working Group “Tropospheric ties”

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GFZ Helmholtz-Zentrum Potsdam

HELMHOLTZ GEMEINSCHAFT

JWG Tropospheric ties

IAG Joint Working Group 1.3 „Tropospheric ties“

Chair: R. Heinkelmann, Vice-Chair: J. Dousa

under

- IAG Commission 1 „Reference Frames“
  Chair: G. Blewitt
  Current website: http://iag.geo.tuwien.ac.at/c1/

joint with

- IAG Sub-Commission 4.3 „Remote Sensing and Modeling of the Atmosphere“
  Chair: M. Schmidt
  Current website: http://iag-comm4.gge.unb.ca/iag_sc43.htm

JWG Tropospheric ties

IAG Joint Working Group 1.3 „Tropospheric ties"

Chair: R. Heinkelmann, Vice-Chair: J. Dousa

members:

Kyriakos Balidakis (Germany)

Elmar Brockmann (Switzerland)

Sebastian Halsig (Germany)

Gregor Möller (Austria)

Angelyn W. Moore (USA)

Tobias Nilsson (Germany)

Rosa Pacione (Italy)

Tzvetan Simeonov (Bulgaria)

Peter Steigenberger (Germany)

Kamil Teke (Turkey)

Daniela Thaller (Germany)

Xiaoya Wang (China) → next talk!

Pascal Willis (France)

Florian Zus (Germany)

Current ITRF ties

Goal: constrain space geodetic techniques for ITRF level computation through common parameters.

Currently applied ties for ITRF (ITRF2014, Altamimi et al., 2016) computation:

Station coordinates: $\boldsymbol{x}, \dot{\boldsymbol{x}}$

- **„local ties":** epochal Cartesian difference vectors between antenna reference points $\Delta \boldsymbol{x}_{VLBI-GNSS}(t_m) = \boldsymbol{x}_{VLBI}(t_m) - \boldsymbol{x}_{GNSS}(t_m)$, measured by local survey at epoch t_m, epoch of application t_a is decided by combination center
  $\boldsymbol{\sigma}_{\Delta x(t_m)}$ given from measurement and horiz./vert. scaled by combination center

  Problem: several large disagreements between measured and calculated local ties!
- **„co-movement constraints":**

  $\Delta \dot{\boldsymbol{x}}_{VLBI-GNSS} = \dot{\boldsymbol{x}}_{VLBI} - \dot{\boldsymbol{x}}_{GNSS} = \mathbf{0}$, set for certain sites, not for all sites, application is decided by combination center

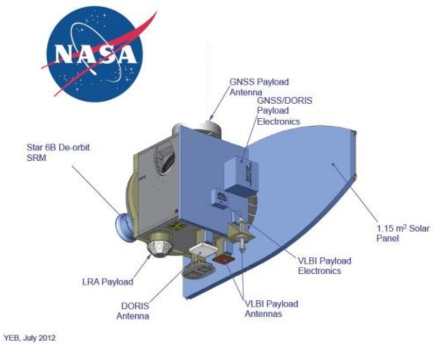
ERP (Earth Rotation Parameters): $\boldsymbol{x_p}, \boldsymbol{y_p}, \boldsymbol{UT}, \dot{\boldsymbol{x}}_{\boldsymbol{p}}, \dot{\boldsymbol{y}}_{\boldsymbol{p}}, \boldsymbol{LOD}$

- **„global ties"**: aligns the external orientation of the techniques w.r.t. interim frame: UT refers to TIO and CIO from VLBI, CPO from VLBI neglected

Tie research

"Satellite ties": positional difference vectors between antenna reference points at co-location satellites, measured prior to start (measurements can hardly be repeated once in orbit)

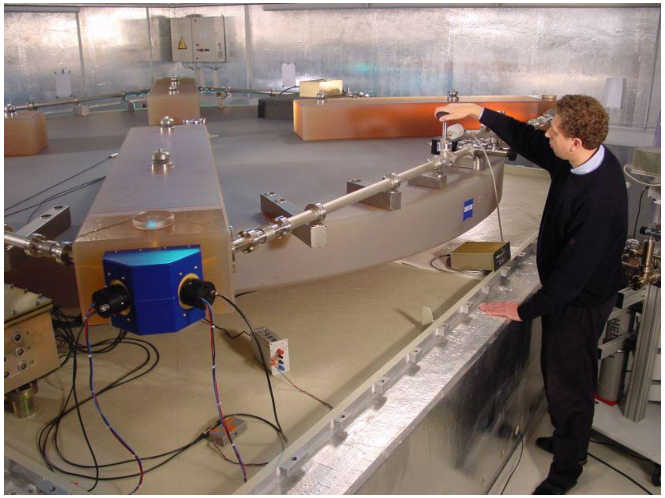
- currently available:
  - checked: GNSS-SLR
    GRACE satellites (GNSS receiver, SLR retro-reflector)
    several GNSS satellites (GNSS emitter, SLR retro-reflectors)
  - checked: GNSS-SLR-DORIS
    altimeter satellites, e.g. JASON-2 (GNSS receiver, SLR retro-reflector, DORIS receiver)
  - experimental: GNSS-VLBI(-SLR)
    observations of GLONASS satellites by VLBI ground segment
- planned:
  - co-location satellites: GNSS-SLR-VLBI (VLBI transmitter)
    examples: GRASP (NASA), E-GRASP (CNES), E-GRIP (Swiss)
- allows determination of s/c location by various techniques, currently s/c locations are not „part of ITRF"



More tie research

More (alternatively or additional) ties

- **IAG WG 1.1.1 „Co-location using Clocks and New Sensors"**
  Chair: U. Schreiber



- topics:
  - highly accurate time and frequency transfer
  - ultra-stable clocks
  - co-location targets

- closely interacts with the IERS WG on Site Survey and Co-location and the Joint WG 1.3 on Tropospheric Ties

Tropospheric ties: definition

Goal: constrain space geodetic techniques for ITRF level computation through common parameters of the atmosphere

Tropospheric ties, definition:

use of atmospheric parameters and/or constants for the ITRF level computation

Requirement for tropospheric ties:

knowledge about the expected (systematic) differences between atmospheric parameters obtained by different co-located sensors that observe about at the same time

Common atmospheric parameters

Currently available atmospheric parameters for microwave techniques: GNSS, DORIS, VLBI

$$\delta\rho_{trp}(z,\alpha) = mf_d(z)ZHD + mf_w(z)ZWD + mf_g(z)[G_N \cos\alpha + G_E \sin\alpha]$$

where:

$\delta\rho_{trp}(z,\alpha)$: slant total delay (m) with azimuth α and zenith distance z

very well suited for comparison, but requires observations in the same direction at the same time (if not explicitly scheduled this is very unlikely), estimated parameters introduce temporal correlations

Note1: current ITRF computation is on parameter level!

Note2: very large number of slant total delays!

$mf_{d/w/g}$: mapping functions of dry (hydrostatic), wet delays and gradients, calculated

ZHD: zenith hydrostatic delay (m), calculated

should be consistently calculated for precise tie (next slides)

ZWD: zenith wet delay (m), estimated

$G_{N/E}$: gradient in north or east direction (m), estimated

should be identically defined (parameter model, length and constraints) to avoid interpolation effects

ZHD consistent calculation

Well known (e.g. IERS Conventions 2010, Davis et al., 1985, Saastamoinen, 1972/73)

$$ZHD = \frac{2.2768\,p}{1 - 0.00266\cos 2B - 0.0028H}$$

where

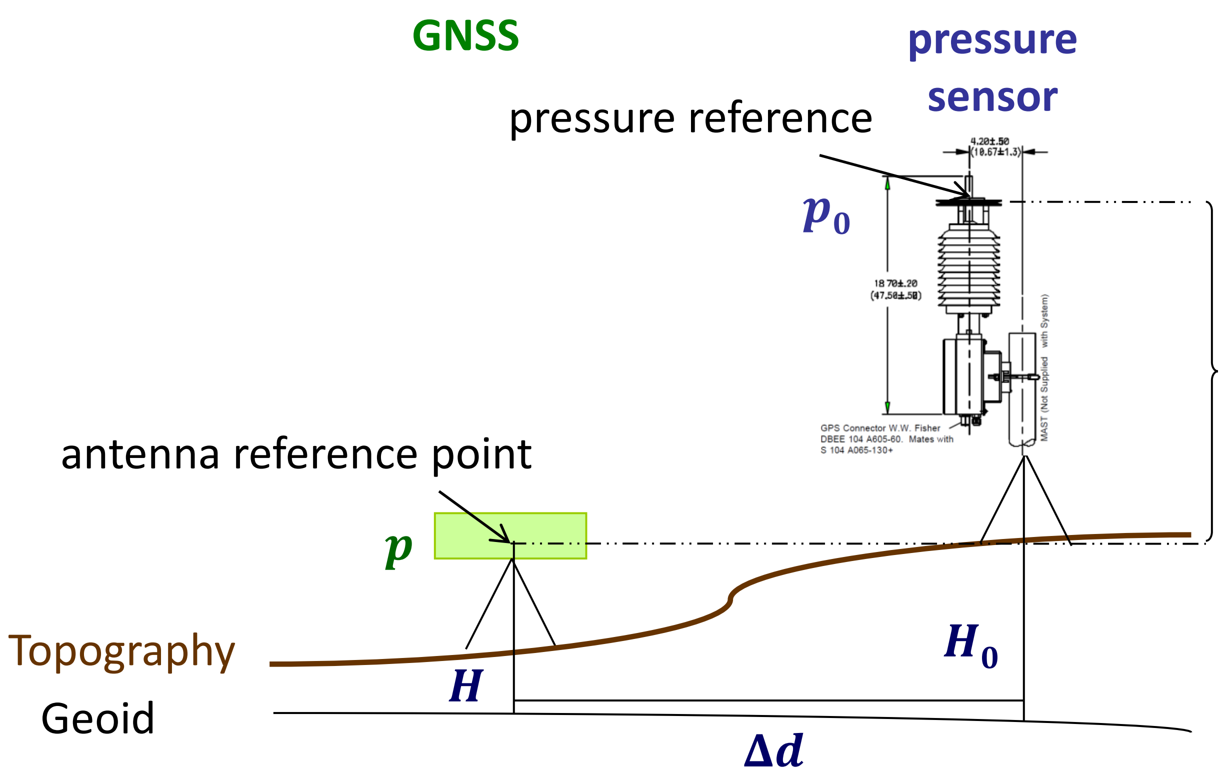
p atmospheric pressure at the antenna reference point (hPa)

Variations of latitude (B) and altitude (H) in the above equation are negligible.

→ The accuracy of ZHD depends entirely on **the accuracy of the atmospheric pressure**!

Consistent ZHD → consistent p

Sketch of co-location with pressure sensor



Vertical distance

$$\Delta H = H_0 - H > 0$$
$$\Rightarrow$$
$$p > p_0$$

$$p = p_0 \cdot \left(1 - \frac{\gamma (H - H_0)}{T_0}\right)^{\frac{g}{R_L \gamma}}$$

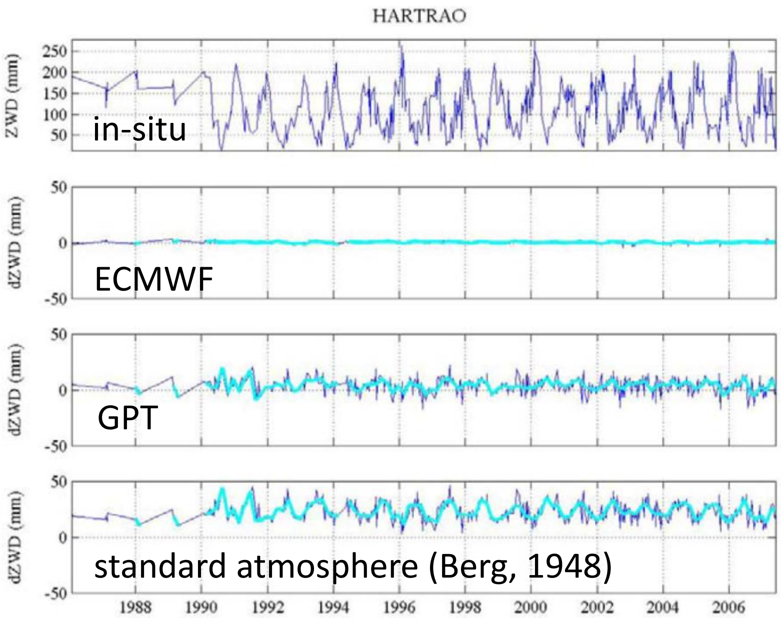
Horizontal distance

$\Delta d \Rightarrow ?$

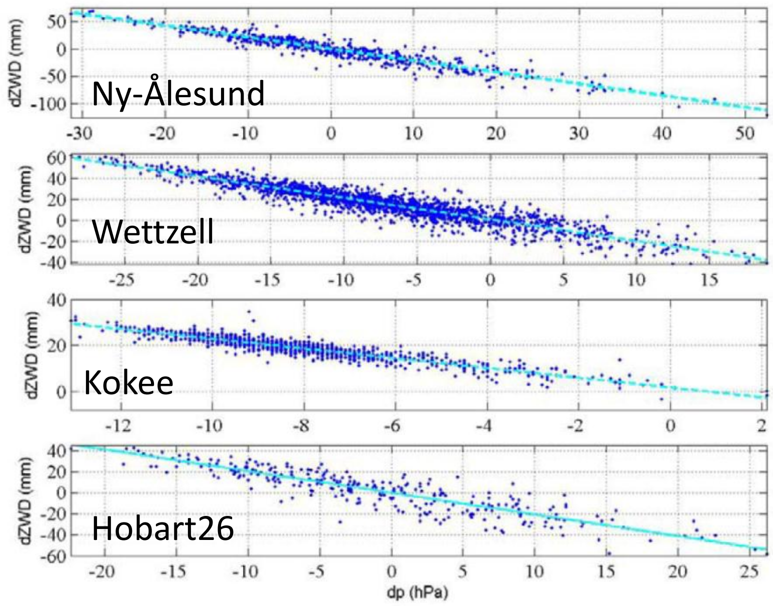
Hypsometric pressure reduction to the altitude of the antenna reference point: $p = p(H)$

Appropriate pressure data

ZWD based on various pressure data



ZWD correlations with p



Average ZWD change per change of pressure ≈ -2.1 mm/hPa (-90% of ZHD).

The rest -0.2 mm/hPa is absorbed by other parameters (e.g. station height error). This causes systematically wrong ZTD.

For ZWD with 1 mm precision, p has to be known with < 5 hPa absolute accuracy.

mf consistency

For precise tropospheric tie, the **same mapping functions** (mf) should be applied by the techniques, e.g. VMF1.

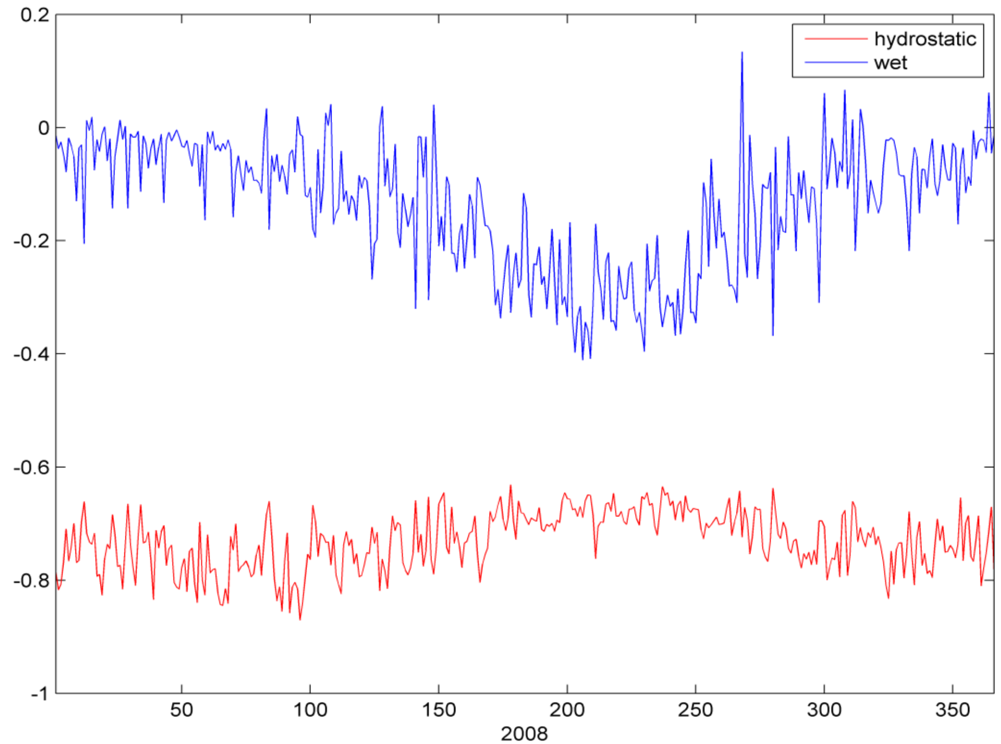
In addition, mf depend on the **locations of the sensors**, in particular $mf = mf(H)$

Example Tsukuba $\Delta H \approx 17$ m

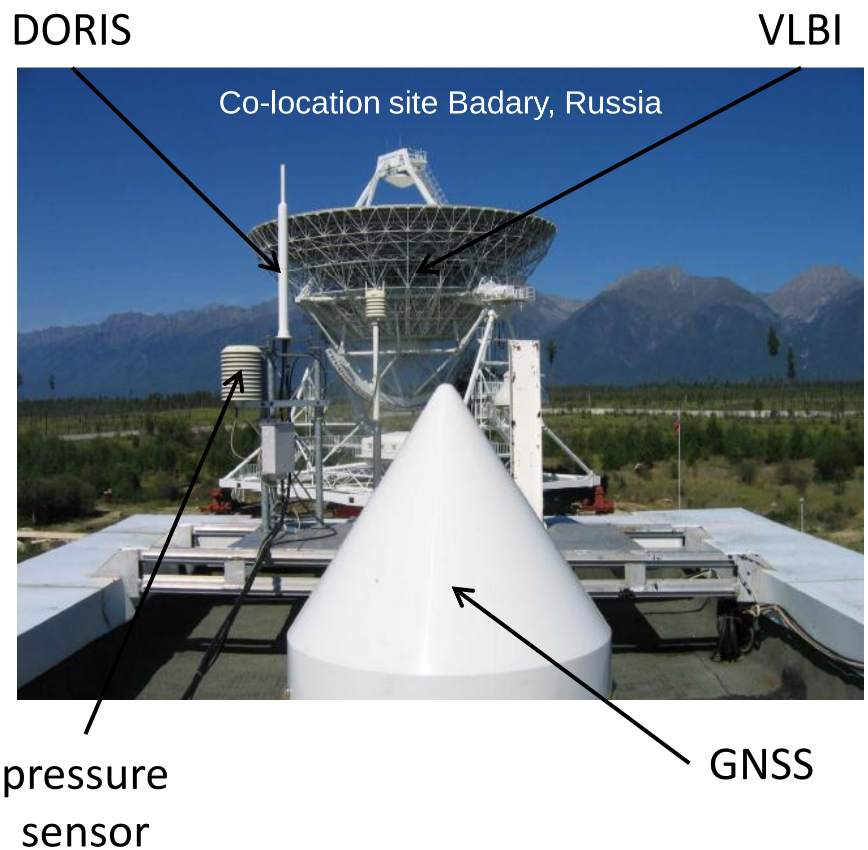
Same mapping functions at different height cause different zenith delays

Figure shows the max. case for elevation angle $e = 5°$

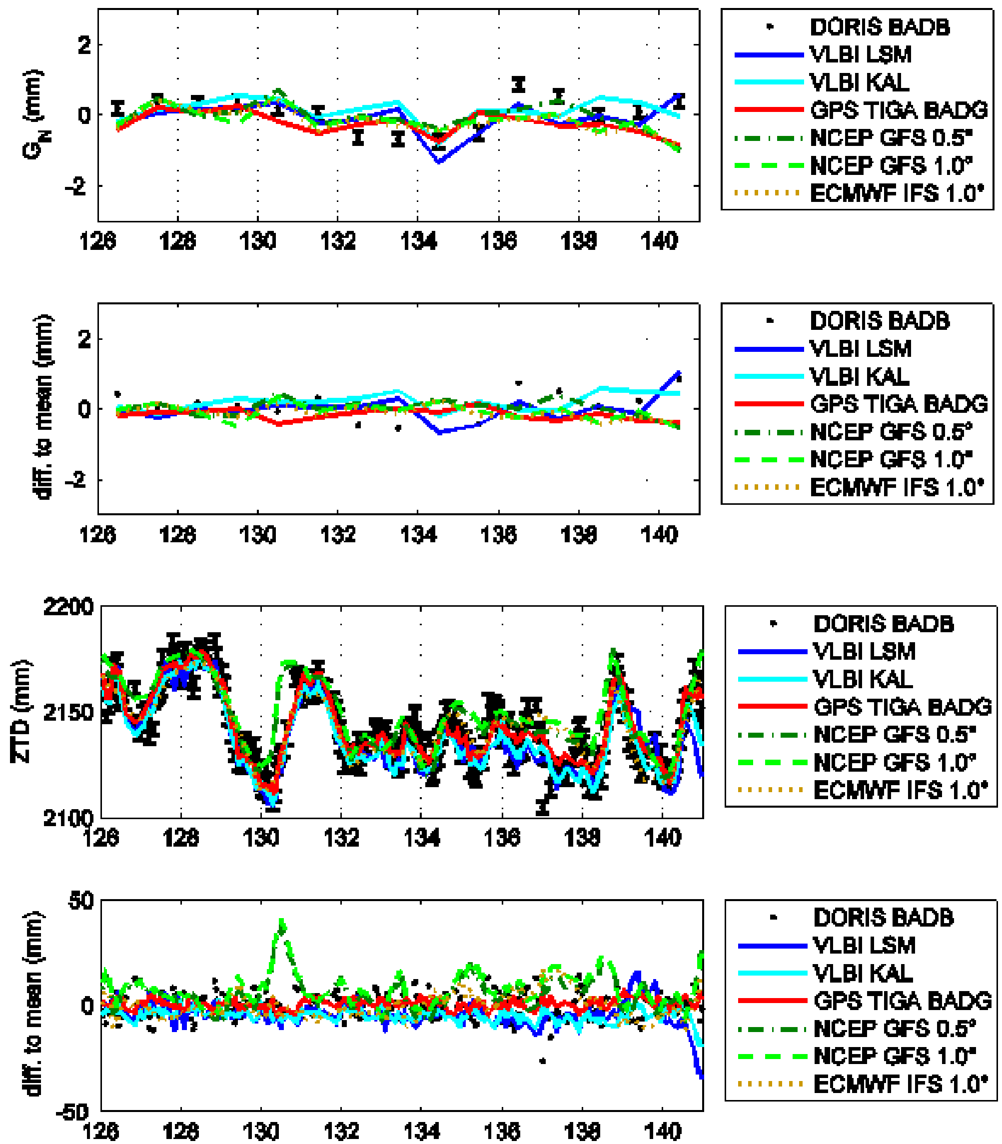
Note: for 1 mm-accuracy this effect is negligible on average if $\Delta H < 100$ m



Example: comparison of atmospheric parameters

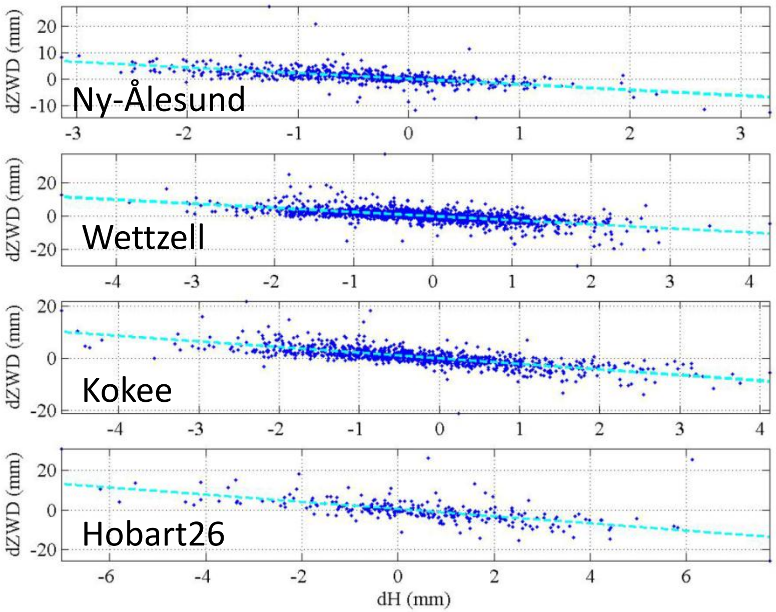


$$ZTD = ZHD + ZWD$$



Outlook: tropospheric ties

Correlation of ZWD with station height H

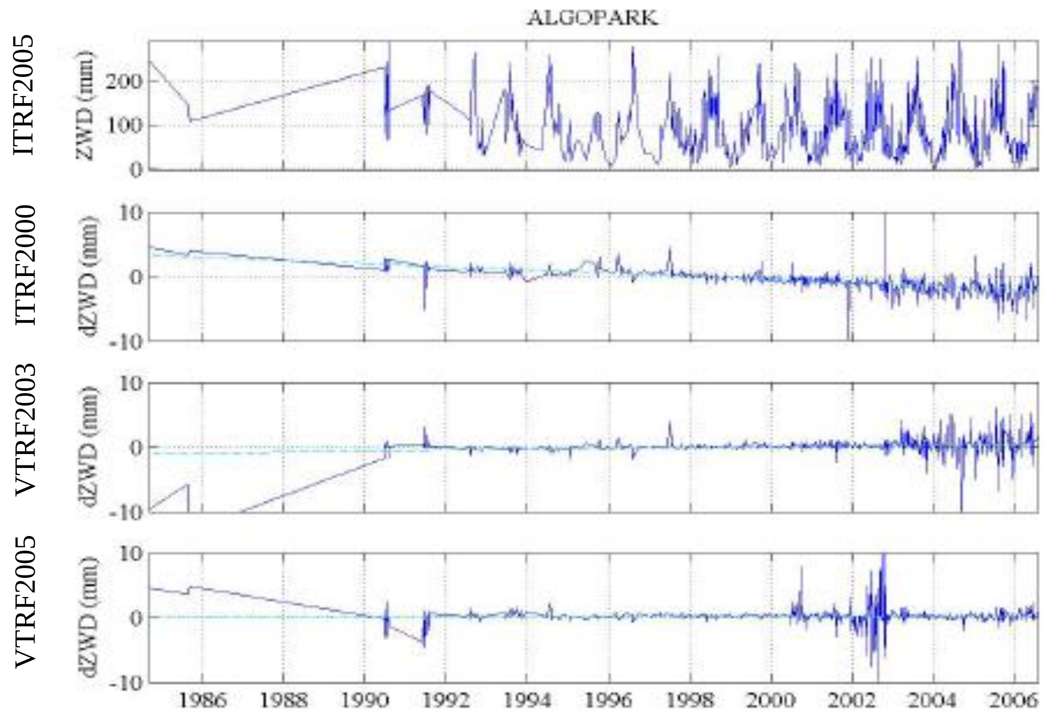


Average ZWD change per 1 mm change of station height $\approx -2.1\ \mathrm{mm/mm}$ or vice versa **1 mm ZWD change corresponds to $-0.4\ \mathrm{mm}$ station height change**!

Multi-technique combination of ZWD can be a tied constraint for station heights!

Outlook: tropospheric ties

ZWD correlation with TRF (here: ZWD based on various TRF)



obvious lin. trend in ZWD

Note: ITRF2000 had several problems with the shift of the origin's z-component!

JWG Tropospheric Ties - objectives

- Extensive comparisons of tropospheric parameters
- Theoretical modeling based on hydrostatic equilibrium and comparable assumptions
- Numerical modelling involving numerical weather models
- Testing combinations with the application of tropospheric ties

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If you want to contribute, to become a member or a corresponding member of the JWG Tropospheric ties, contact us:

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Thank you!

repository

extra slides

Atmospheric refractivity of VLBI signals

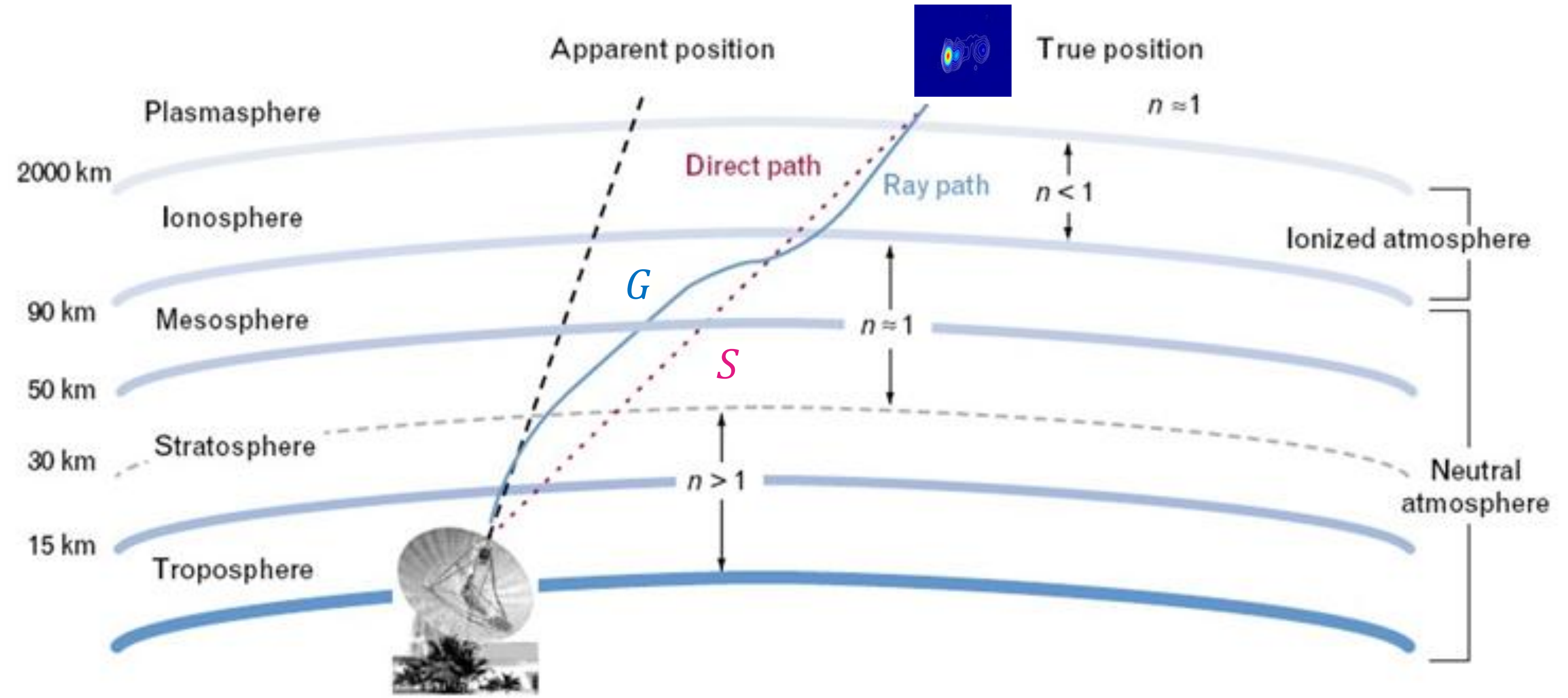


Figure *after Hunt et al. (2000)*:
2D atmospheric propagation of a radio signal. The example shows the situation for the phase ($n < 1$ "phase advance" in ionized atmosphere). While for groups of signals, the refractive index is always $n > 1$ ("group delay").

Atmospheric refractivity of VLBI signals

Effects on microwaves in the atmosphere depend on the **refractive index** n, the relation between the vacuum speed of light c and the actual propagation speed v:

$$n = \frac{c}{v}$$

For an infinitesimal small piece of the signal path, **propagation speed** is given through

$$v = \frac{ds}{dt} \Rightarrow dt = \frac{n(s)}{c} ds$$

Integration over the entire signal path L yields the **signal travel time**

$$\Delta t_L = t_2 - t_1 = \frac{1}{c} \int_L n(s) ds$$

The **excess path length** is the difference between the actual path L and the theoretical straight line the signal would propagate in case of absence of the atmosphere G:

$$\delta\rho_{atm} = L_E - G = \int_L n(s) ds - G = \int_L (n(s) - 1) ds + (S - G)$$

where S denotes the length of the actual ray path.

Refraction causes two effects: **signal delay** and **signal bending**.

Note: the bending is usually so small that it can be neglected.

Troposphere - refraction

Neglecting the bending $(S - G)$ the tropospheric correction is obtained through:
$\delta\rho_{trp} = \int (n(s) - 1) ds$ and with the refractivity $N = (n - 1) \cdot 10^6$ we get

$$\delta\rho_{trp} = 10^{-6} \int N(s) ds$$

The **refractivity of moist air** is (*Thayer, 1974*):

$$N = k_1 \frac{P_d}{T} Z_d^{-1} + k_2 \frac{P_w}{T} Z_w^{-1} + k_3 \frac{P_w}{T^2} Z_w^{-1}$$

where

P_d Partial pressure of dry air (hPa)

P_w Partial pressure of water vapor (hPa)

T Temperature (K)

k_i Empirical coefficients, $i \in \{1,2,3\}$ (K/hPa, K/hPa, K^2/hPa)

$Z_{d,w}$ Compressibility of dry and moist air, respectively

Troposphere – hydrostatic part

Because of the large mixing ratio of dry gases, **dry air** follows to a very high degree the hydrostatic law and can thus be modeled knowing the **air pressure p (hPa) on ground**. Therefore the dry and wet tropospheric constituents are then separately treated.

To get the tropospheric delay in zenith direction, we apply mapping functions:

$$\delta\rho_{trp}(z) = m_{trp,d}(z)\delta\rho^0_{trp,d} + m_{trp,w}(z)\delta\rho^0_{trp,w}$$

$$\delta\rho^0_{trp,d} = ZHD = \frac{2.2768\,p}{1 - 0.00266\cos 2B - 0.0028H}$$

where

B	Latitude of the station
H	Altitude of the station (m)
$\delta\rho^0_{trp,d}$	Dry tropospheric delay in zenith direction (mm)

Troposphere – wet part and gradients

The water vapor is not in hydrostatic equilibrium and thus the zenith wet delay cannot be simply modeled based on ground meteorological observations; it remains unknown and gets estimated as unknown parameters in the adjustment. For each station, zenith wet delays and gradients are estimated with a certain temporal resolution depending on the availability and density of observations.

To account for horizontal asymmetry the gradient term is considered:

$$\delta\rho_{grd} = m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

where

m_{grd}	Gradient mapping function depending on the zenith distance z
$G_{N,E}$	Horizontal gradient components in north (N) and east (E) directions
α	Azimuth angle

Troposphere – complete model

The atmospheric delay of a **VLBI group delay** observable reads:

$$\tau_{atmo} = \delta\rho_{trp,2}(z_2) - \delta\rho_{trp,1}(z_1)$$

where the station-wise contributions have to be separated. The entire model reads:

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

ZHD and the mapping functions are computed, z and α are known from geometry and ZWD and G_N and G_E are estimated.

Comment: Consequently, for each observation we have six unknowns (three per station) what results in an underdetermined equation system that is not solvable by least squares. For a scan (all observations at the same epoch), however, if the scan is observed by >7 stations the redundancy $r = n - u = \sum_{i=1}^{I-1}(i) - I \cdot 3 > 0$ is given. To separate gradients from zenith delay, we need observations at different zenith distances. To separate north from east gradients, we need observations at different azimuth. Therefore geodetic scheduling varies z and α per time to a large extent.

Troposphere – complete model

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

The **slant total delay** is the complete refractive information depending on zenith distance and azimuth of a single observation. The estimated part is, however, not available on observation level (LSM), it is available on parameter level and has a coarser temporal resolution (the one of the ZWD and the one of the $G_{N,E}$). As a consequence **slant total delays that incorporate the same parameters are correlated** (should be considered for assimilation by the corresponding stochastic model!).

Alternative:

$$ZTD = ZHD + ZWD$$

The alternative representation (accepting loss of generality) is the **zenith total delay**. It is independent from gradients (gradient part is zero). It has the temporal resolution either of the ZHD (single observation) or of the ZWD (parameter length). The first results again in **correlations**, while for the second a surface pressure **mean value** during the parameter definition interval should be used for ZHD computation.

Accuracy of atmospheric parameters

- **Absolute accurate air pressure** (< 5 hPa accuracy) must be known and must be applied for mm-accurate ZWD or ZTD determination during parameter estimation.

- **It is not sufficient** to determine ZTD with air pressure (> 5 hPa accuracy) and to use accurate air pressure in post-processing to get mm-accurate ZWD via

$$ZWD = ZTD - ZHD_{accurate} \quad ✗$$

- However, ZTD can be "corrected", if both, the accurate pressure and the pressure used for parameter estimation are known by considering the excess part that went into other parameters -0.2 mm/hPa. But this is only an **average "correction"**.

Accuracy of atmospheric parameters

Absolute accurate air pressure! How to get it?

- At VLBI sites, atmospheric **pressure** has been **recorded during VLBI observations**. This is very important for accurate ZWD!

However, **observed pressure** is subject to inhomogeneities, missing values, outliers, ...
→ needs to be homogenized

- Alternatives?

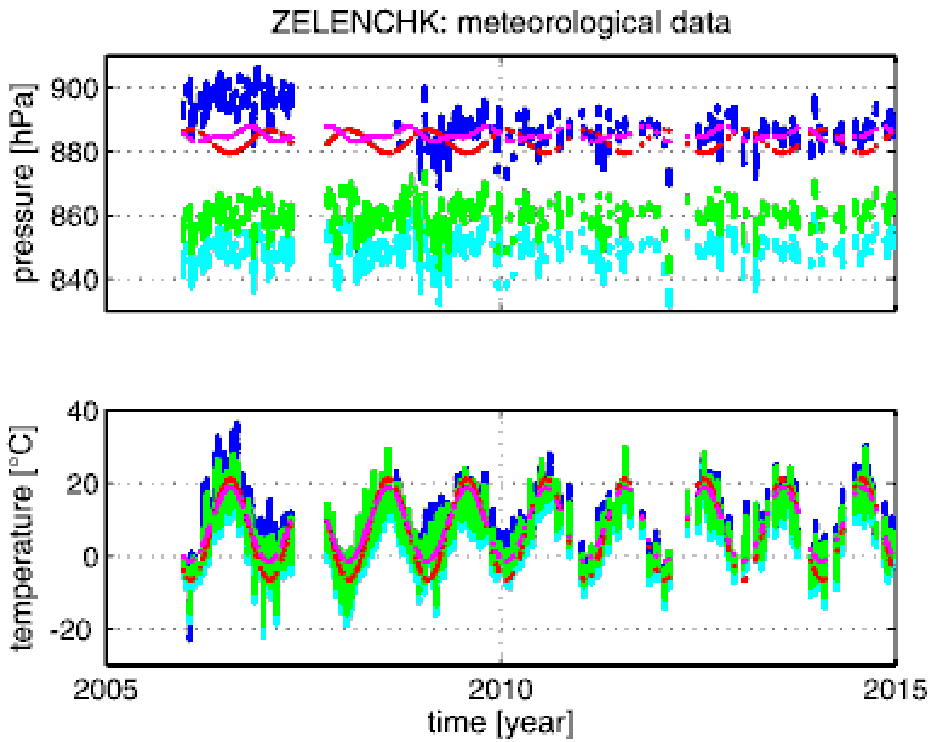
- Pressure from **empirical models**, GPT, GPT2 → no diurnal cycle, no inter-annual variations, no trends → cause scatter and various small systematics

- Pressure from **numerical weather models** have limited horizontal resolution, limited temporal sampling → sometimes mean value is not representative

Accuracy of atmospheric parameters

Example: observed pressure

→ needs to be homogenized, sometimes needs decision about the absolute mean value, needs substitutes (in case of missing values and outliers)



in-situ observed values (IVS), original mean value (incl. break)

mean value by hypsometric extrapolation of surface pressure from WMO site(s) in the vicinity

mean value by hypsometric extrapolation of surface pressure of ERA Interim (Dee et al., 2011)

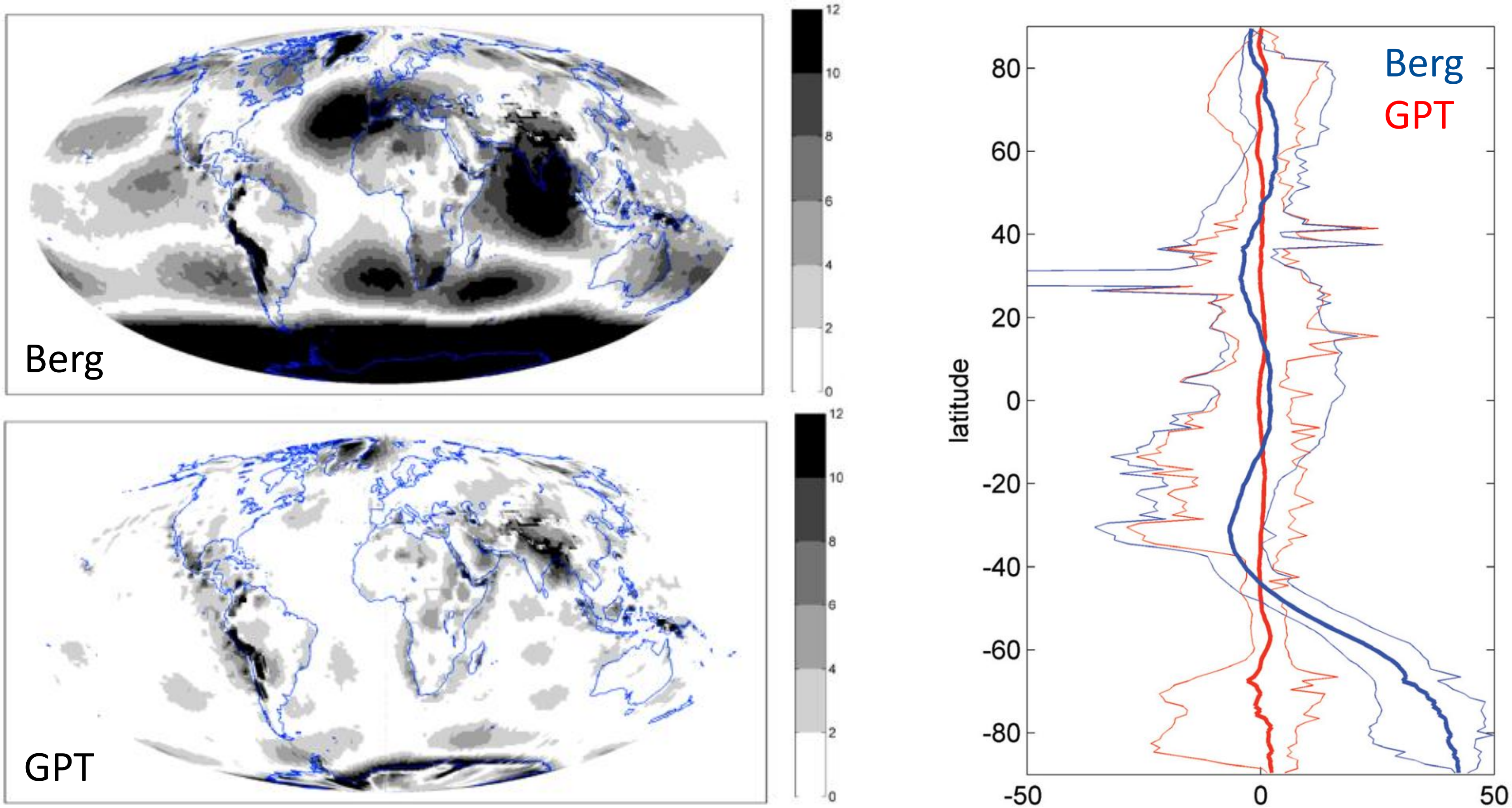
GPT (Boehm et al., 2007)

GPT2 (Lagler et al., 2013)

Heinkelmann, et al., IAG Symp., 2016 (accepted)

Accuracy of atmospheric parameters

Example: differences of models vs. ECMWF



Boehm, et al., IVS Memo, 2008

Accuracy of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

ZWD and gradients are **estimated**, partial derivatives are the mapping functions.

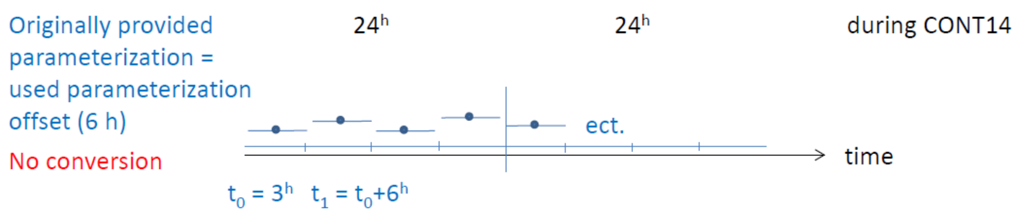
The parameters in LSM must be pre-defined. They depend on

- **the parameter model**, e.g. offset or piece-wise linear function etc.

Accuracy of atmospheric parameters

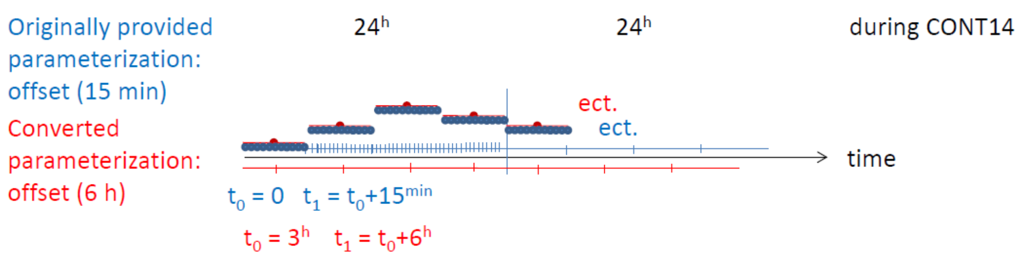
- Example: different parameterizations for gradients

GNSS TIGA parameterization



goal: comparison of gradients from different techniques

GNSS PPP parameterization



weighted mean value

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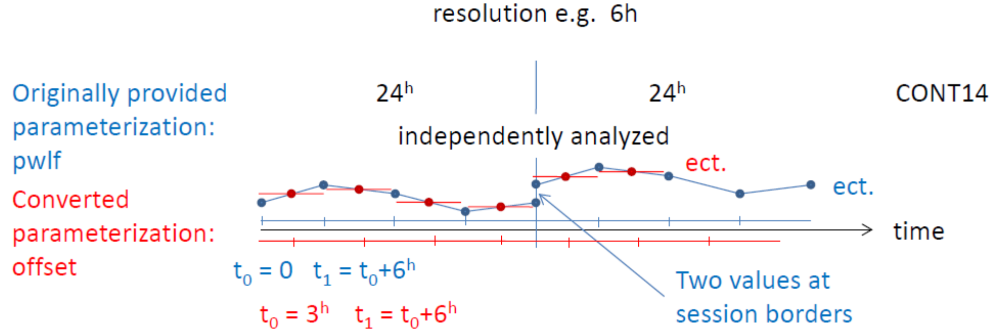
Accuracy of atmospheric parameters

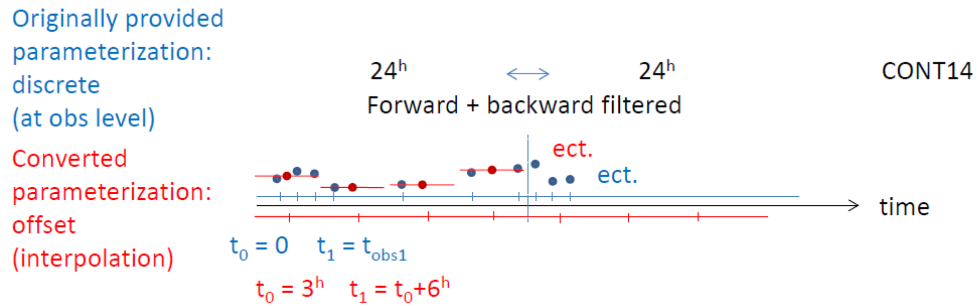
- Example: different parameterizations for gradients

VLBI LSM parameterization



problem: inconsistency at session borders (2 values)
best solution: average in the middle of the interval

VLBI KAL parameterization

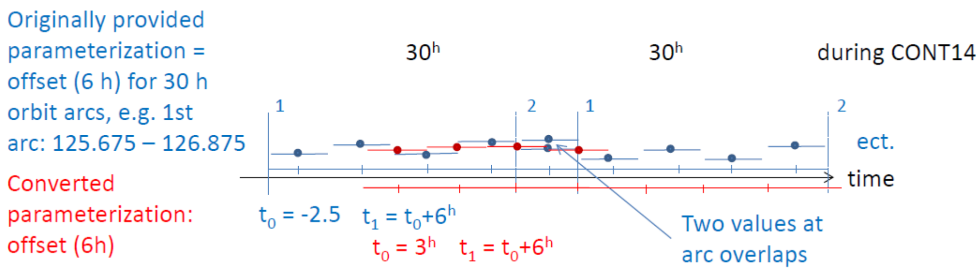


problem: Kalman filtered values do already temporally correlate with all other values

Accuracy of atmospheric parameters

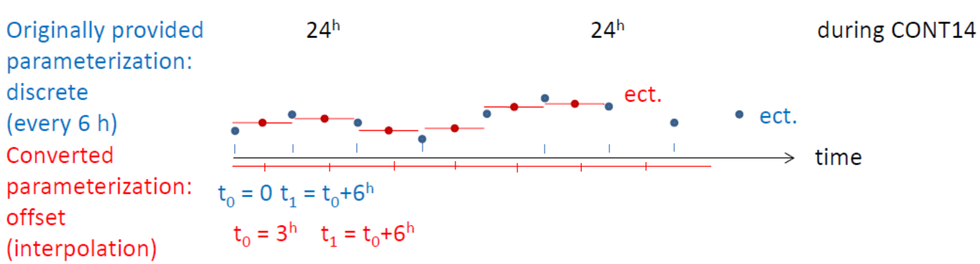
- Example: different parameterizations for gradients

DORIS parameterization



problem: averaging causes considerable smoothing
best solution: same time basis

NWM parameterization



problem: weather model values are discrete, they do not represent a time interval
best comparison: parameter close to NWM epoch and short interval length

Accuracy of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

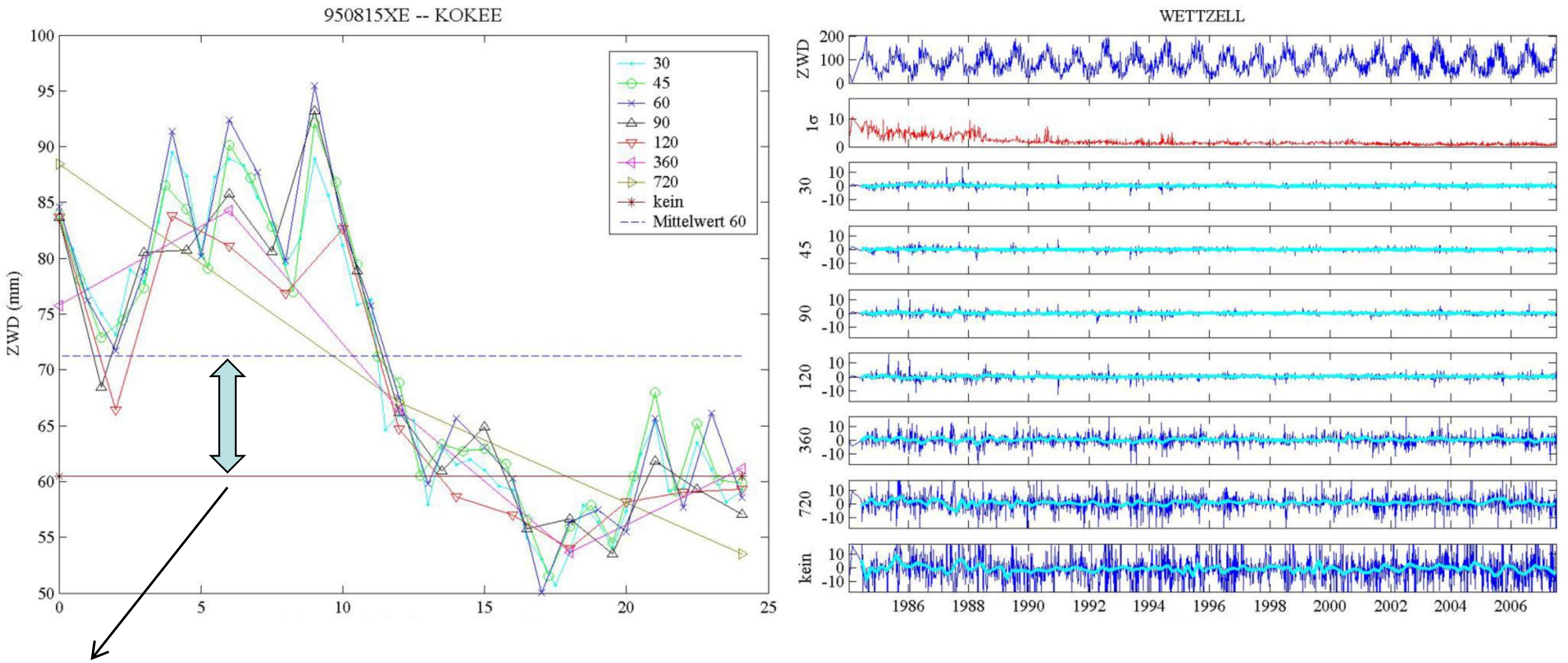
ZWD and gradients are **estimated**, partial derivatives are the mapping functions.

The parameters in LSM must be pre-defined. They depend on

- the parameter model, e.g. offset or piece-wise linear function etc.
- **the parameter length** (e.g. 30 min, 2 h, etc.) and

Accuracy of atmospheric parameters

- Example: parameterization (here: ZWD (mm) based on various interval lengths)



Difference between the average value of the 60min parameters and the ZWD value estimated with 24h length (mainly because of inhomogeneous density of observations)!

Accuracy of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

ZWD and gradients are **estimated**, partial derivatives are the mapping functions.

The parameters in LSM must be pre-defined. They depend on

- the parameter model, e.g. offset or piece-wise linear function etc.
- the parameter length (e.g. 30 min, 2 h, etc.) and
- the parameter relative constraint (e.g. 20 mm/sqrt(h)).

Accuracy depends on

- the **quality of the observations** (group delays)
- the **quality of all correction/reduction models** applied on the observation level
- the **accuracy of the mapping functions**
- the **inter-parameter correlations** in the adjustment
  - most of all with the gradients (in particular in case of small z)
  - with the station height (in particular in case of small z)
  - with the station clock (in particular in case of limited geometry)

Accuracy of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

ZWD and gradients are **estimated**, partial derivatives are the mapping functions.

The parameters in LSM must be pre-defined. They depend on

- the parameter model, e.g. offset or piece-wise linear function etc.
- the parameter length (e.g. 30 min, 2 h, etc.) and
- the parameter relative constraint (e.g. 20 mm/sqrt(h)).

Accuracy depends on

- the **quality of the observations** (group delays)
- the **quality of all correction/reduction models** applied on the observation level
- the **accuracy of the wet mapping function**
- the **inter-parameter correlations** in the adjustment
  - most of all with the gradients (in particular in case of small z)
  - with the **station height** (in particular in case of small z)
  - with the station clock (in particular in case of limited geometry)

VLBI for atmospheric/climate studies

- Pro:
  - **very accurate** estimation of **ZWD and gradients** possible
  - some stations have **very long time series** (> 30 years)
  - **long-term consistency** is very good (no change of equipment at VLBI antenna)
  - VLBI directional antenna allows for very low elevation observation, **good decorrelation of zenith delay and gradients**

- Con:
  - **lower temporal sampling** of observations in comparison to GNSS
  - **discontinuous** observation (24h sessions 2-3 times per week)
  - **lower number of stations** in comparison to GNSS

- Conclusions:
  - **VLBI alone does not provide enough spatio-temporal sampling to conduct atmospheric/climate studies on global scales**
  - **VLBI is very useful for calibration of GNSS (GRUAN or other) atmospheric data** at co-location sites

Comparison of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

Customary initial assumption: co-located microwave geodetic instruments „are subject to the same atmosphere“. → Yes, but different sampling!
Customary conclusion: atmospheric parameters should be comparable. → No!

Some reasons:

- observations do not have the same spatio-temporal sampling
- atmosphere is not isotropic
- atmosphere is not static
- devices have different spatial positions
- devices have different visibilities, horizon masks, natural elevation cut-offs, multi-pathing
- instruments are not identical
- some instruments are covered by radome
- instruments may be replaced or otherwise changed over time
- parameters can contain other effects with elevation dependent signature

Comparison of atmospheric parameters

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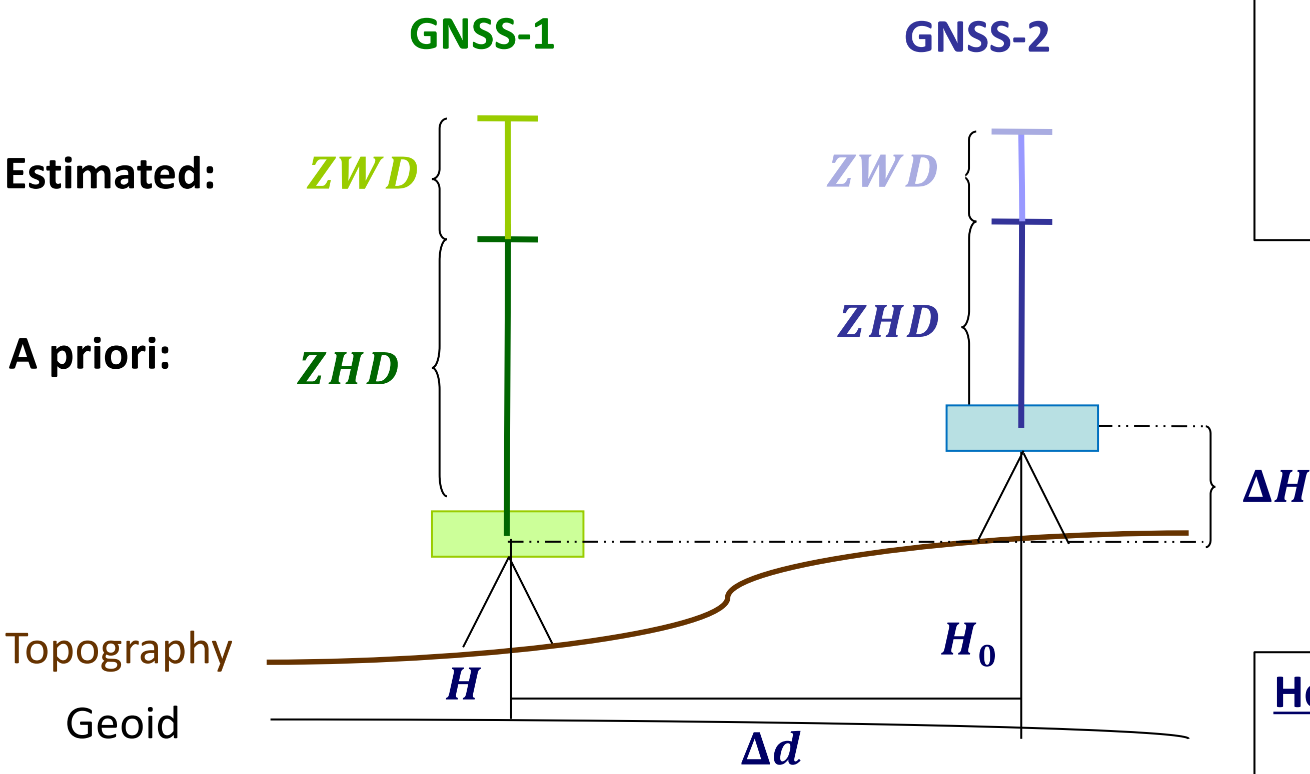
Consequence: atmospheric parameters are not directly comparable, but the whole term (slant total delay) should be comparable

tropospheric tie definition:
the expected (systematic) difference between atmospheric parameters obtained by different co-located sensors that observe about at the same time.

Comparison of atmospheric parameters

Example: co-located GNSS



Vertical distance

$$\Delta H = H_0 - H$$
$$\Rightarrow$$
$$ZHD > ZHD$$
$$ZWD > ZWD$$

Horizontal distance

$$\Delta d \Rightarrow ?$$

Comparison of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

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the expected (systematic) difference between atmospheric parameters obtained by different but co-located sensors that observe about at the same time.

What differences can be expected and how can they be modeled?

1. **Hardware and hardware changes**
2. Different locations of the sensors
3. Different reduction models and analysis options
4. Different parameterization, synchronization, interpolation, ...
5. Different space geodetic techniques

Comparison of atmospheric parameters

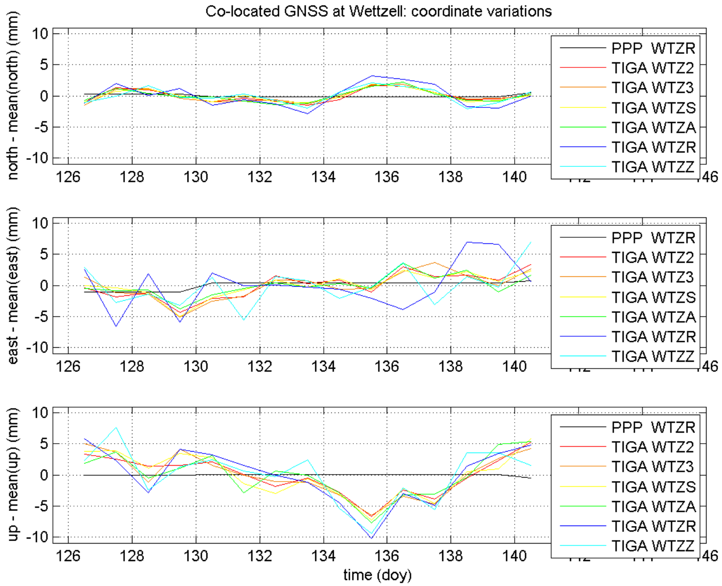
Example: co-located GNSS at Wettzell

Table 3 Mean distances (WGS84) between GNSS antenna reference points at Wettzell, Germany, w.r.t. WTZR. *The stations WTZ2, WTZ3, and WTZS are the same antenna.

IGS name	mount	distance (m)	
		horizontal	vertical
WTZ2*	7.5 m steel mast with concrete block foundation of 1 m depth*	68.65	-2.61
WTZ3*	same as wtz2*	68.65	-2.61
WTZS*	same as wtz2*	68.65	-2.61
WTZA	steel plate on concrete survey tower (building)	3.06	-0.17
WTZR	steel plate on concrete survey tower (building)	0	0
WTZZ	steel plate on concrete survey tower (building)	1.59	-0.15

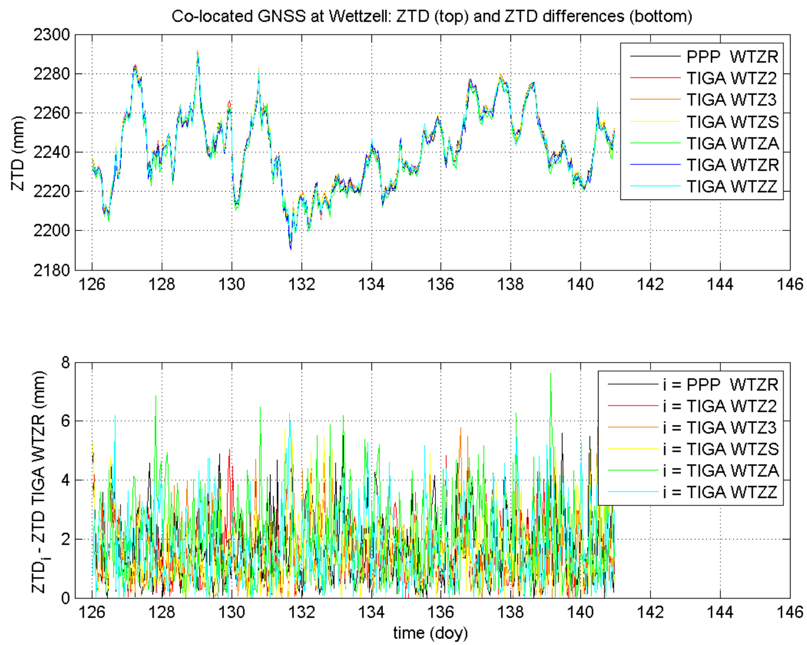
Table 2 GNSS antennas and recievers during the CONT14 campaign at Wettzell, Germany. *The stations WTZ2, WTZ3, and WTZS are the same antenna feeding three different receivers.

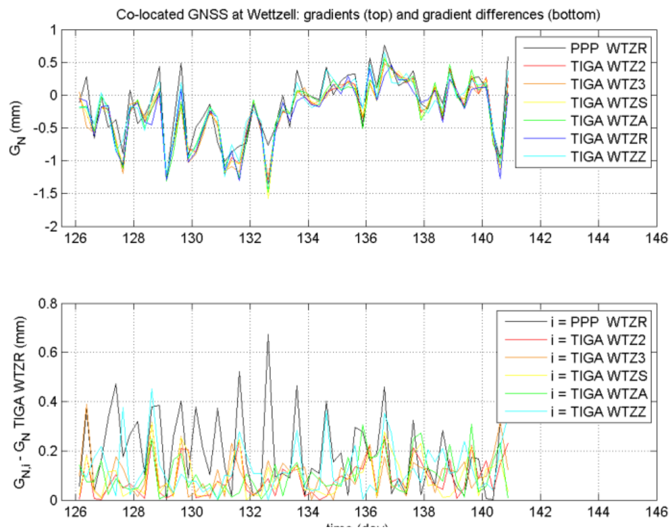
IGS name	antenna	dome	receiver
WTZ2*	LEIAR25.R3*	LEIT*	LEICA GR25
WTZ3*	LEIAR25.R3*	LEIT*	JAVAD TRE_G3TH DELTA
WTZS*	LEIAR25.R3*	LEIT*	SEPT POLAR X2
WTZA	ASH700936C_M	SNOW	ASHTECH Z-XII3T
WTZR	LEIAR25.R3	LEIT	LEICA GR25
WTZZ	LEIAR25.R3	LEIT	JAVAD TRE_G3TH DELTA

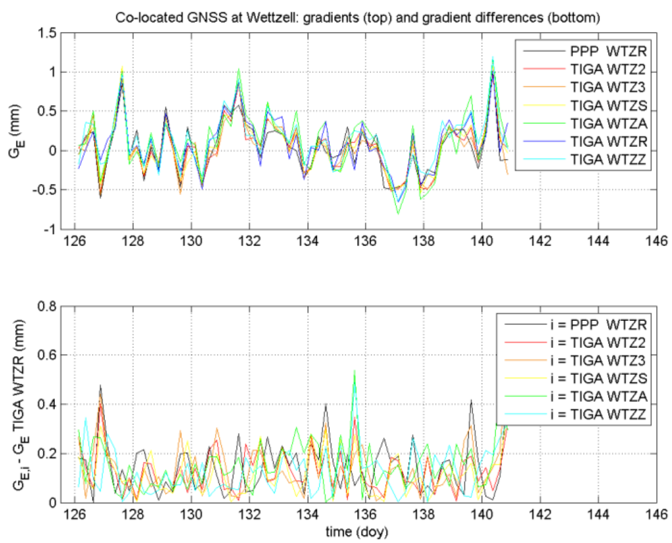


Comparison of atmospheric parameters

Example: co-located GNSS at Wettzell







Comparison of atmospheric parameters

Example: co-located GNSS at various European sites (EUREF)

- Largest mean difference (~ 1 cm), where antenna is covered by radome
- Larger mean differences (> 5 mm), where ΔH rel. large
- Larger scatter ($> 1\ cm$), where horizontal distance $\Delta d > 50$ km

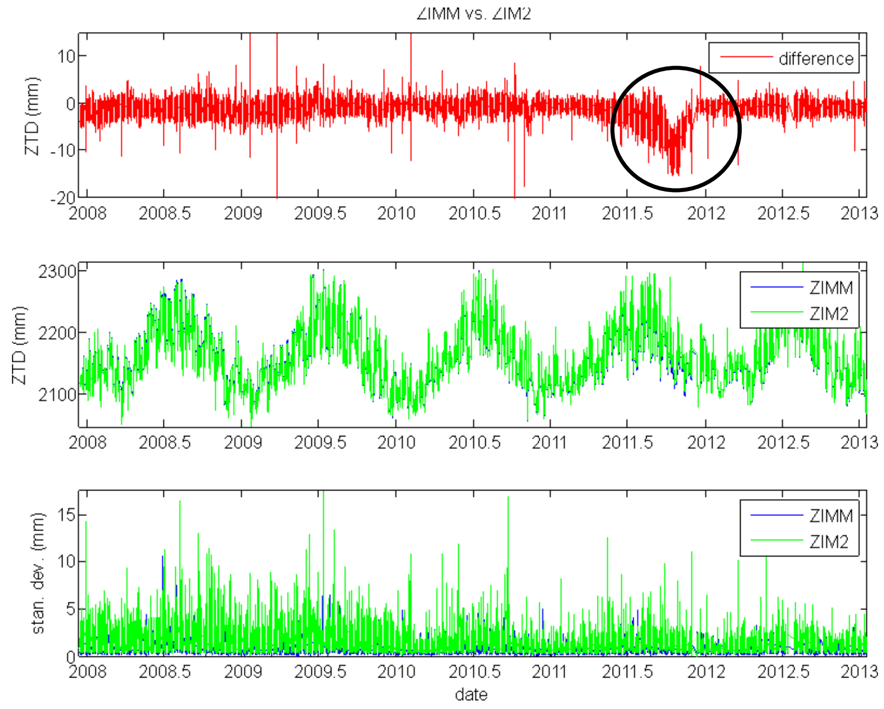
Horizontal distance
$\Delta d \Rightarrow$ larger scatter

GNSS (1)	GNSS (2)	from - to EUREF reprocessing routine operation	mean difference (mm)	standard deviation (mm)	comments
BOGI	BOGO	2001-11-23 - 2006-12-28 2002-09-20 - 2013-01-18	-0.5 -0.1	3.1 3.7	-4.3 mm (i)
BORJ	BORK	2005-06-08 - 2006-12-28 2006-12-22 - 2007-06-03	-1.8 -1.6	2.8 1.5	
HERS	HERT	2003-03-17 - 2006-12-28 2003-08-15 - 2013-01-18	0.3 2.9	1.9 3.0	+2.9 mm (ii) +1.0 mm (i)
JOZ2	JOZE	2002-10-22 - 2006-12-28 2003-09-12 - 2013-01-18	-3.9 -2.6	4.0 4.3	-6.2 mm (ii) -4.1 mm (i)
MATE	TARS	2004-11-27 - 2005-04-12 2004-12-18 - 2005-04-12	-2.4 -9.7	8.6 8.8	d=51 km, dH=408 m
MOP2	MOPI	2008-08-16 - 2013-01-18	10.8	5.1	 
MEDI	MSEL	2004-09-06 - 2006-12-28 2004-10-09 - 2013-01-18	-3.2 -4.0	2.9 8.6	
NYA1	NYAL	1999-09-07 - 2006-12-28	0.1	1.6	
ONSA	SPT0	2001-09-04 - 2006-12-28 2002-07-05 - 2013-01-18	-6.0 -6.3	10.3 10.6	d=68 km, dH=147 m
SVTL	PULK	2008-05-17 - 2013-01-18	3.1	13.5	d=90 km, dH=24.5 m
TLMF	TLSE	2002-06-17 - 2006-12-28 2010-03-26 - 2013-01-18	-1.8 -4.2	4.6 2.6	-3.6 mm (ii)
TRO1	TROM	1999-08-30 - 2006-12-28	-1.9	1.9	
YEBE	VILL	2000-09-29 - 2006-12-28 2001-05-27 - 2013-01-18	-7.5 -9.0	11.4 12.4	d=74 km, dH=325 m
WTZR	WETT	1996-01-06 - 1997-02.01	-2.9	11.0	
ZIM2	ZIMM	2007-12-14 - 2013-01-18	-1.3	2.0	+3.5 mm (ii)

Comparison of atmospheric parameters

Example: co-located GNSS at Zimmerwald (Switzerland)

- systematic difference caused by change of pre-amplifier of ZIMM antenna



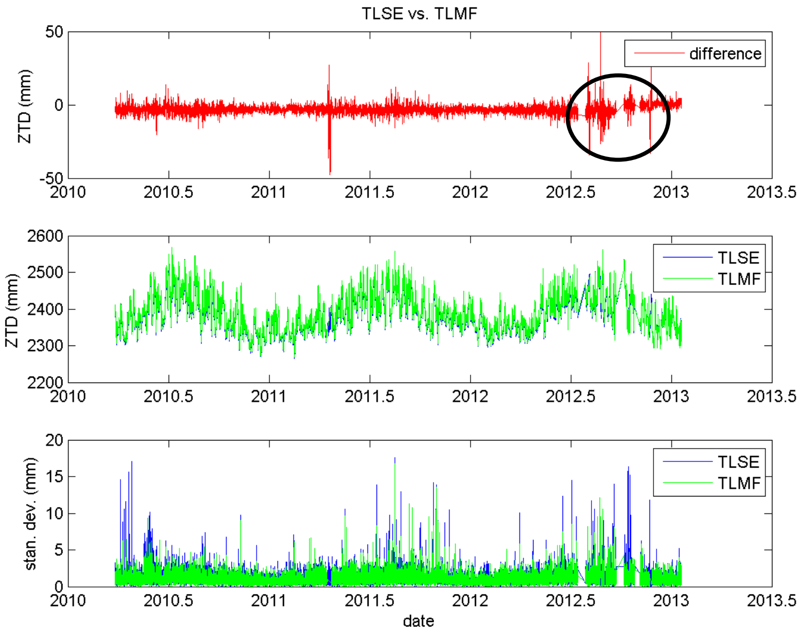
reference: http://www.euref-iag.net/symposia/2012Paris/06-26-p-Switzerland.pdf

Comparison of atmospheric parameters

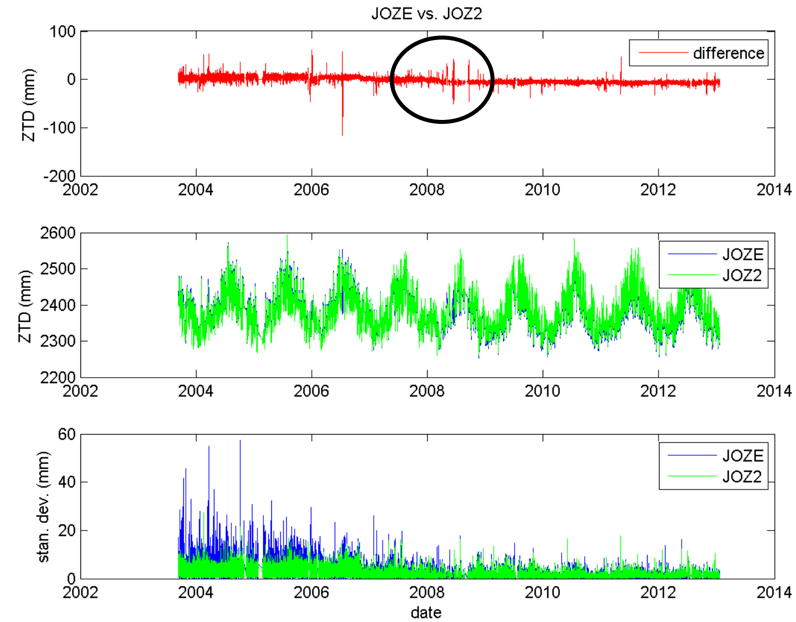
Example: co-located GNSS at two European sites (Toulouse, Jozefoslaw)

- systematic differences caused by antenna and radome change
- receiver change seems to cause no significant systematic difference

TLMF 10003M010 2008 09 03 LEIAT504GG
TLMF 10003M010 2012 09 28 TRM57971.00



JOZ2 12204M002 2002 01 03 ASH701941.B
JOZ2 12204M002 2008 03 14 LEIAT504GG



GFZ
Helmholtz-Zentrum
Potsdam

HELMHOLTZ
GEMEINSCHAFT

Comparison of atmospheric parameters

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Comparison of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

$ZHD = ZHD(H)$: Davis et al. (1985) based on Saastamoinen

$$ZHD = \frac{(0.0022768 \pm 0.0000005)\cdot p}{1 - 0.00266\cdot\cos(2B) - 0.00028\cdot H}$$

→ $p = p(H)$ significant

↓ $B \neq B(H)$

↘ H [km] negligible

$$p = p_0 \cdot \left(1 - \frac{\gamma(H - H_0)}{T_0}\right)^{\frac{g}{R_L \gamma}}$$

$\gamma = -0.0065\ \mathrm{K}\cdot\mathrm{m}^{-1}$ average lapse rate

$R_L \approx 287.058\ \mathrm{m}^2\cdot\mathrm{s}^{-2}\cdot\mathrm{K}^{-1}$ specific gas constant

Tie: ΔZHD due to air pressure difference by analytical equation :

$$\Delta ZHD = ZHD(p_0) - ZHD(p)$$ ✓

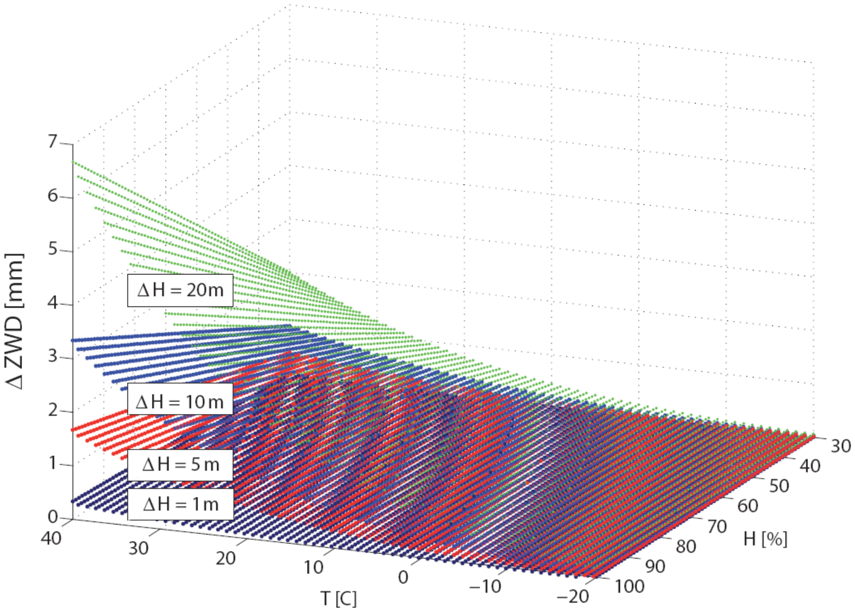
Comparison of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)ZHD + m_{trp,w}(z)ZWD + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

$ZWD = ZWD(e,T)$: Saastamoinen (1972, 1973

$$ZWD = \frac{0.0022768 \cdot e \cdot (1255/T + 0.05)}{1 - 0.00266 \cdot \cos(2\phi) - 0.00028 \cdot H}$$

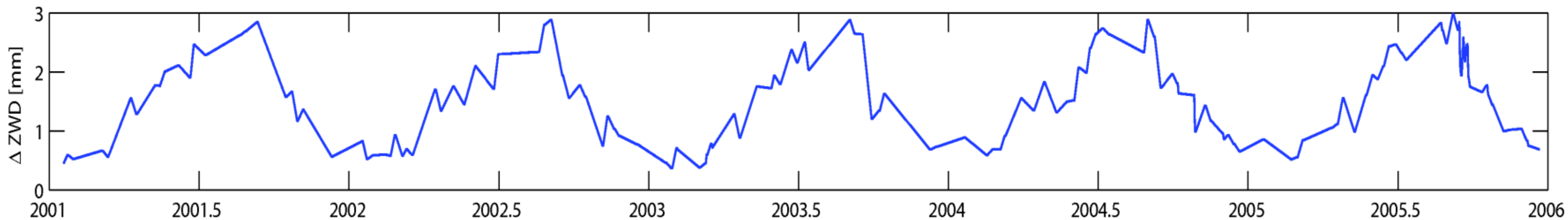
$$\Delta ZWD = ZWD(e_0, T_0) - ZWD(e, T)$$



$ZWD = ZWD(H)$: Brunner & Rüeger (1992)

$$\Delta ZWD = \frac{-2.789 \cdot e}{T^2}\left(\frac{5383}{T} - 0.7803\right)\gamma(\Delta H)$$

Tsukuba: $\Delta H = 17$ m (using in situ meteorology)



Comparison of atmospheric parameters

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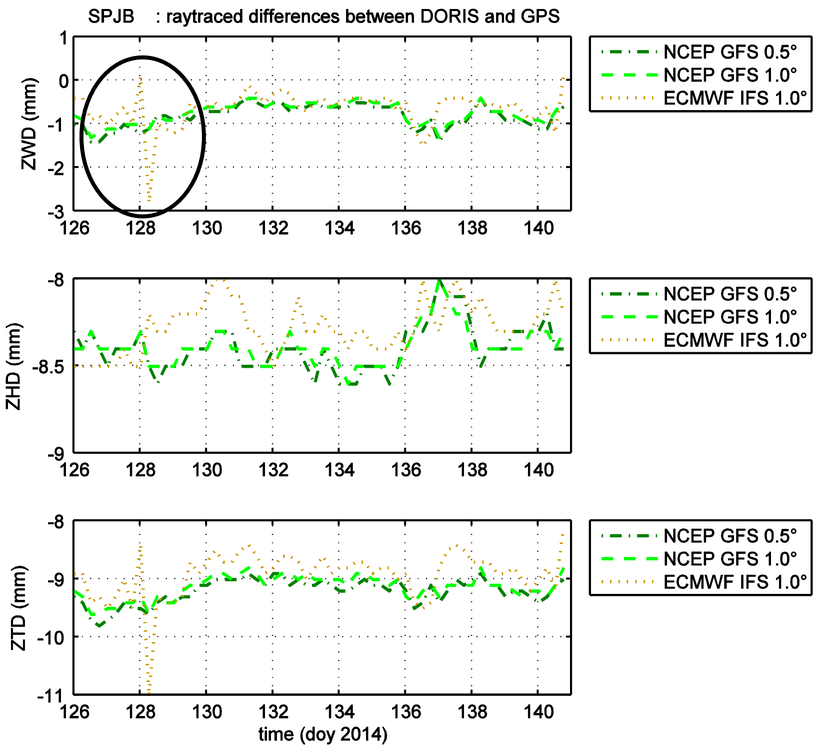
$ZWD = ZWD(H)$: more modern models available

e.g. Dousa & Elias, JGR (2014)

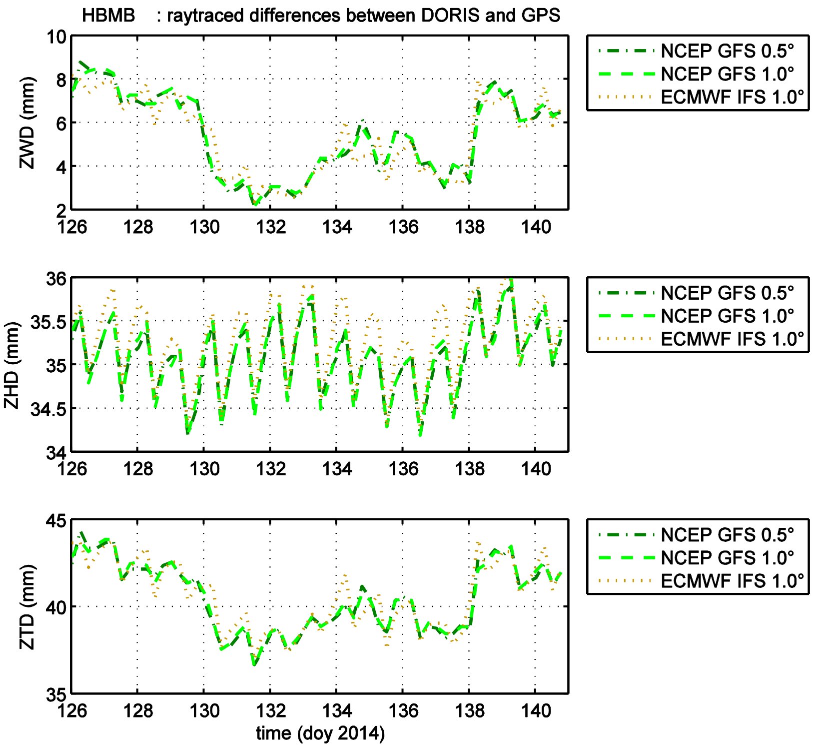
Comparison of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)\delta\rho^0_{trp,d} + m_{trp,w}(z)\delta\rho^0_{trp,w} + m_{grd}(z)[G_N \cos\alpha + G_E \sin\alpha]$$

ΔZTD: difference from numerical weather model (here during CONT14 by F. Zus)



$\Delta H = 28.68$ m

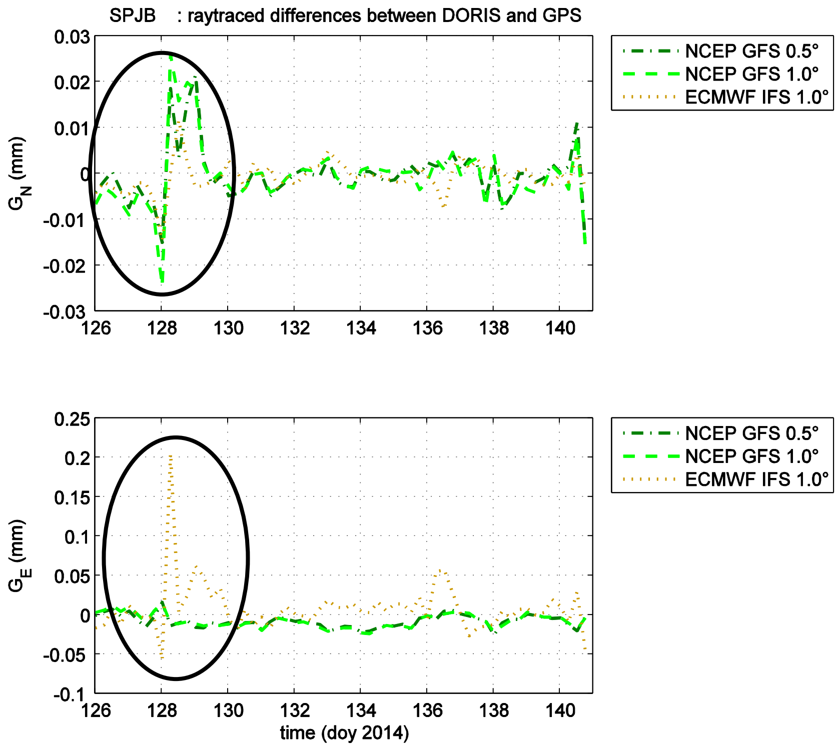


$\Delta H = -152.22$ m

Comparison of atmospheric parameters

$$\delta\rho_{trp}(z,\alpha) = m_{trp,d}(z)\delta\rho^0_{trp,d} + m_{trp,w}(z)\delta\rho^0_{trp,w} + m_{grd}(z)[G_N\cos\alpha + G_E\sin\alpha]$$

$\Delta G_{N,E}$: difference from numerical weather model (here during CONT14 by F. Zus)



Weather event occurs with a time delay at two stations separated by 1.75 km

$$\Delta d = 1747.7 \text{ m}$$

Comparison of atmospheric parameters

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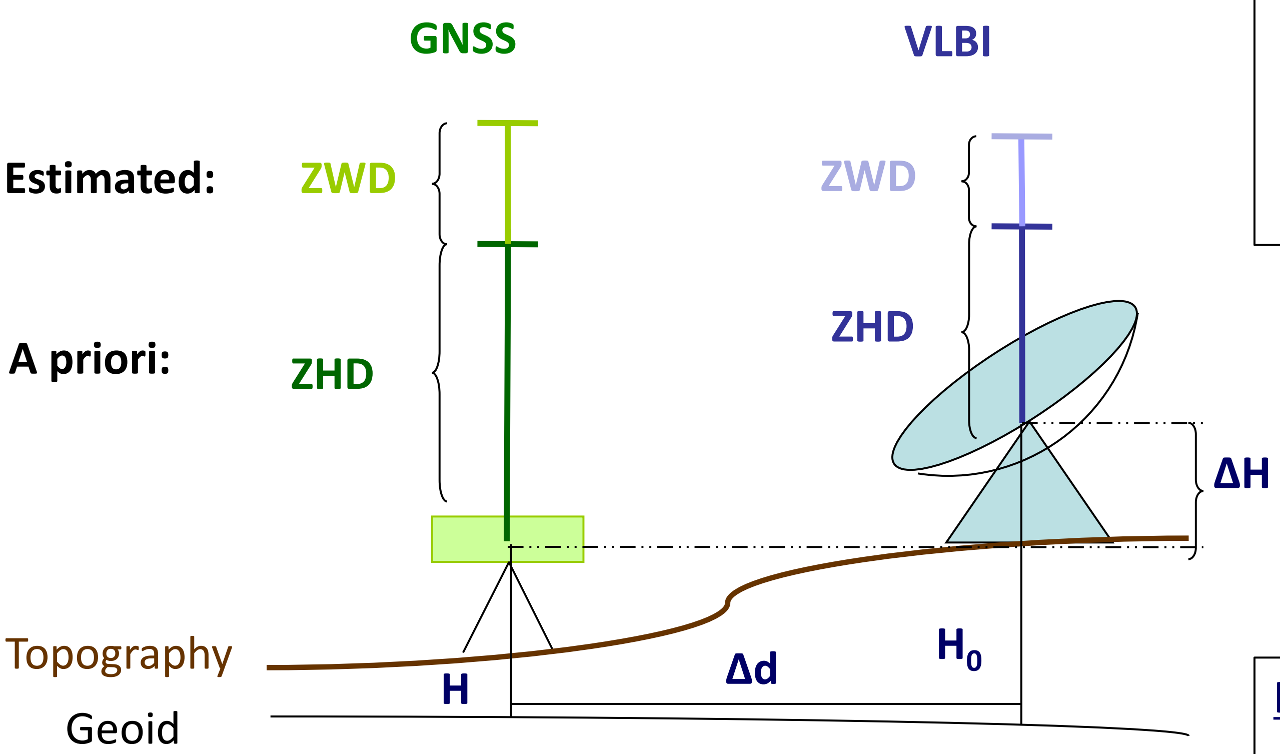
Comparison of atmospheric parameters

Example: co-located GNSS & VLBI



Vertical distance

$$\Delta H = H_0 - H$$

$$\Rightarrow$$

$$ZHD > ZHD$$

$$ZWD > ZWD$$

Horizontal distance

$$\Delta d \Rightarrow ?$$

Comparison of atmospheric parameters

Site	GPS	VLBI	ΔH (m)	Site	GPS	VLBI	ΔH (m)
Ny-Ålesund	NYAL	7331	8.83	Algonquin P.	ALGO	7282	23.11
	NYA1	7331	3.10	Fairbanks	FAIR	7225	13.09
Onsala	ONSA	7213	13.71	Kokee	KOKB	7298	9.23
Svetloe	SVTL	7380	9.36	Westford	WES2	7209	1.75
Medicina	MEDI	7230	17.15	Fort Davis	MDO1	7613	-398.08
Noto	NOT1	7547	16.89	Pietown	PIE1	7234	16.95
Matera	MATE	7243	7.72	North Liberty	NLIB	7612	15.22
Wettzell	WTZR	7224	3.10	Brewster	BREW	7614	11.88
Urumqi	URUM	7330	1174.37	Fortaleza	FORT	7297	3.63
Tsukuba	TSKB	7345	17.37	Concepcion	CONZ	7640	-9.76
Hartebeesth.	HRAO	7232	1.54	Hobart	HOB2	7242	24.03

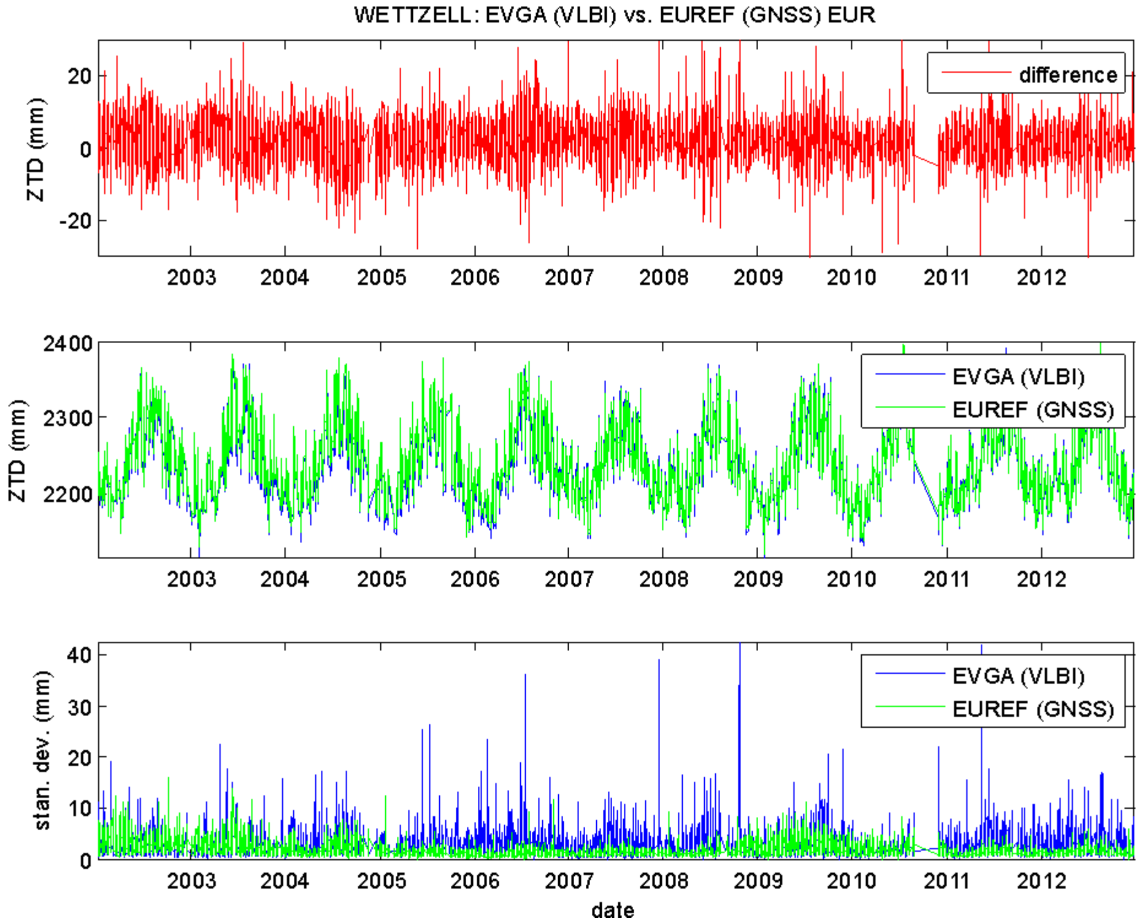
still co-location?

Comparison of atmospheric parameters

Site	GPS	VLBI	Δd (m)	Site	GPS	VLBI	Δd (m)
Ny-Ålesund	NYAL	7331		Algonquin P.	ALGO	7282	89.8
	NYA1	7331	97.5	Fairbanks	FAIR	7225	
Onsala	ONSA	7213	65.9	Kokee	KOKB	7298	
Svetloe	SVTL	7380		Westford	WES2	7209	
Medicina	MEDI	7230	45.6	Fort Davis	MDO1	7613	8020
Noto	NOT1	7547	54.8	Pietown	PIE1	7234	18
Matera	MATE	7243	60.9	North Liberty	NLIB	7612	
Wettzell	WTZR	7224	136.3	Brewster	BREW	7614	
Urumqi	URUM	7330		Fortaleza	FORT	7297	24.5
Tsukuba	TSKB	7345	285.7	Conception	CONZ	7640	
Hartebeesth.	HRAO	7232	162.3	Hobart	HOB2	7242	

still co-location?

Comparison of atmospheric parameters



differences slightly larger in summer

average formal error:
GNSS: 1.8 mm
VLBI: 2.4 mm

Comparison of atmospheric parameters

ZTD at EVGA (VLBI) - EUREF (GNSS) co-locations:

° : antenna is covered by a radome, *: antenna is covered by a snow dome

VLBI (EVGA)	GNSS (EUREF)	# change of antenna	mean diff. (mm)	mean standard deviations (mm) VLBI, GNSS, and VLBI vs. GNSS
MATERA	MATE	3	3.2	2.9, 3.4, 6.2
MEDICINA	MEDI	1	6.0	2.9, 2.7, 6.3
NYALES20	NYA1*	1	1.4	2.5, 1.0, 3.9
ONSALA60°	ONSA°	0	3.1	2.0, 1.2, 4.3
SVETLOE	SVTL°	2	1.3	2.7, 2.5, 6.3
WETTZELL	WTZR*	2	1.7	2.4, 1.8, 4.7
YEBES40M	YEBE	2	-4.0	2.4, 1.3, 5.8
ZELENCHK	ZECK*	2	1.3	3.2, 2.1, 6.7

Conclusion: mean diff. at GNSS-GNSS level, stdev about twice as large