GPS Meteorology with Single Frequency Receivers

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- **Ionospheric correction (SEID)**
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GPS Meteorology

GPS carrier phase observations (L1 & L2) :

$$L_i = \rho + c \cdot (dt_r - dt^s) - I_i + STD + \lambda_i \cdot N_i + \varepsilon$$

Tropospheric products:

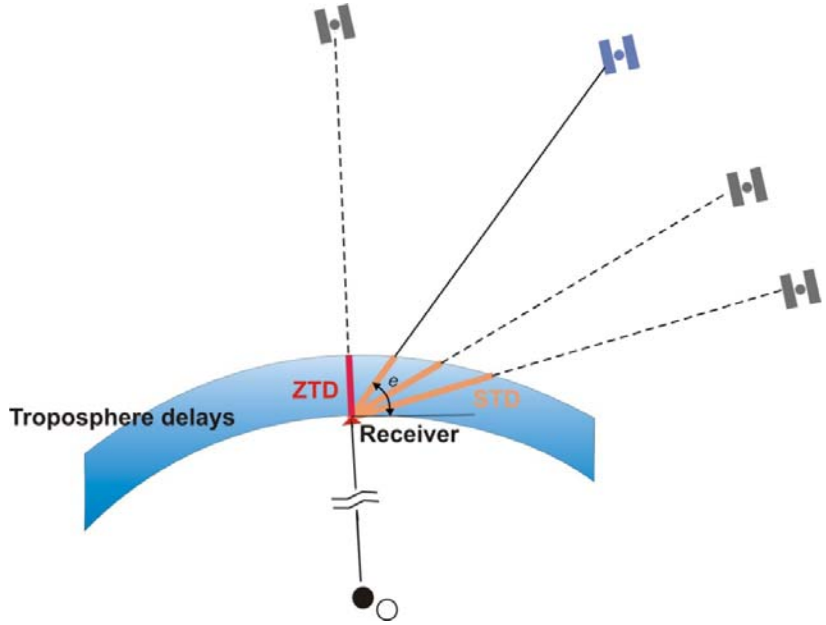
- Slant Total Delay (**STD**):

$$STD = SHD + SWD$$

- Zenith Total Delay (**ZTD**):

$$ZTD = ZHD + ZWD = \frac{SHD}{M_h(e)} + \frac{SWD}{M_w(e)}$$

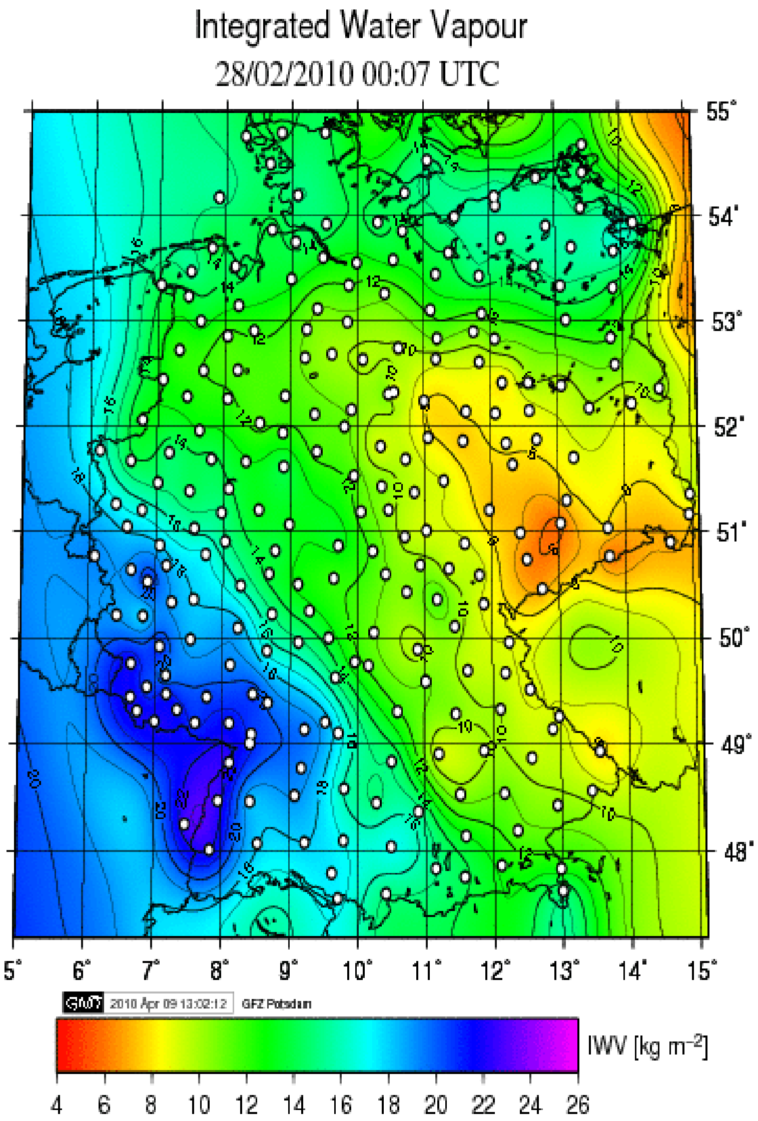
$M_h(e)$: dry Mapping-Function
$M_w(e)$: wet Mapping-Function



- Integrated Water Vapor (**IWV**):

$$IWV = \Pi(T_m) ZWD$$

GPS Meteorology



The accuracy of the GPS-IWV is ~ 1-2 kg m^{-2} (~ 6-13 mm in ZTD).

For regional and short-term forecasts, higher spatial resolution of ZTD/IWV is required. Due to economic reasons, this densification is recommended with single frequency (SF) receivers.

Ionospheric corrections (SEID)

The ionosphere delay is proportional to
Slant Total Electron Content *(STEC)*:

$$d_{ion} = -\varphi_{ion}\frac{c}{f} \approx 40.28\frac{STEC}{f^2}$$

- Ionosphere linear combination L_4 (***I*** is isolated) :

$$L_4 = L_1 - L_2 = \boxed{\lambda_1 N_1 - \lambda_2 N_2} - 40.28 \cdot STEC\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)$$

unknown

L_4 difference between two consecutive epochs i and $i+1$:

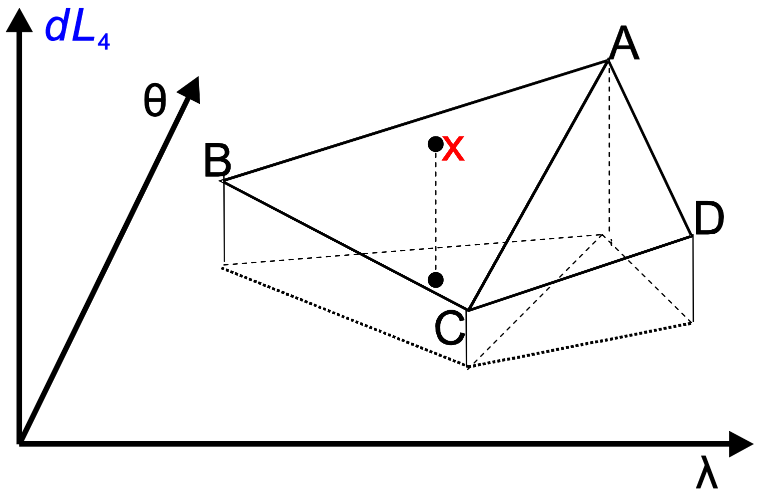
$$dL_4(i+1) = L_4(i+1) - L_4(i) = -40.28 \cdot dSTEC(i+1, i) \cdot \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)$$

Ionospheric corrections (SEID)

1. For a small area dL_4 can be fitted to a plane (on 350 km single layer):

$$dL_4 = a_0 + a_1\Delta\lambda + a_2\Delta\theta,$$

$$\Delta\lambda = \lambda - \bar{\lambda} \text{ and } \Delta\theta = \theta - \bar{\theta}$$



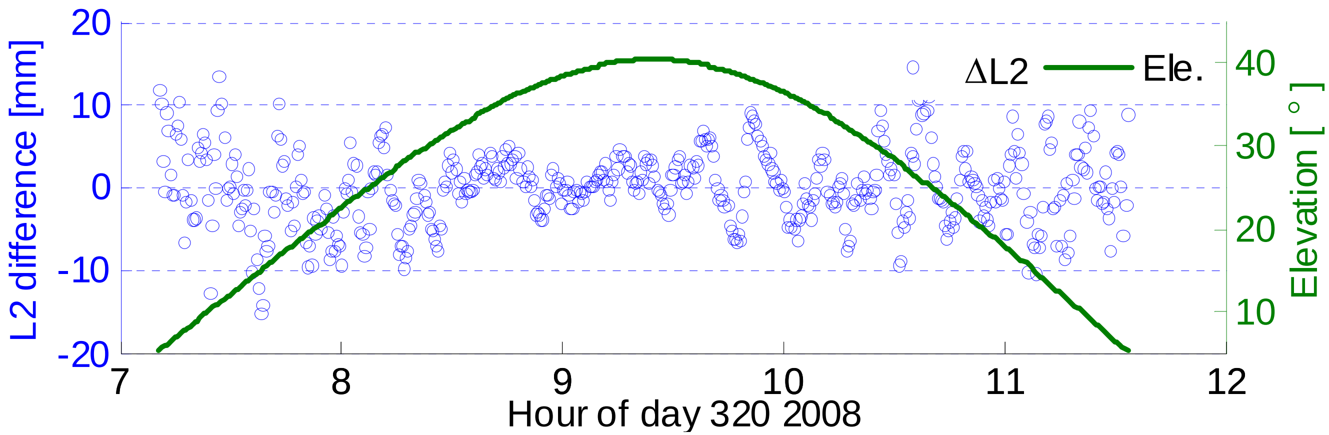
2. For a given SF-station **x**:

$$d\tilde{L}_{4,x} = \hat{a}_0 + \hat{a}_1\Delta\lambda_x + \hat{a}_2\Delta\theta_x$$

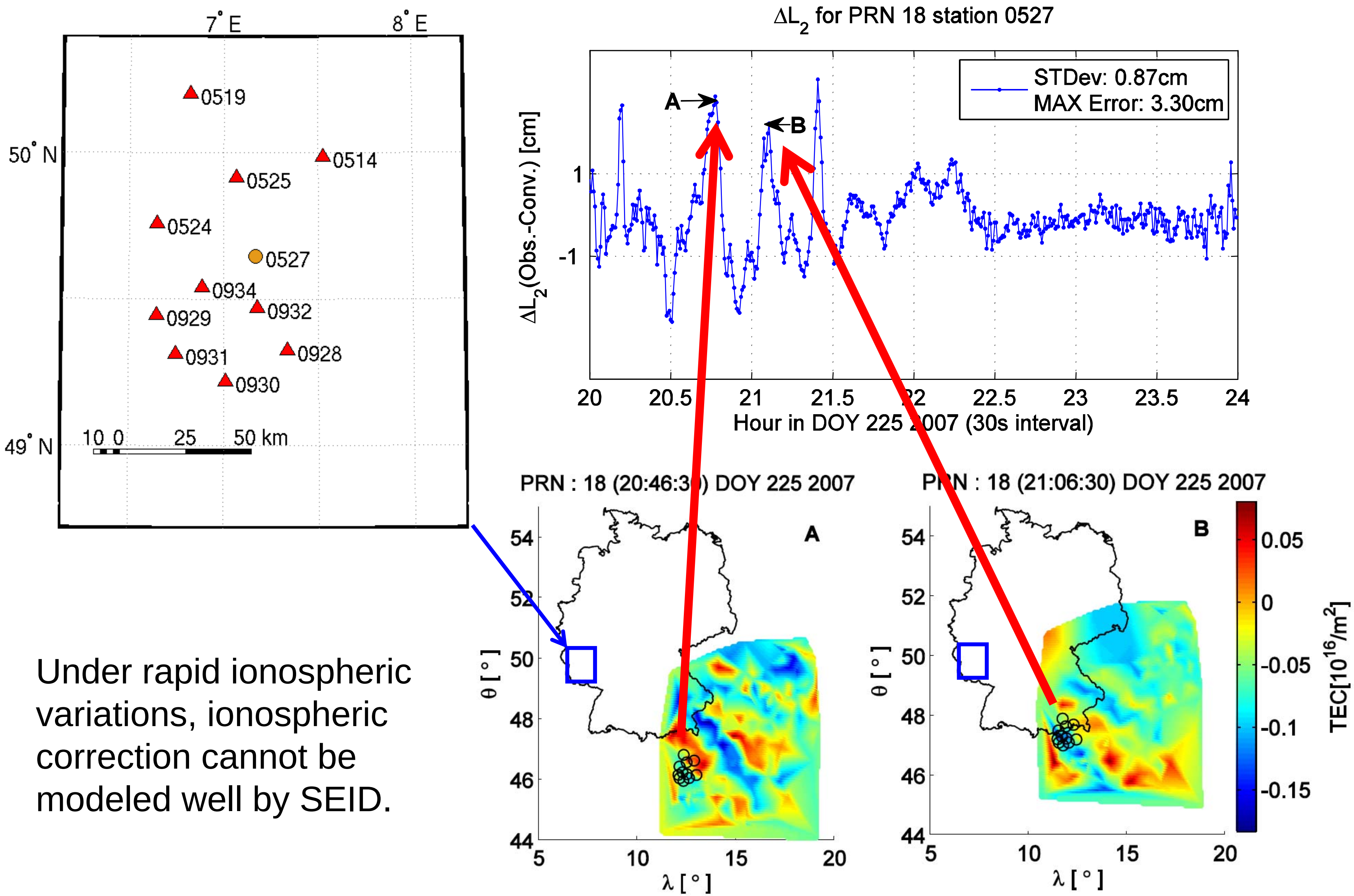
$$\tilde{L}_{4,x}(k) = \tilde{L}_{4,x}(i_0) + \sum_{i_0}^{k} d\tilde{L}_{4,x}(i)$$

3. For the SF-station **x** station the L_2 observations are generated.

$$\tilde{L}_{2,x} = L_{1,x} - \tilde{L}_{4,x}$$



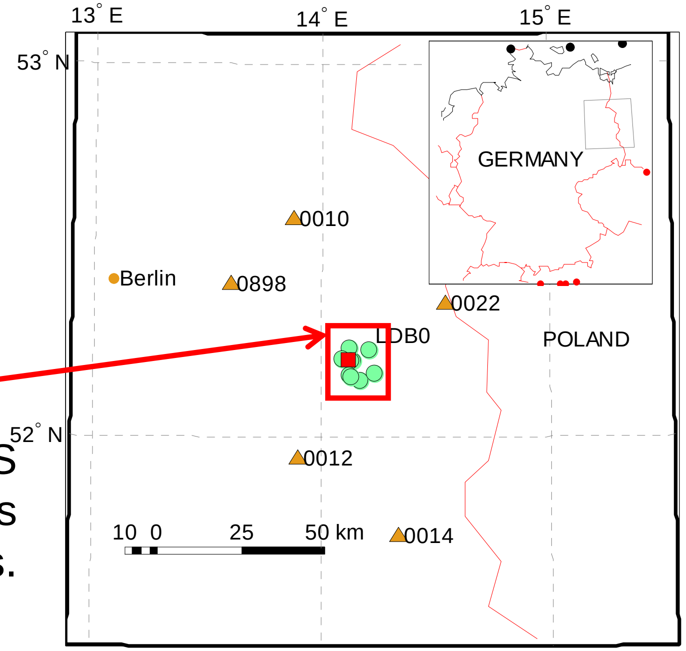
MSTID effect on SEID



Under rapid ionospheric variations, ionospheric correction cannot be modeled well by SEID.

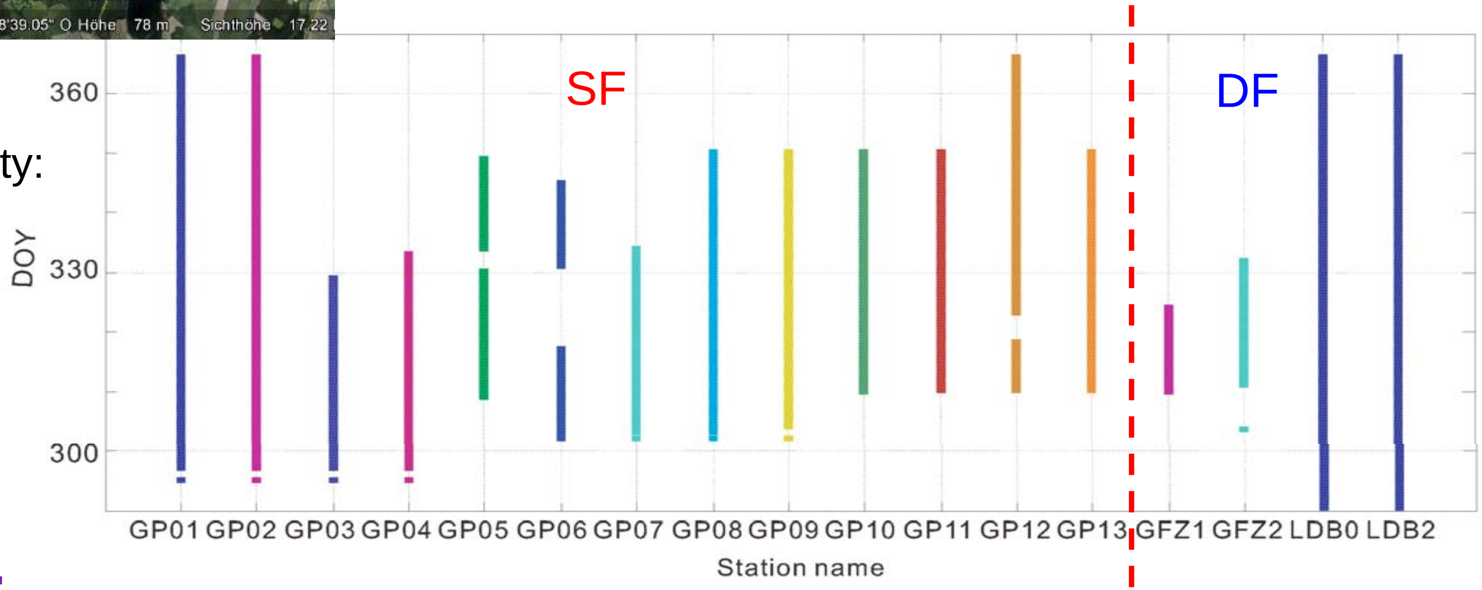
LUAMI campaign

13 SF stations and 2 DF stations for LUAMI campaign in 2008.

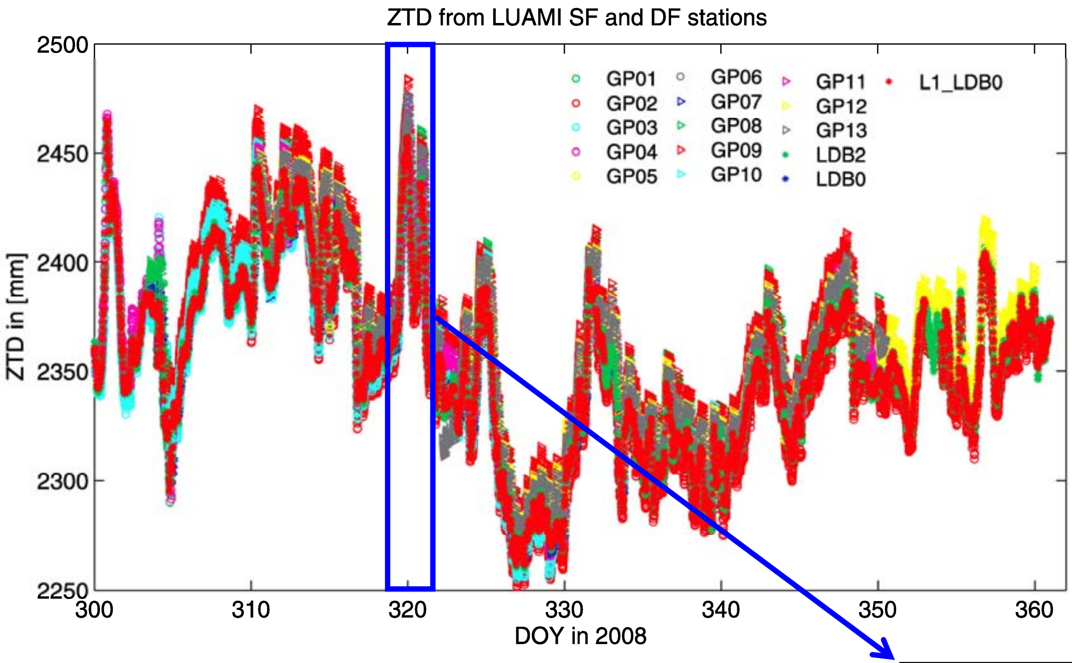


Five CORS stations serve as reference stations.

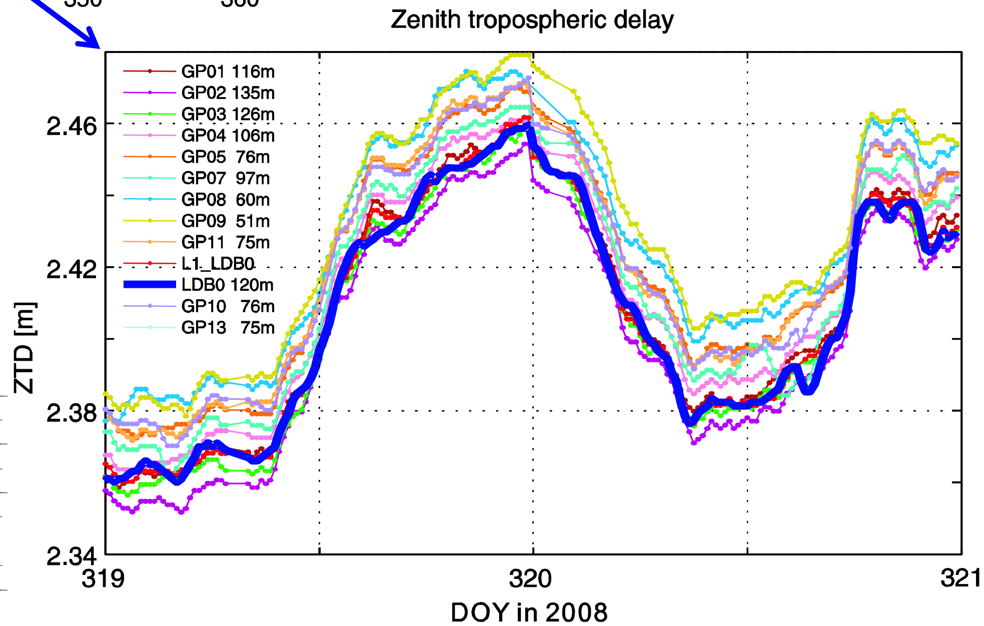
Data availability:



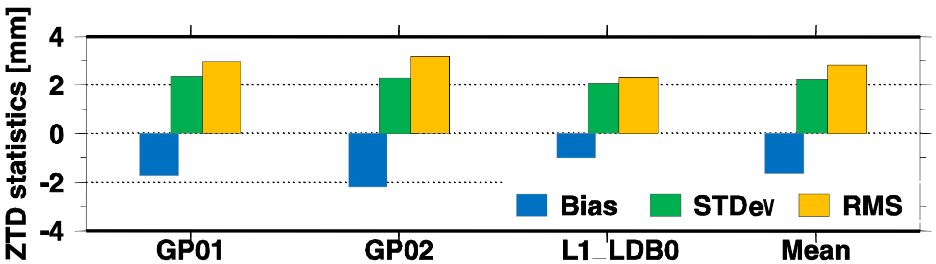
LUAMI: Comparison of ZTD: SF vs DF



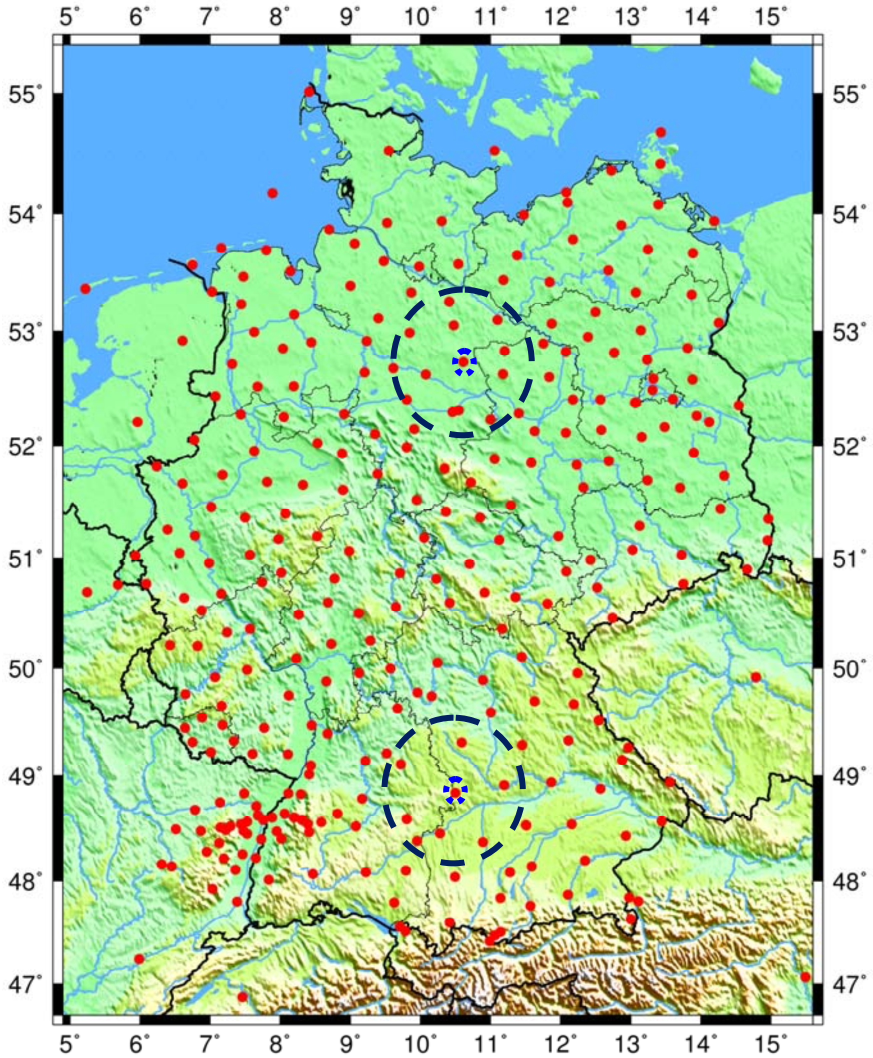
ZTDs are estimated using EPOS software in PPP mode.



Compare to DF result the ZTD RMS of the SF receivers is below 3 mm.



Densification of GPS network



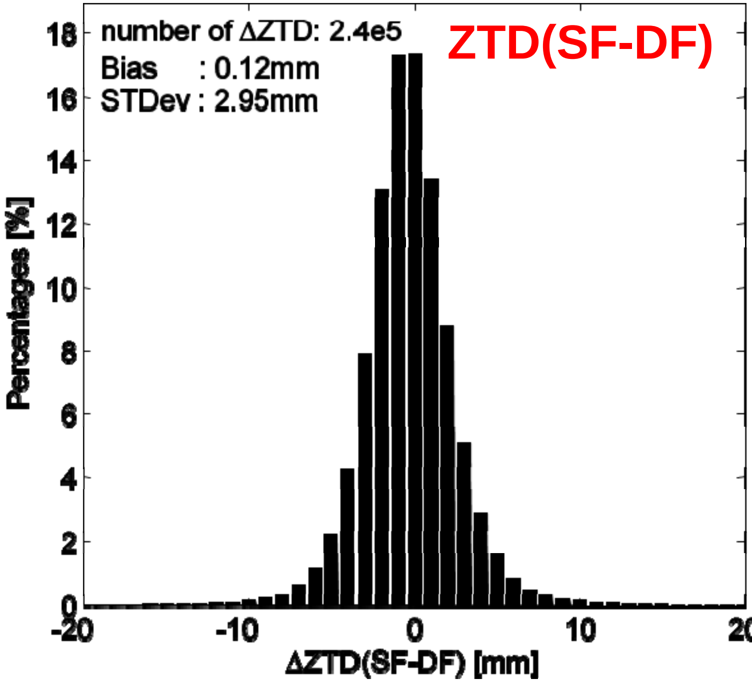
- **simulation study**

Each station regarded as a assumed SF station.

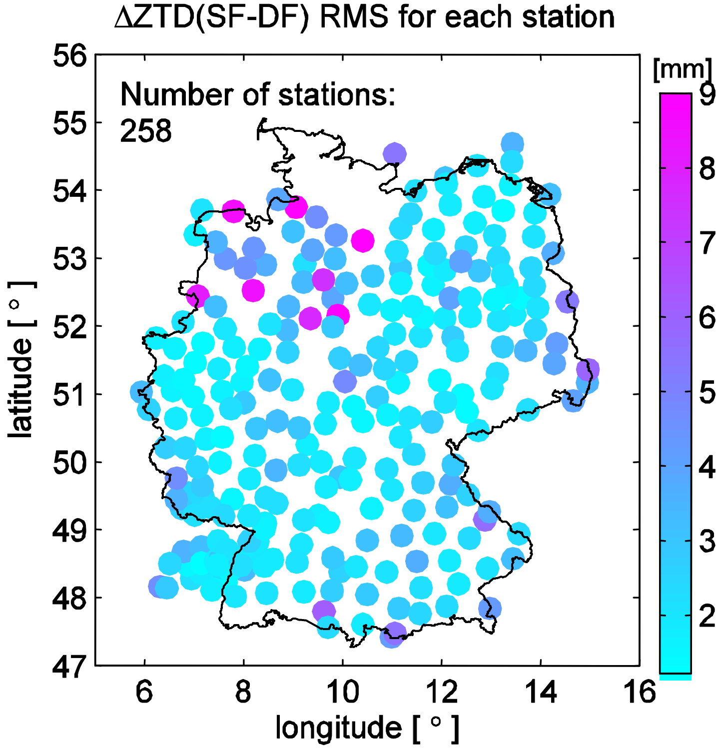
6-10 reference stations within a radius of 100km around the assumed SF station.

Data from DOY 220 to 230 in 2007 is analyzed.

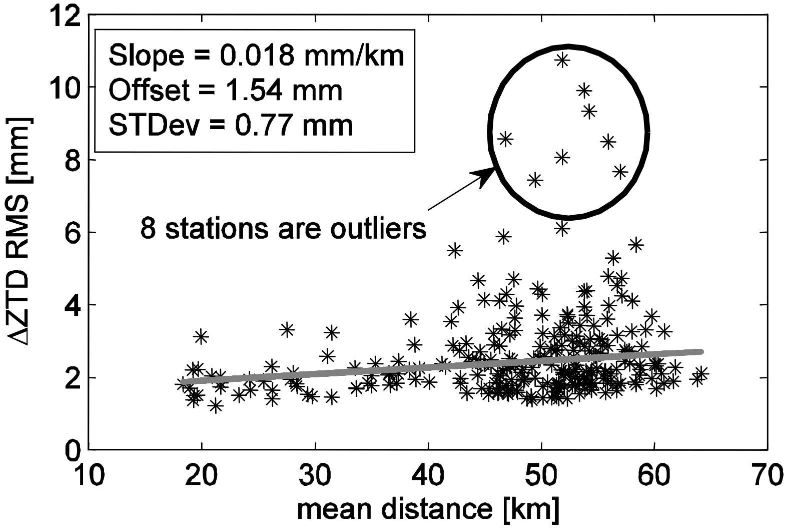
Comparison ZTD from SF and DF



1) Histogram of ΔZTD

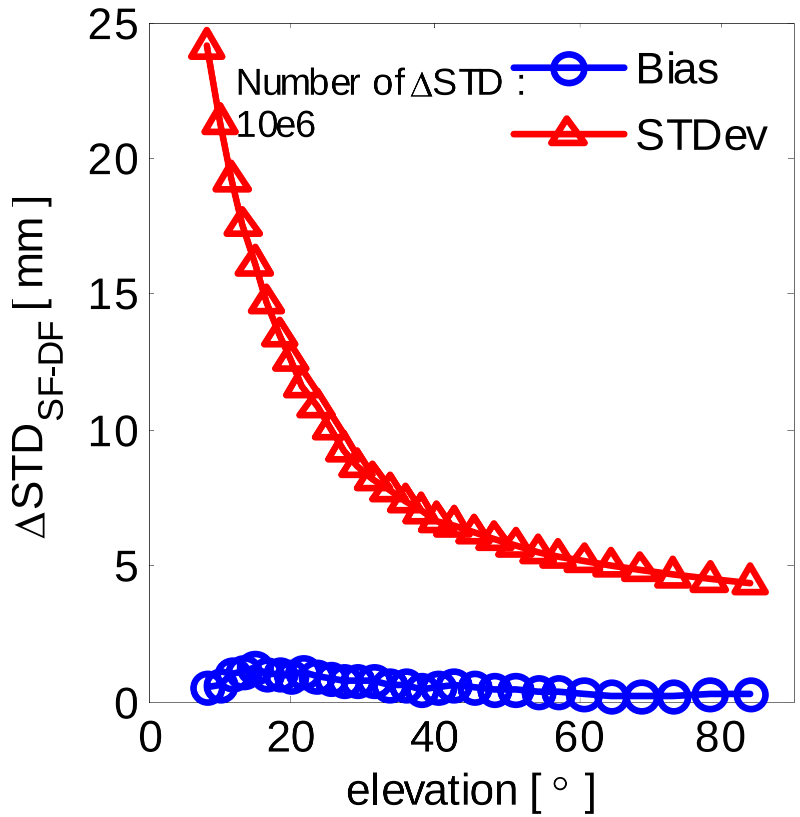


2) ΔZTD RMS for individual station



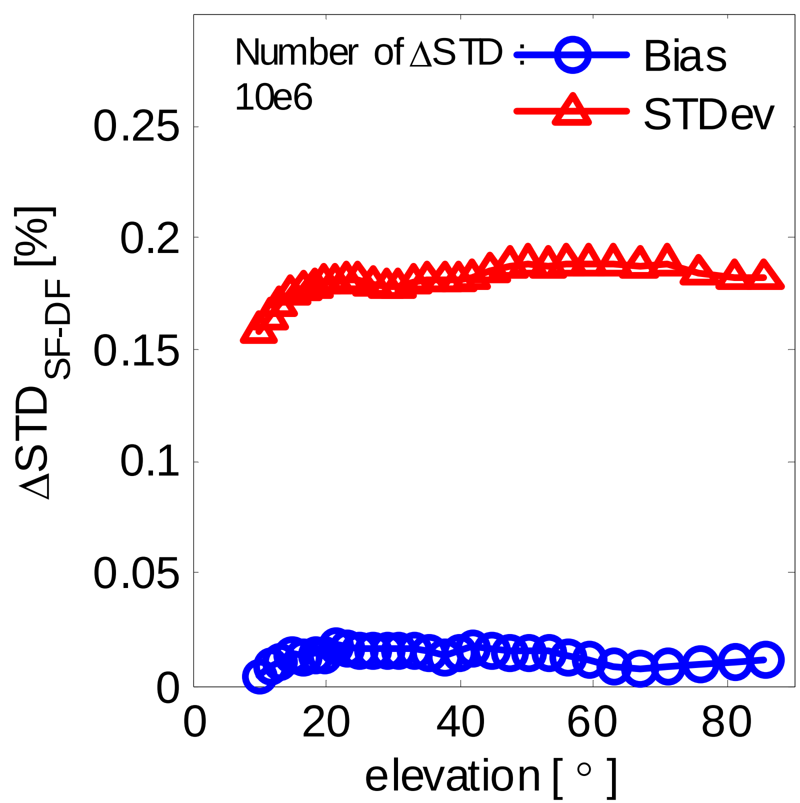
3) RMS of the ΔZTD VS the mean distance from the test station to the reference stations.

Comparison of STD from SF and DF



$$\Delta \mathrm{STD} = \mathrm{STD}_{SF} - \mathrm{STD}_{DF}$$

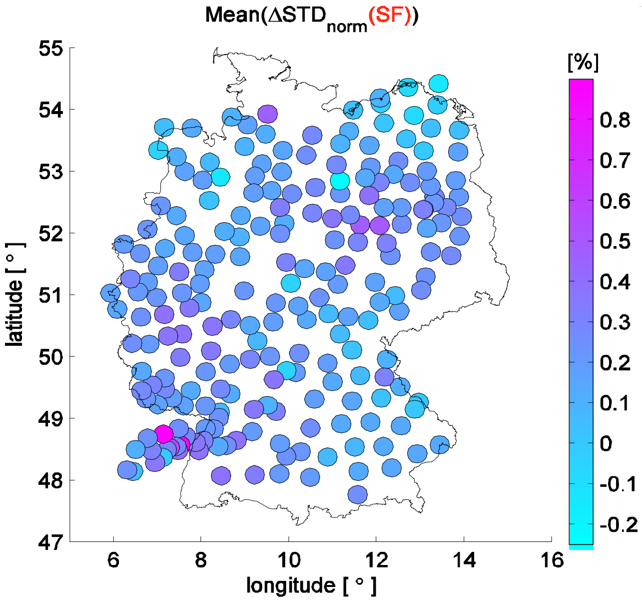
Absolute STD errors

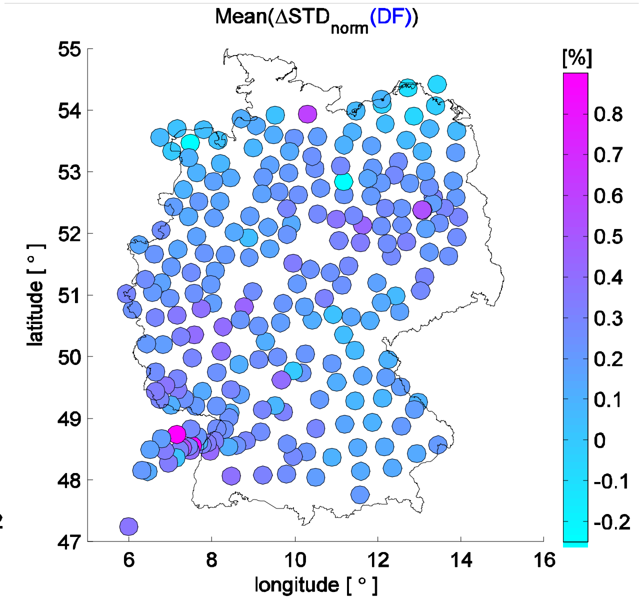


$$\Delta \mathrm{STD}_{rel} = \frac{\Delta \mathrm{STD}}{\mathrm{STD}_{DF}}$$

Relative STD errors

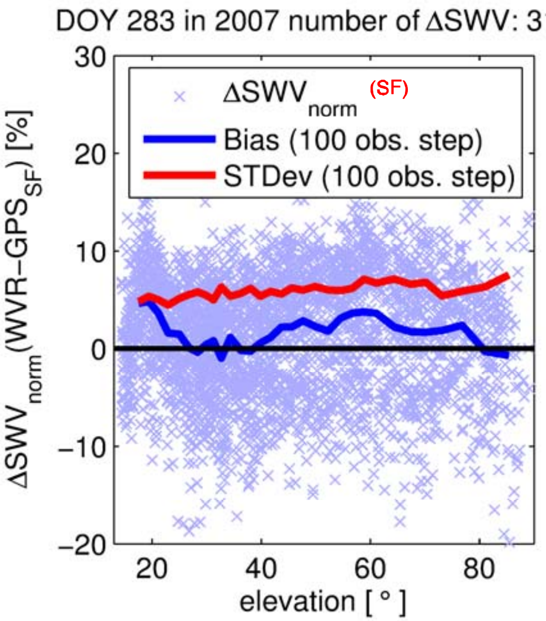
Comparison of STD with ECMWF and WVR

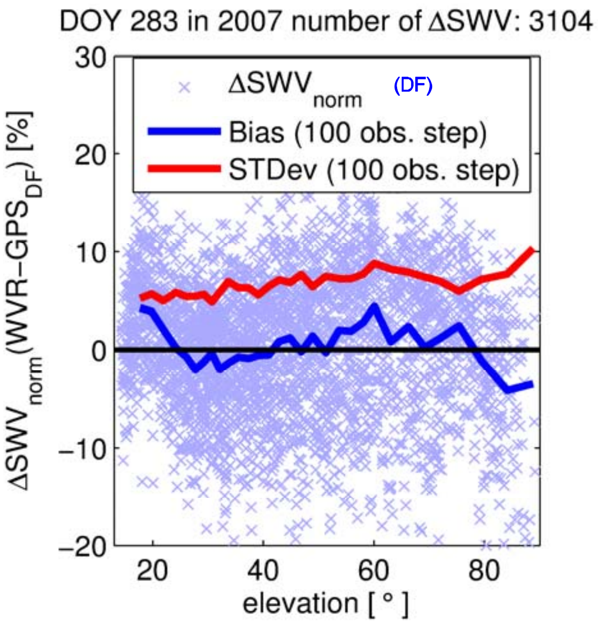




STDs are compared with ray-traced STDs through a numerical weather model (ECMWF) (Zus et al. 2012, Radio Science)

$$\Delta \mathrm{STD}_{rel} = \frac{\mathrm{STD}_{ECMWF} - \mathrm{STD}_{GPS}}{\mathrm{STD}_{ECMWF}}.$$





For one GPS-Station, collocated with a Water Vapor Radiometers (WVR), SWVs are validated.

$$\Delta \mathrm{SWV}_{rel} = \frac{\mathrm{SWV}_{WVR} - \mathrm{SWV}_{GPS}}{\mathrm{SWV}_{WVR}}.$$

Summary

- For densification the existing GPS DF networks with SF receivers the SEID (Satellite-specific Epoch-differenced Ionospheric Delay) was developed,.

- The LUAMI-campaign results shows that the ZTDs retrieved from the SF receivers show a RMS of 3 mm compared with those ZTDs from the DF receivers.

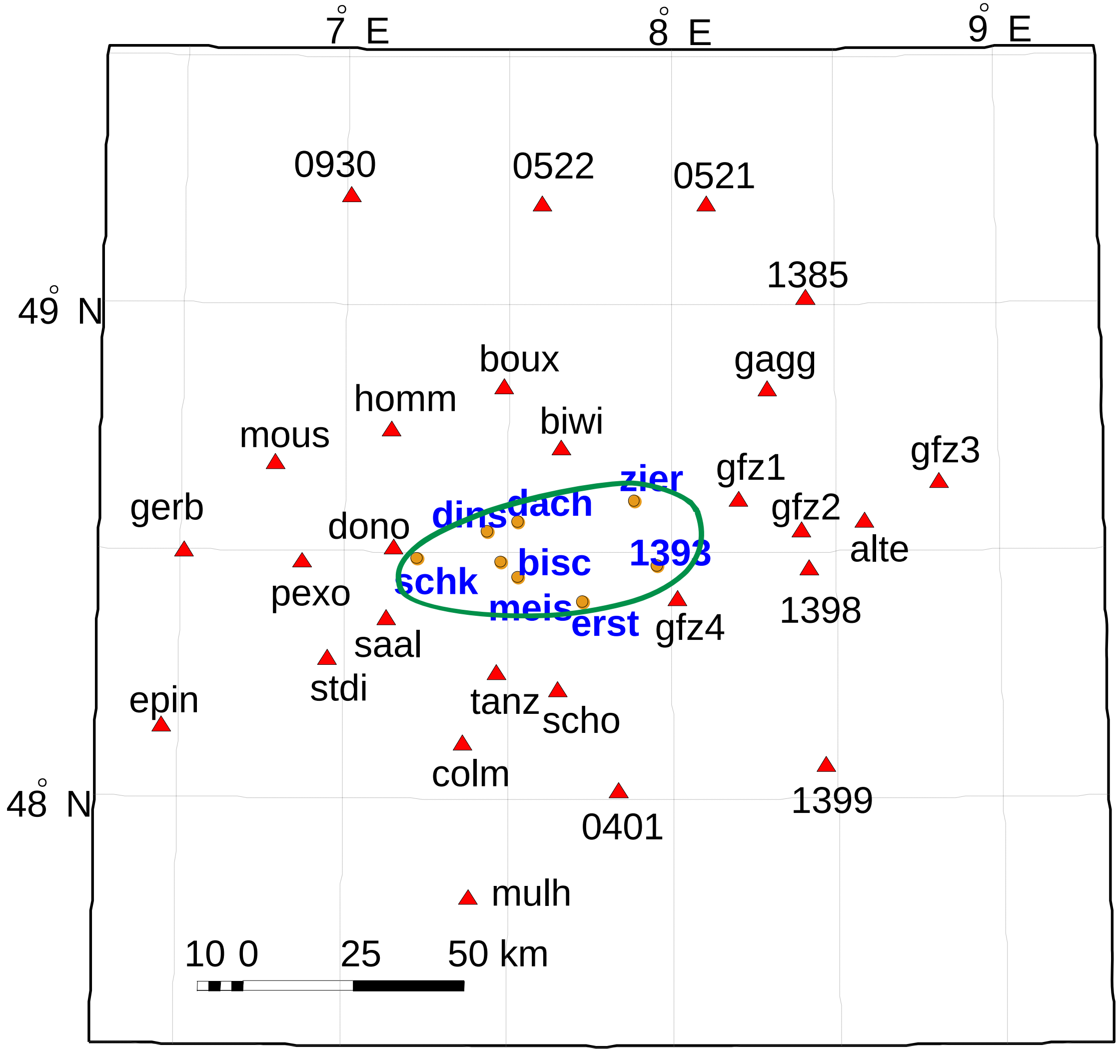
- In the simulation study the tropospheric products from the SF data were compared with those from DF-data, the observations of a WVR and the analyses of a numerical weather model (ECMWF).

- The validation studies showed that the quality of the SF data is fully sufficient for atmosphere sounding.

- The SEID method may speed up the densification of existing ground GPS networks with SF receivers.

Thank you!

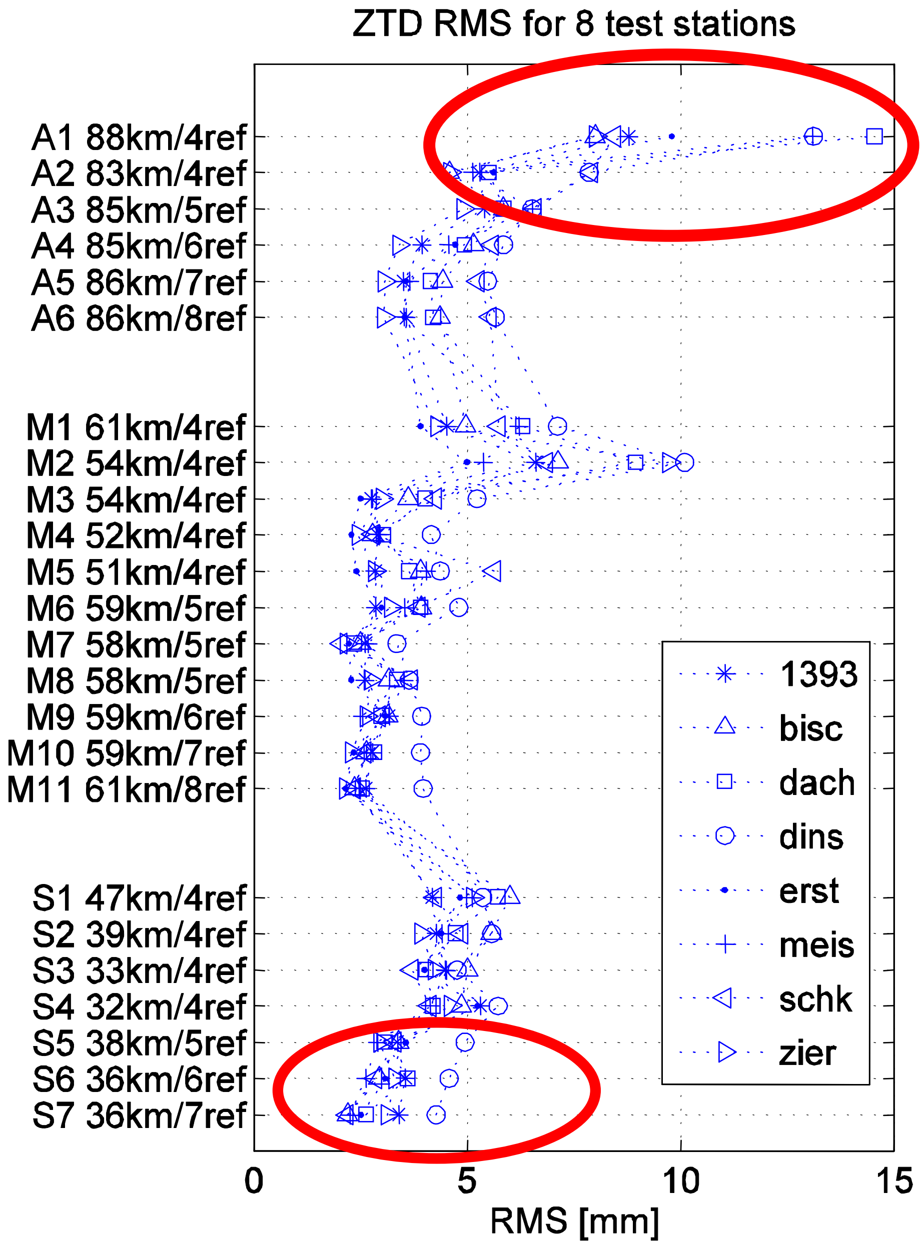
Densification Test



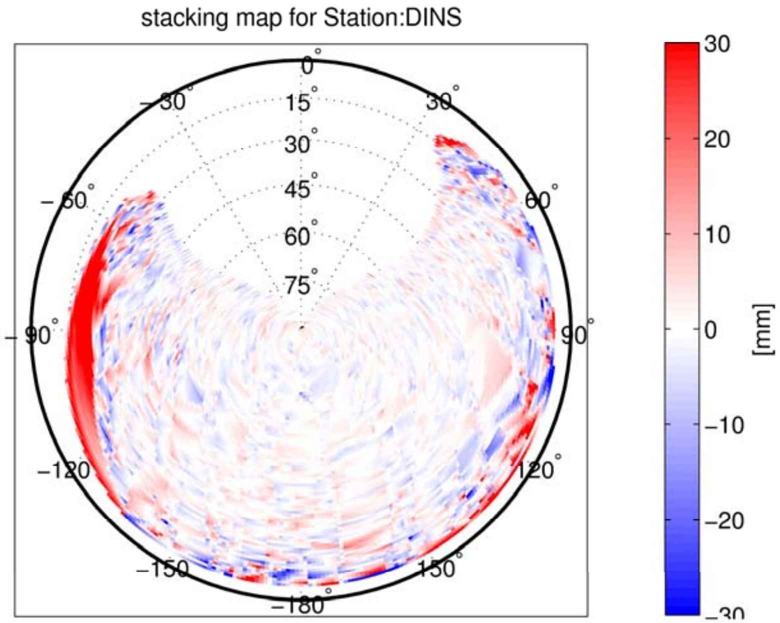
8 DF stations are assumed to be SF stations to simulate the densification.

24 densification scenarios with averaged reference station to test SF station separations from 33 to 87 km and the number of reference stations is from 4 to 8.

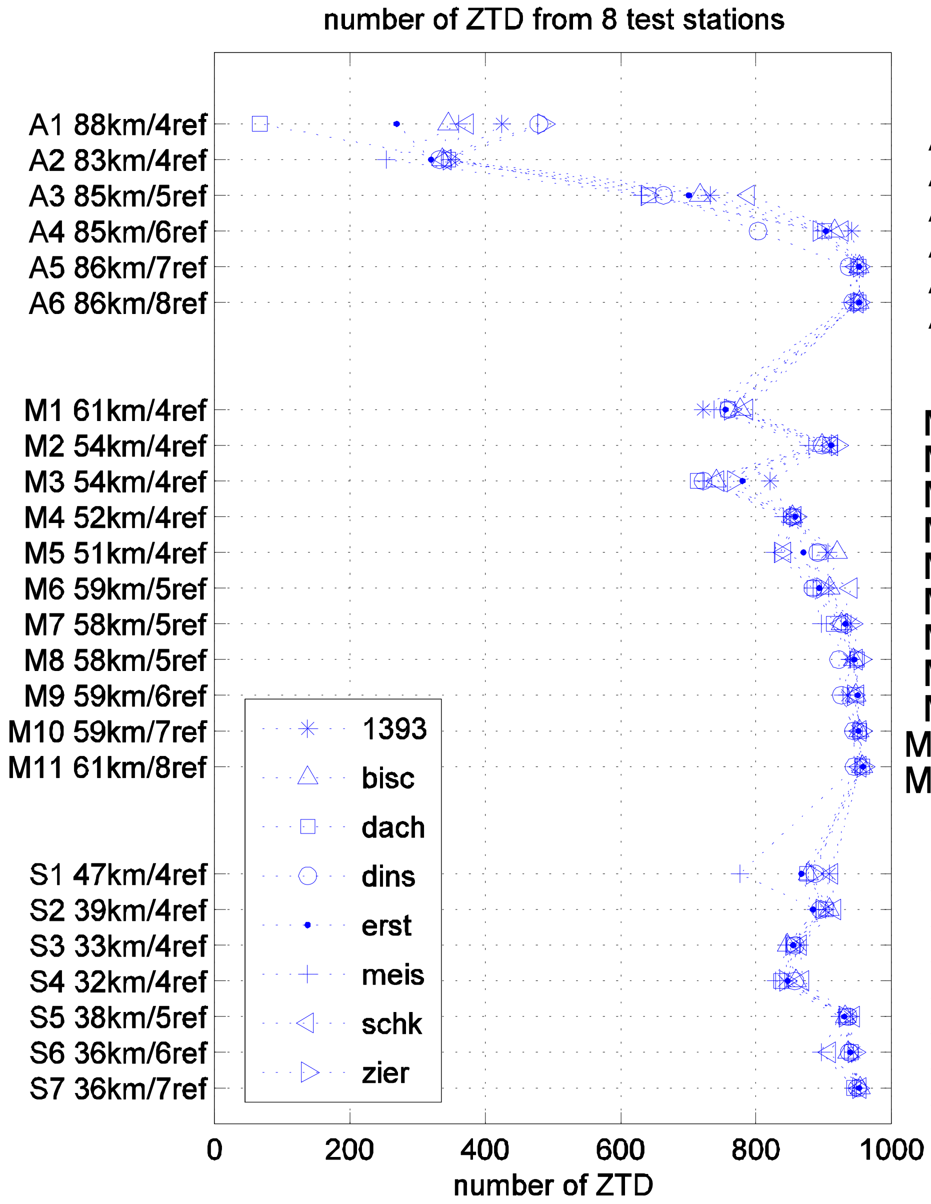
Densification Test

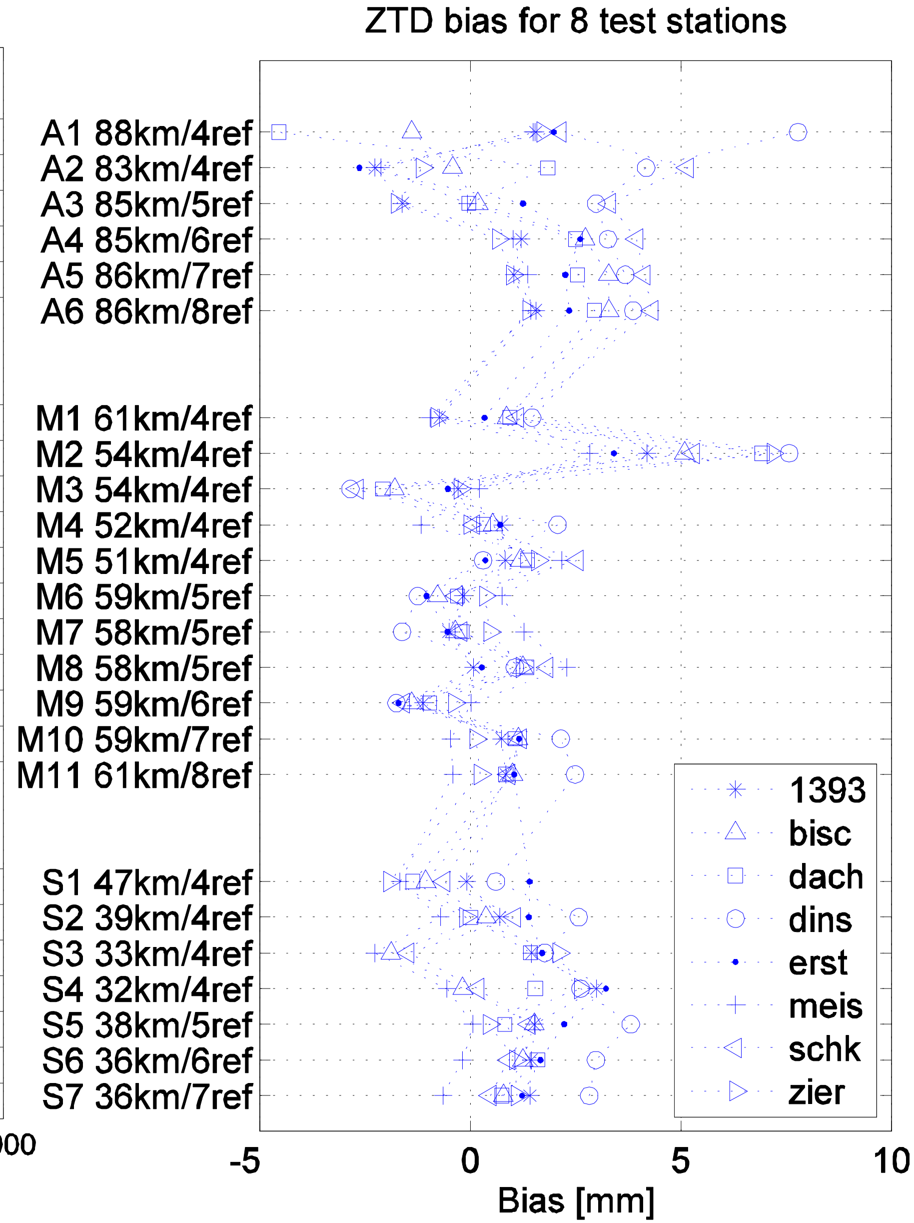


RMS of the ZTD differences between the DF and SF results for each test station in the 24 densification scenarios.

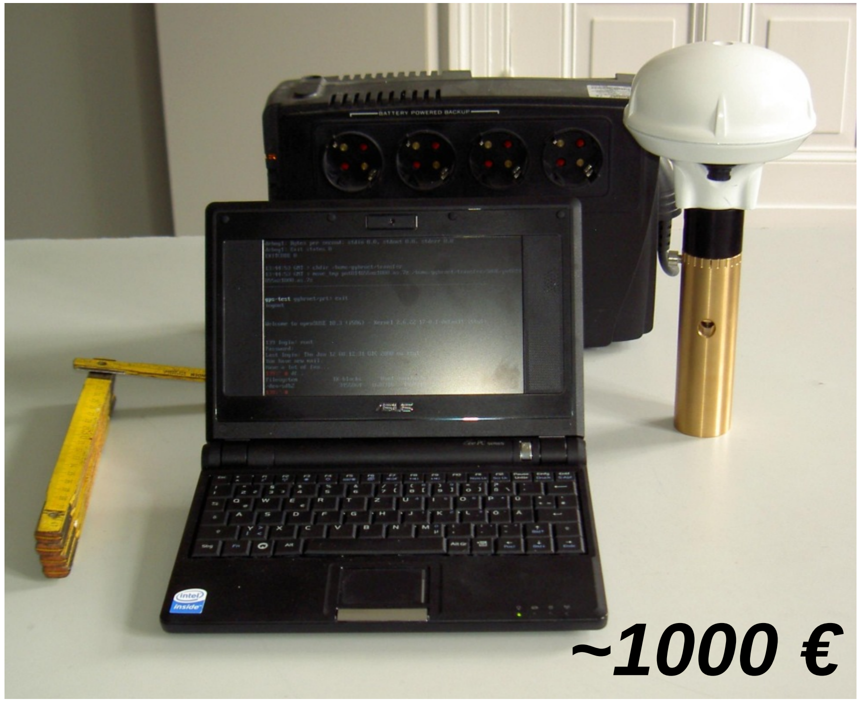


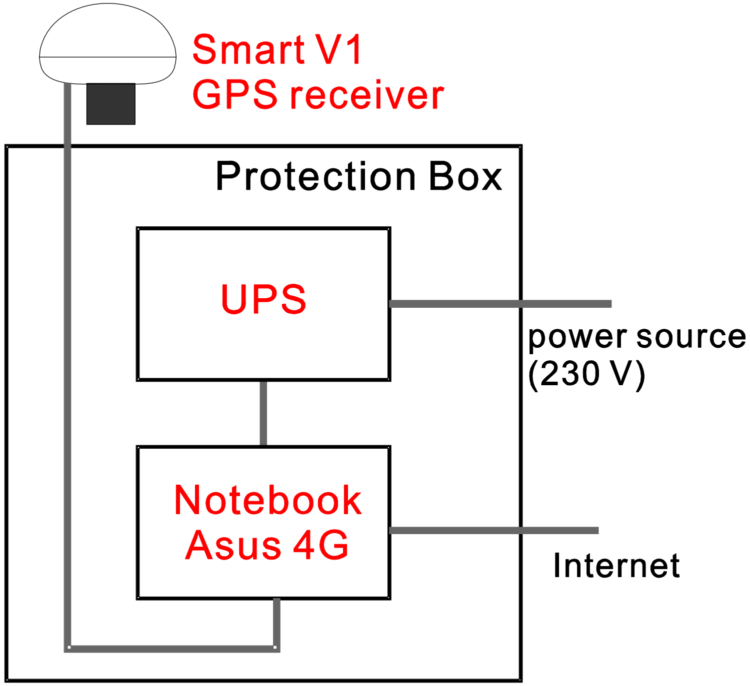
Densification Test





Single frequency GPS receiver





Number of channels	14 L_1-GPS
Receiver card	NovAtel's OEMV-1
Measurement precision (RMS)	C/A Code: 4 cm; Phase: 1.5 mm
Power consumption	1.2 W