TOMOREF operator for assimilation of GNSS tomography wet refractivity fields

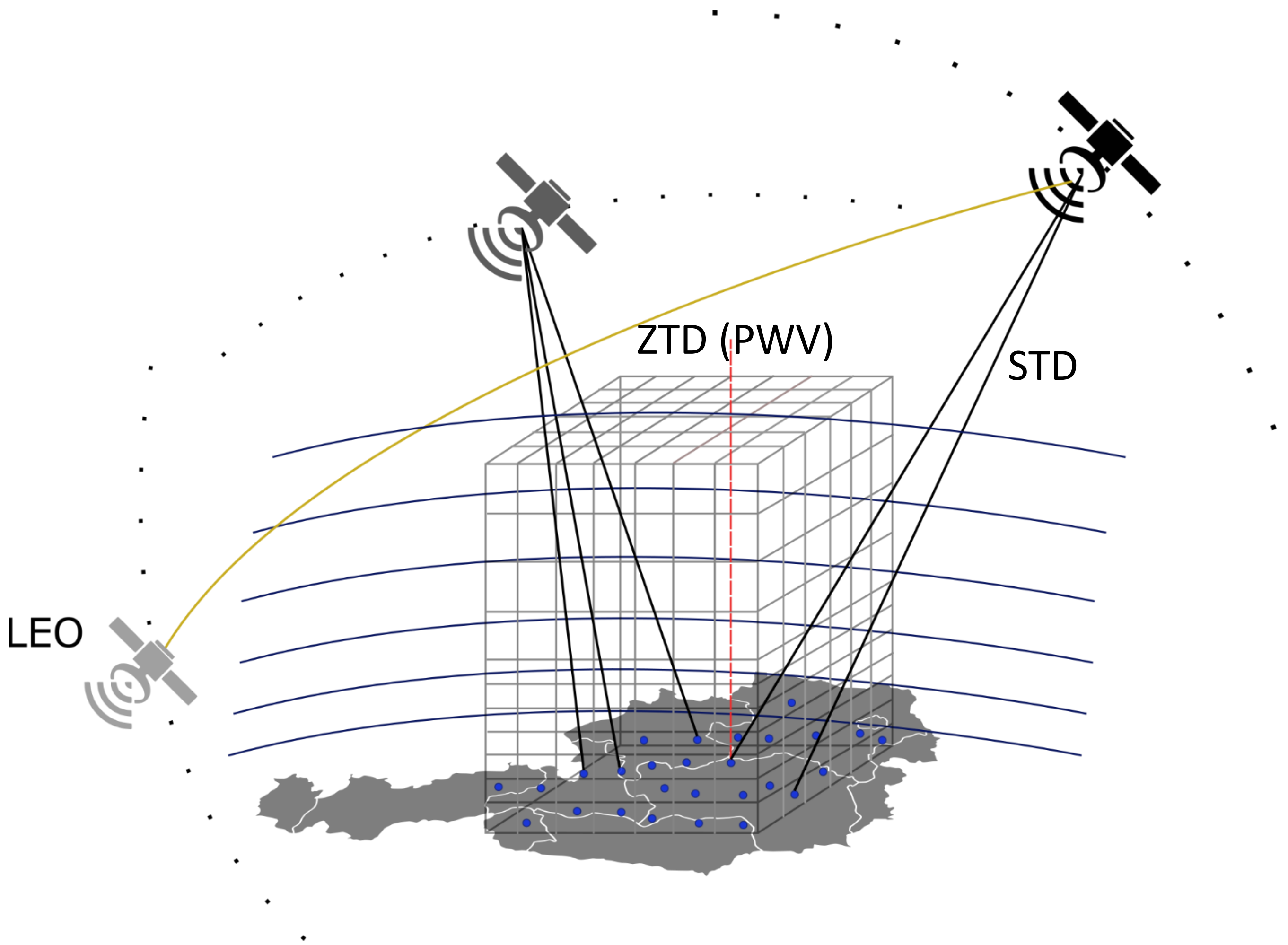
Natalia Hanna (1), Estera Trzcina (2), Maciej Kryza (3), Witold Rohm (2)

(1) Department of Geodesy and Geoinformation, TU Wien, Austria (natalia.hanna@geo.tuwien.ac.at)

(2) Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, Poland

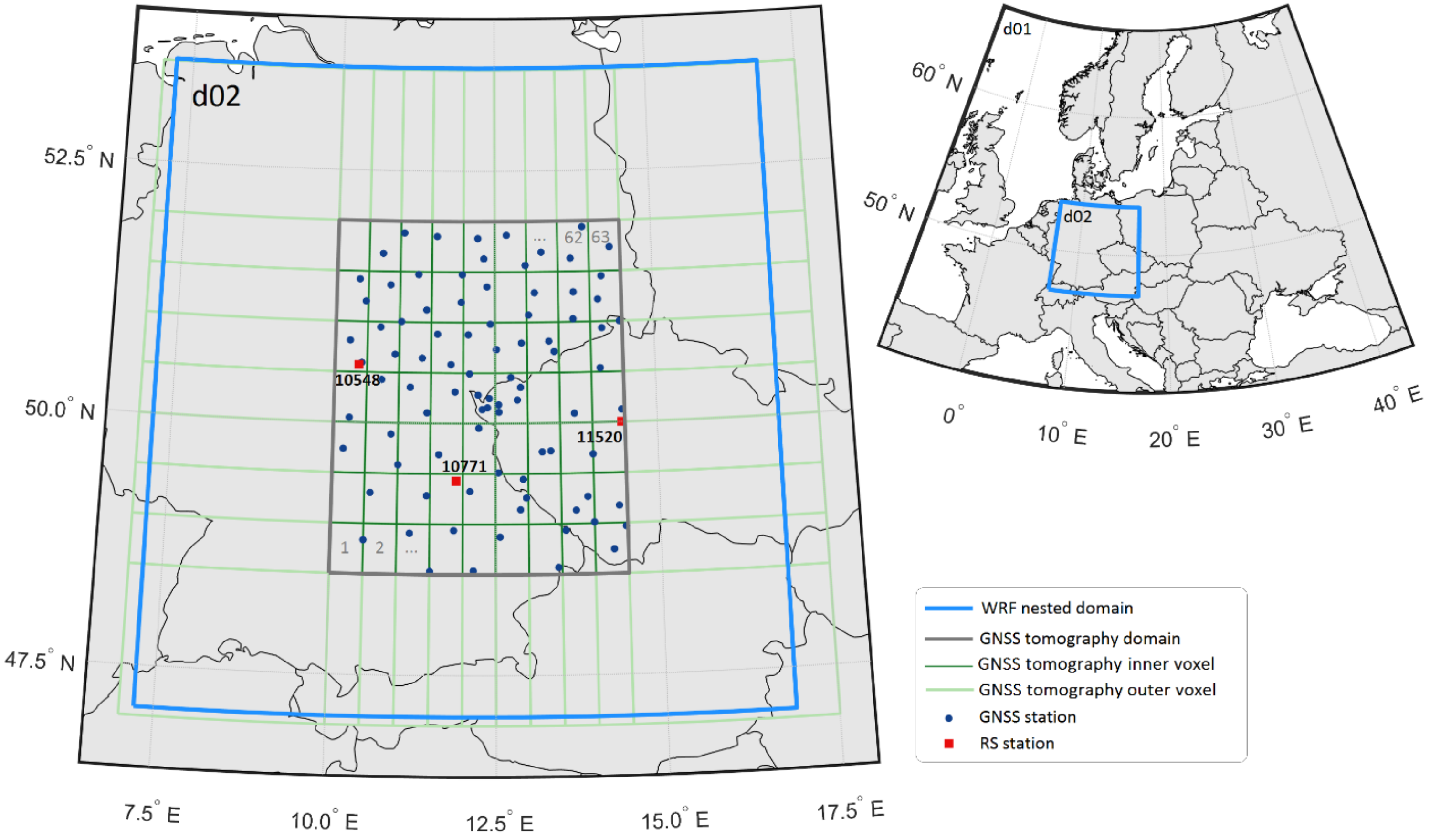
(3) Department of Meteorology and Climatology, University of Wroclaw, Poland

GNSS data assimilation: State-of-the-art



- ZTD/PWV operators (integrated observations in the zenith direction) – GPSZTD/GPSPW operators
- Radio occultation operator (total refractivity, bending angle) – GPSREF operator
- STD/SIWV (slant observations in the satellite directions) – not implemented in the WRF DA
- GNSS tomography wet refractivity fields – new TOMOREF operator (implemented in the WRF DA)

Refractivity field assimilation - GPSREF



Firstly, we have assimilated total refractivity values using the existing GPSREF operator. The total refractivity was calculated in the following way:

$$N_w + N_h = N$$

tomography outputs | ALADIN-CZ model | assimilated

Hanna, N., Trzcina, E., Möller, G., Rohm, W., and Weber, R. (2019): Assimilation of GNSS tomography products into the Weather Research and Forecasting model using radio occultation data assimilation operator, Atmos. Meas. Tech., https://doi.org/10.5194/amt-12-4829-2019.

Wet refractivity field assimilation – TOMOREF

The TOMOREF operator was build based on the following function:

$$N_w = \mathcal{H}(p, m, T) = \frac{p}{\epsilon} \cdot \left(\frac{k_2'}{T} + \frac{k_3}{T^2} \right) \cdot \frac{m}{1 + \frac{m}{\epsilon}}$$

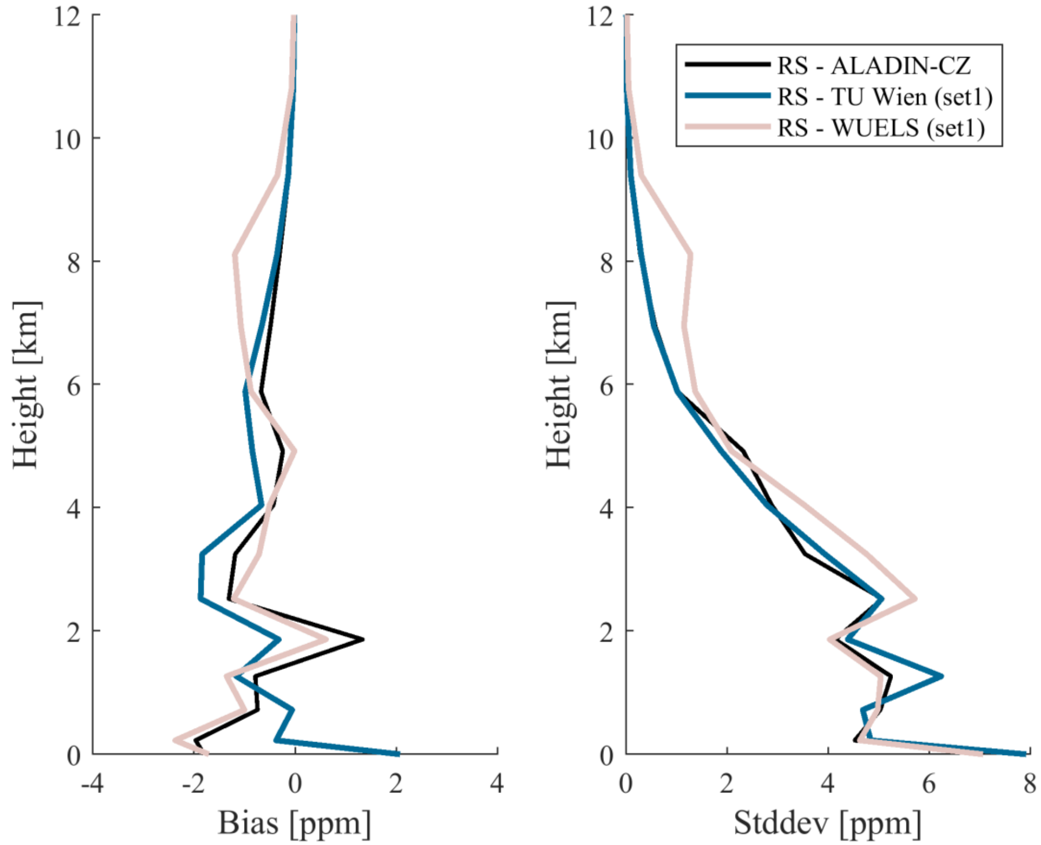
Where p is the atmospheric pressure in Pa, m is the water vapour mixing ratio in $kg \cdot kg^{-1}$, T is the temperature in K. The empirical constants $k_2' = 2.21 \cdot 10^{-1} K \cdot Pa^{-1}$ and $k3 = 3.73 \cdot 10^3 \; K2 \cdot P^{-1}$ are given by Bevis et al. (1994). The ratio between gas constants of dry air and water vapor $\epsilon = 0.622$ is used.

It consists of three parts:

Forward	Tangent Linear	Adjoint
p, m, T $\downarrow$ N_w	$\delta p, \delta m, \delta T$ $\downarrow$ δN_w	δN_w $\downarrow$ $\delta p, \delta m, \delta T$

Trzcina, E., Hanna, N., Kryza, M., and Rohm, W., (2020). TOMOREF operator for assimilation of GNSS tomography wet refractivity fields in WRF DA system, JGR: Atmospheres, under review.

TOMOREF: Observation errors



Observation errors have been set based on the comparison of tomography results with radiosonde profiles (2 weeks period)

Height [km]	Nw error [ppm]
< 1.5	$0.1 \cdot N_w$
1.5 – 5.5	$0.2 \cdot N_w$
5.5 – 8.0	3.0
8.0 – 10.0	2.0
> 10.0	0.2

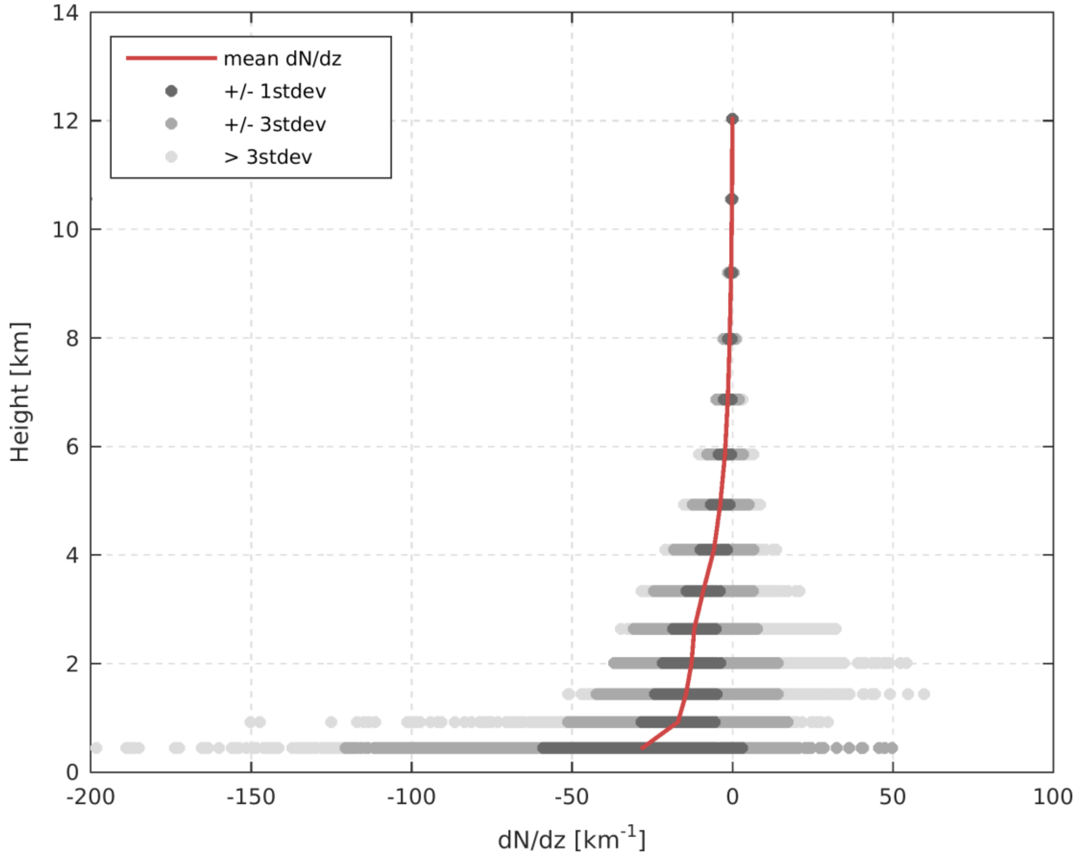
TOMOREF: Quality control

1) Based on the percent error

$$\left|\frac{O-B}{(O+B)/2}\right|$$

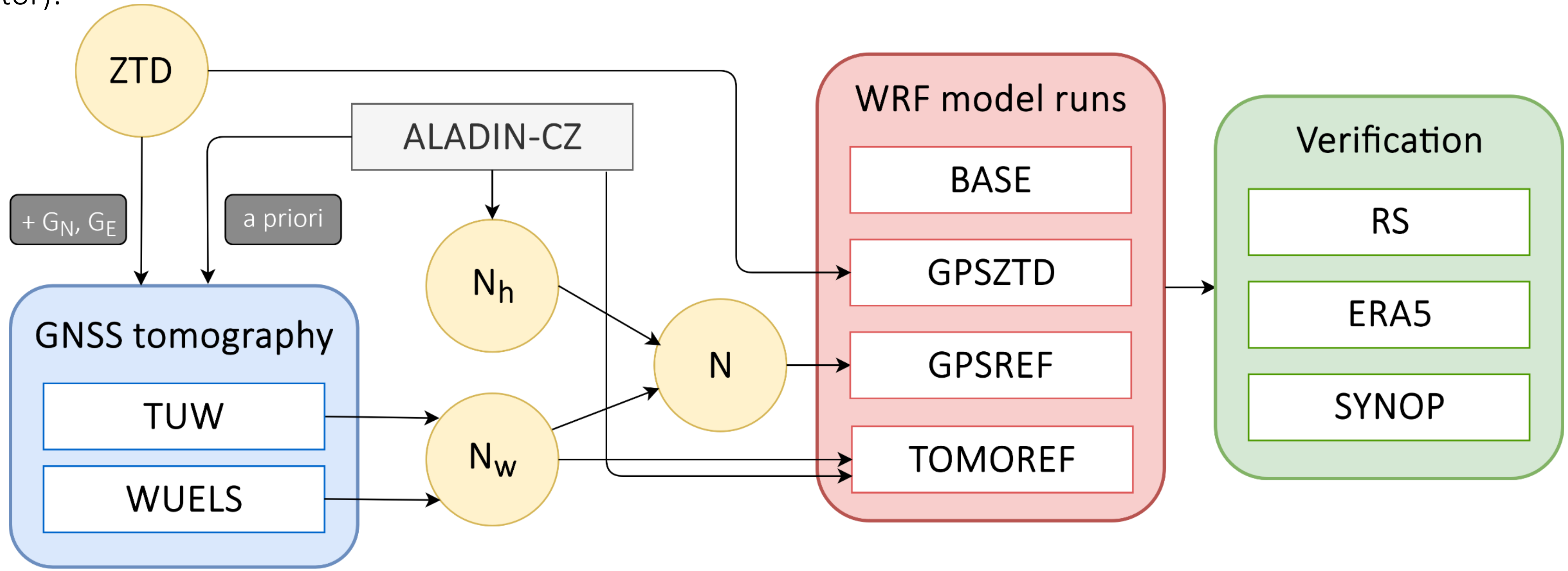
Height [km]	Max percent error	QC flag
< 2.5	0.15	-31
2.5 – 5.5	0.30	-32
> 5.5	0.15	-33

2) Based on the vertical gradient of N_w (QC flag -34)



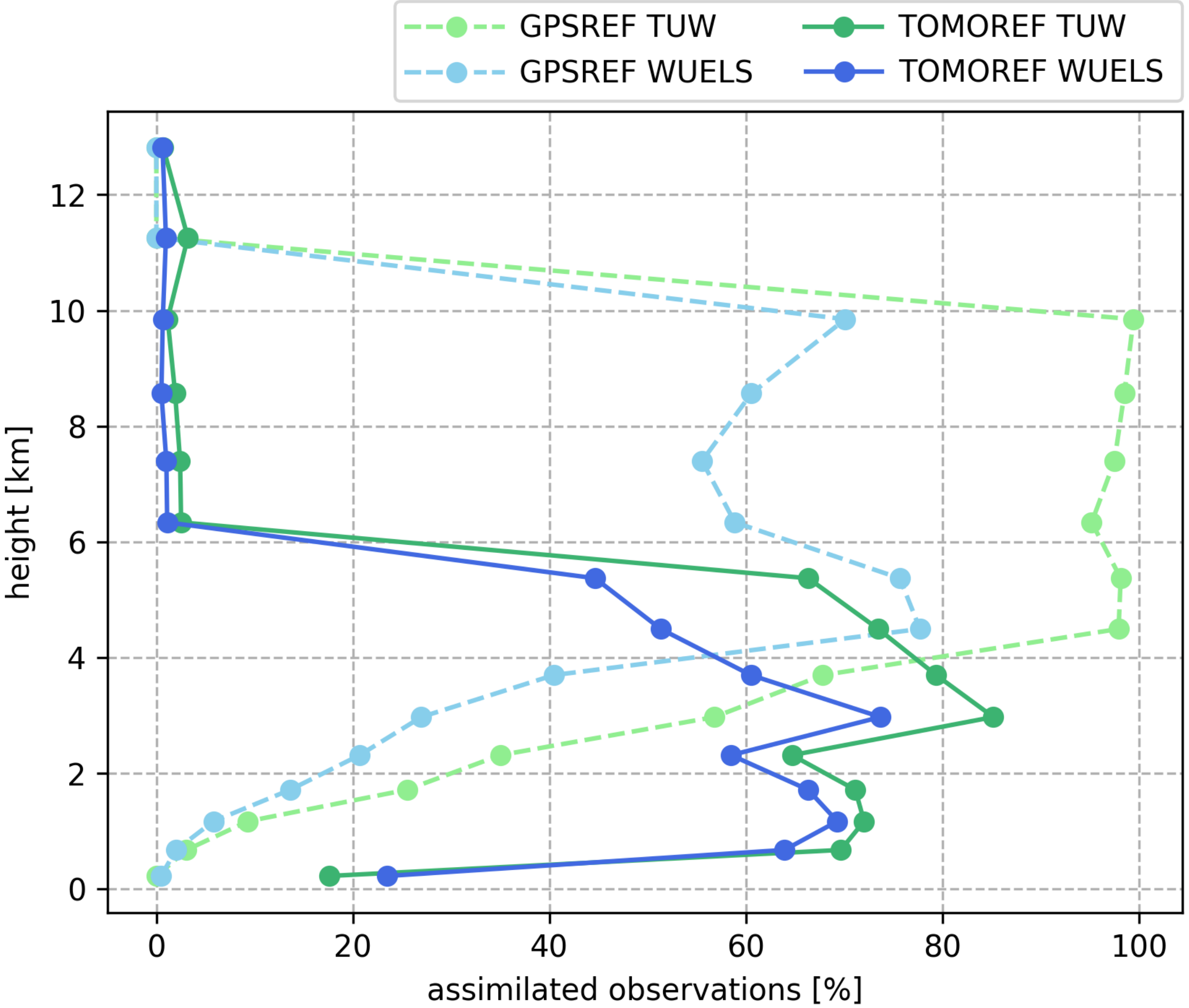
Experiment design

We conducted 7 different experiments: 1) BASE (forecast run without data assimilation); 2) GPSZTD; 3) GPSREF TUW (for the tomographic results from TUW model); 4) GPSREF WUELS (for the tomographic results from WUELS model); 5) TOMOREF TUW; 6) TOMOREF WUELS; 7) ALADIN (for the tomographic a priori data assimilated using TOMOREF operator):



Central Europe, 29 May – 14 June 2013

Assimilation results



GPSREF

0 - 2 km: < 20 % of observations are assimilated

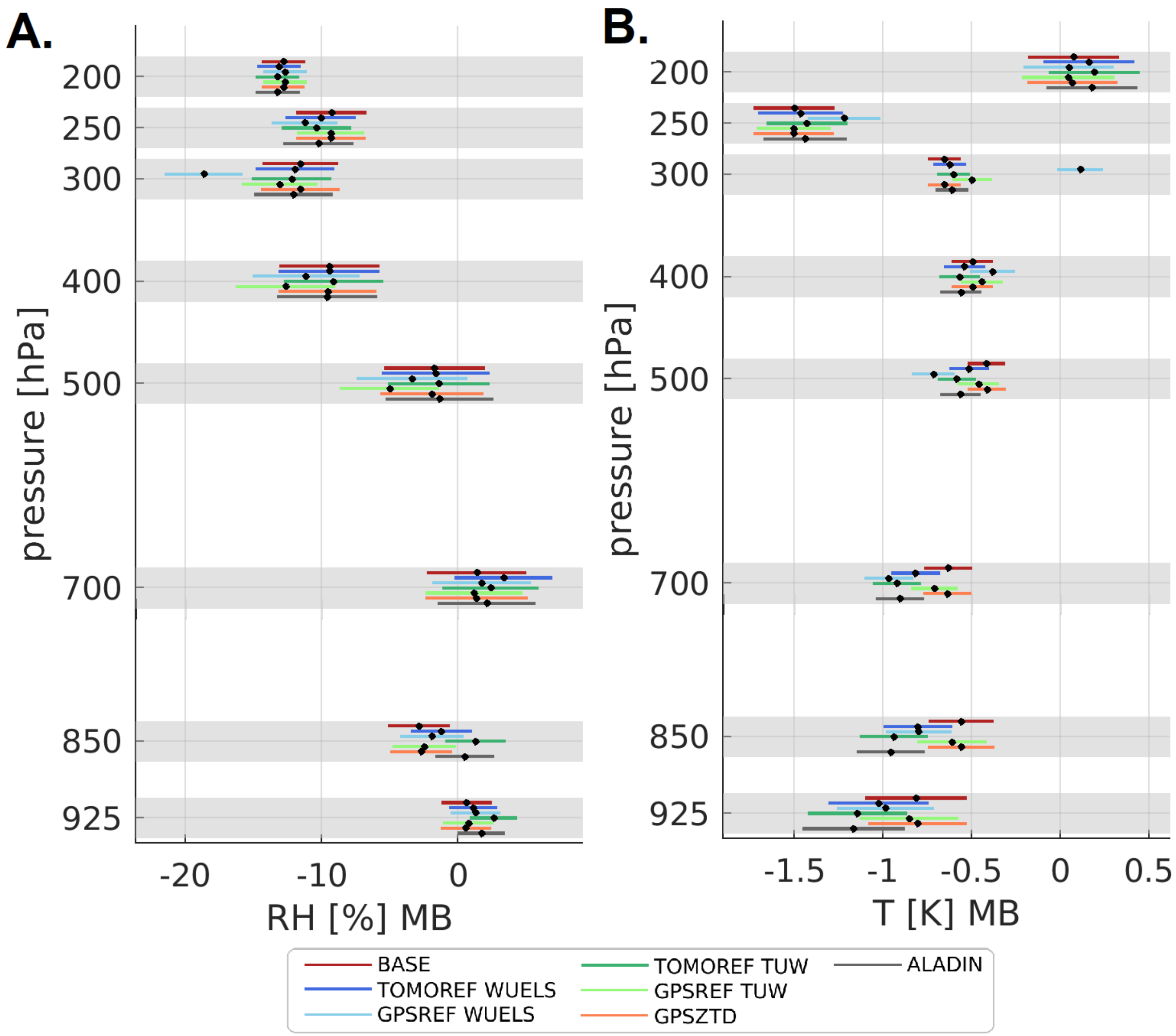
> 6 km: 60-95 % of observations are assimilated

TOMOREF

0 - 2 km: ≈70 % of observations are assimilated

> 6 km: < 5 % of observations are assimilated

RS comparison

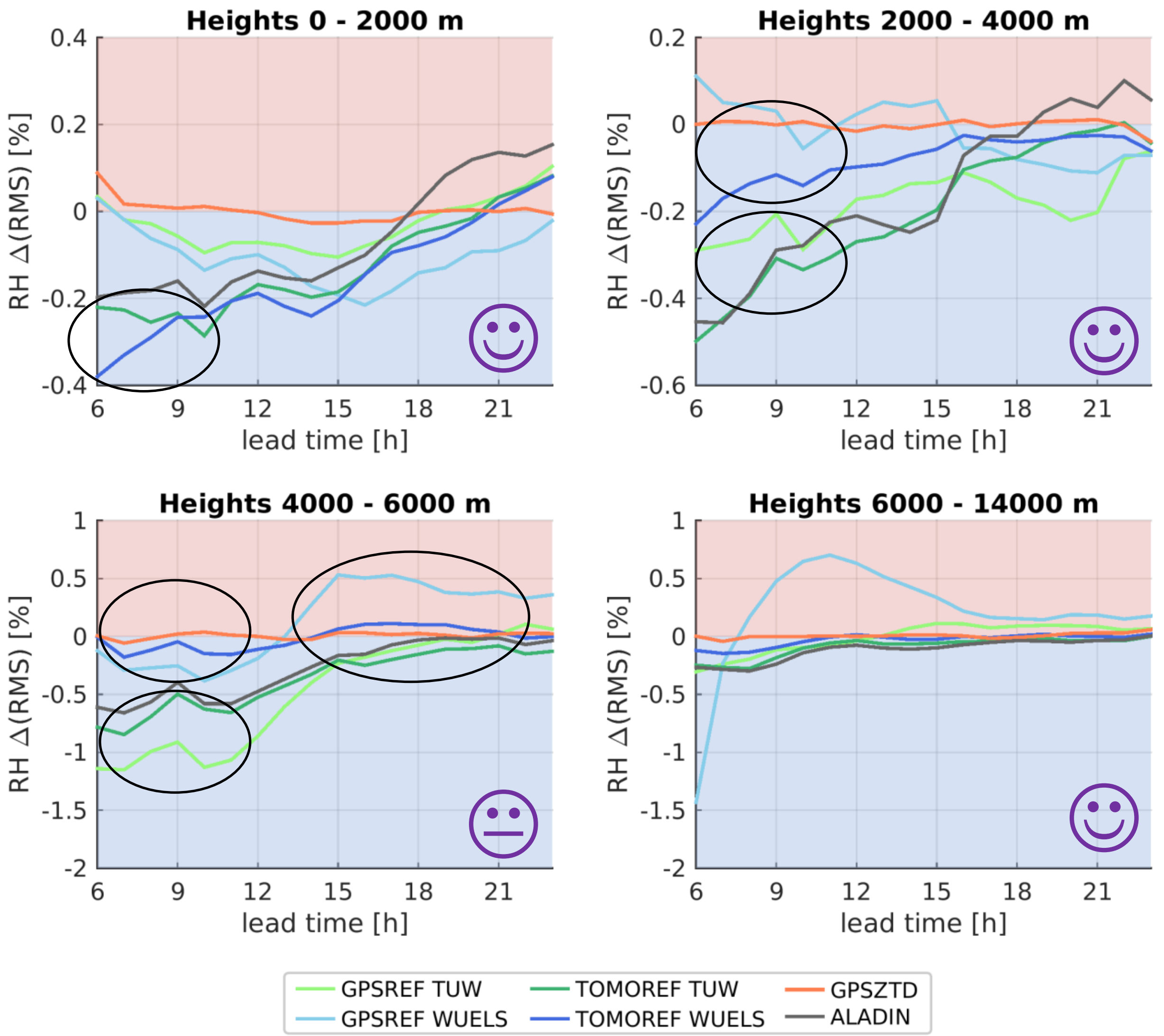


The statistics of mean bias (MB) for both meteorological parameters (RH, T) vary with height.

- A negative impact on the forecast of RH at the pressure level 300 hPa when GPSREF operator is used (eliminated by the application of TOMOREF operator);
- In terms of temperature, no improvement in the weather forecast was noticed when TOMOREF operator was used.

The values of MB in the upper part of the troposphere (above 400 hPa) depend on the changing horizontal location of the radiosonde, which does not rise in the perfect vertical direction.

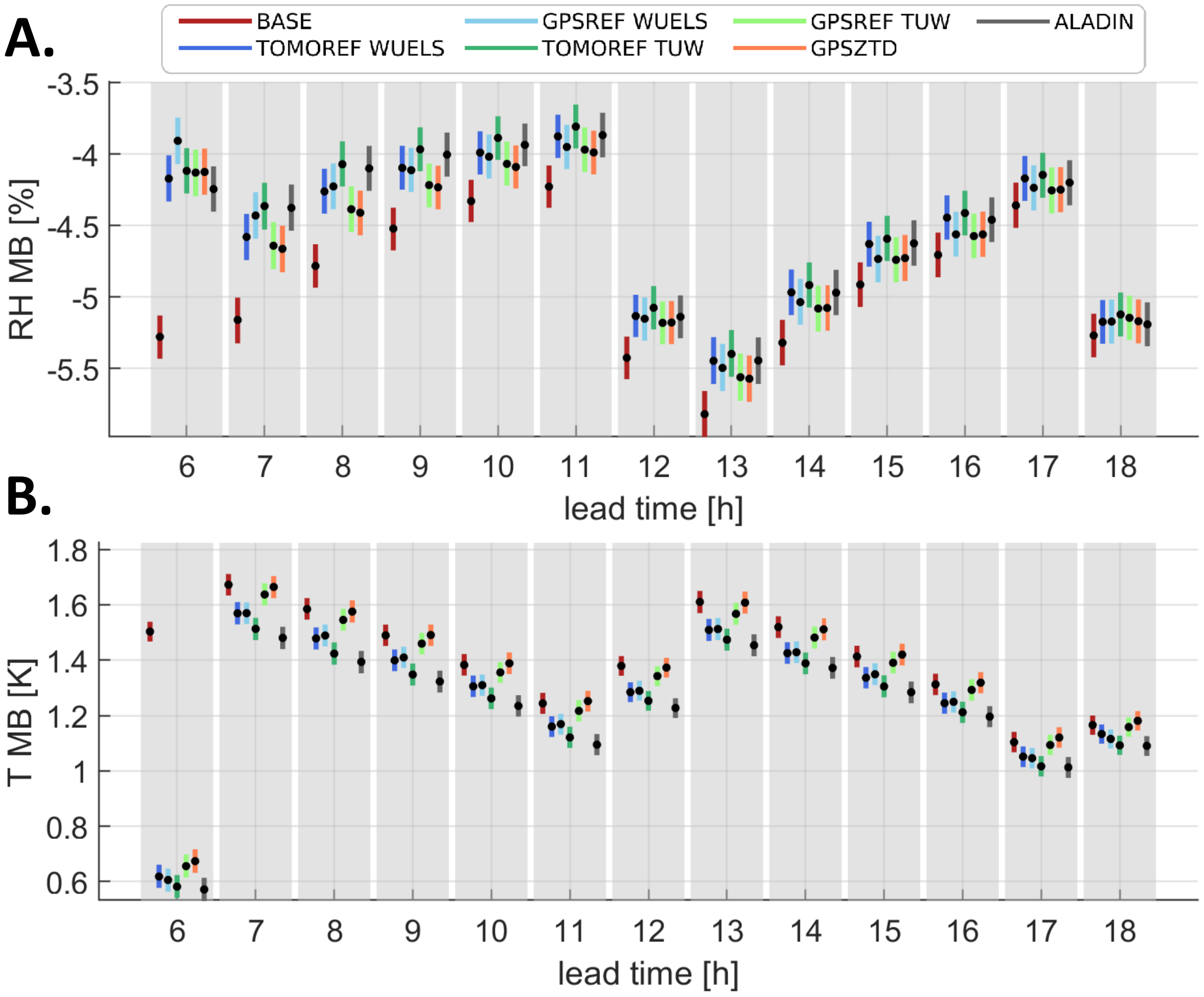
ERA5 comparison



In terms of RH, the assimilation of the GNSS products for both models (TUW, WUELS) using the TOMOREF operator:

- Gives better results by approximately 0.1-0.5% in the lower part of the troposphere (0-2 km) than operators GPSREF and GPSZTD (up to 10 h of the forecast);
- For heights between 2 and 4 km decreases the rms value by approximately 0.1% when compared to the GPSREF operator;
- In the middle part of the troposphere (4-6 km; up to 7 h of the lead time) gives better result than the BASE run but worse than the GPSREF run;
- In the upper troposphere, the advantage of the TOMOREF operator over the GPSREF operator is evident through the entire forecast period.

SYNOP comparison



In terms of RH (panel A):

- All runs overestimate the observed RH, with MB in a range of -3.5% to -6.0%;
- In the first hours of the forecast (6-8 hours of the lead time), each case of the assimilation improves the value of MB for RH by approximately 1% compared with the BASE run;
- In the next hours of the forecast (9-14), significant improvement in RH is evident mainly for the TOMOREF (TUW, WUELS) and ALADIN assimilation runs.

In the case of T (panel B):

- The maximal improvement of MB (~1 K) is visible for all assimilation runs at the assimilation time.
- During the 7-14 hour of the forecast lead time, the significant decrease of MB for T (by 0.1-0.2 K) is aparent mainly for the TOMOREF (TUW, WUELS) and ALADIN assimilation runs.

Conclusions

- The previous studies on assimilation of the total refractivity field from GNSS tomography into the NWP models are based on the available GPSREF observation operator
- The new TOMOREF operator is dedicated to the assimilation of the GNSS tomography 3D field of wet refractivity
- The **positive impact of the GNSS tomography data assimilation on the weather forecast of RH** has been noticed (an improvement of rms up to 0.5% when compared to ERA5)
- The assimilation of the GNSS tomography outputs shows **greater influence on the WRF model than the ZTD assimilation**, what proves the potential of using the GNSS tomography data in weather forecasting
- The impact of the GNSS tomography assimilation in different weather conditions and seasons should be investigated
- The performance of the operator in different regions should be examined.

Thank you for your attention!

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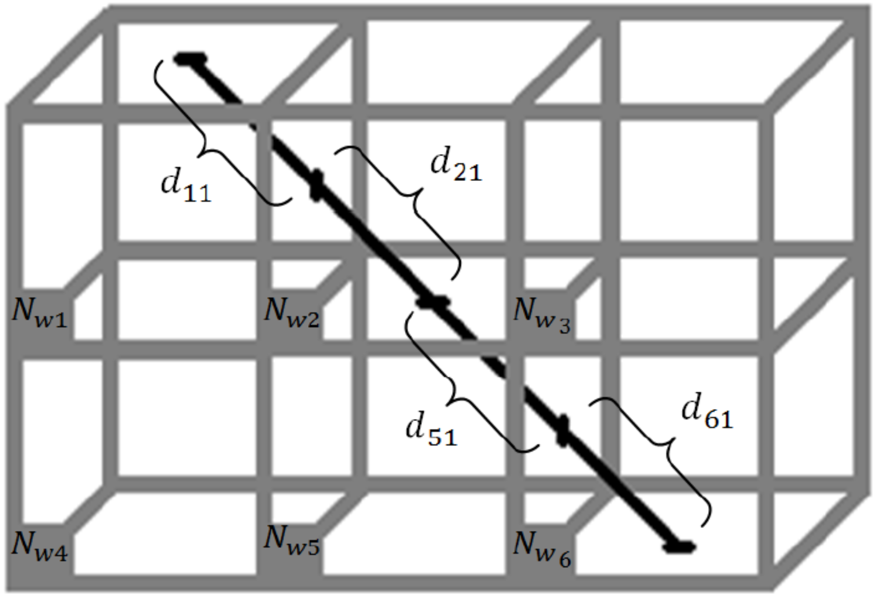
Appendix: GNSS Tomography

GNSS tomography provides the 3D information about wet refractivity distribution



$$SWD = 10^{-6} \int N_w ds$$

$$\underbrace{SWD}_{\text{known}} = A * \underbrace{N_w}_{\text{estimated}}$$

$$A = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nm} \end{bmatrix}$$