TOMOREF operator as a boost to the data assimilation system

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ABSTRACT

The GNSS tomography technique provides a 3-D field of humidity in the troposphere. Contrary to the operationally assimilated Zenith Total Delay (ZTD) observations, representing an integral measurement along the vertical, GNSS tomography provides a suitable vertical resolution to map the outputs to meteorological parameters in various height layers. To combine the GNSS tomography-derived 3-D fields of wet refractivity with the Weather Research and Forecasting (WRF) Data Assimilation (DA) system, a new observation operator, called TOMOREF was built. The new tool has been tested based on wet refractivity fields derived during a very intense precipitation event in central Europe in May 2013. In the presented experiment, a positive impact on the forecast of relative humidity (RH) was noticed (an improvement of RMSE up to 0.5%). Moreover, within 1 hour after assimilation, the GNSS data reduced the bias of precipitation up to 0.1 mm. Also, assimilation of the GNSS tomography data had a greater impact on the WRF model than assimilation of the ZTD. Another experiment testing tomographic outputs assimilation was conducted in calm weather conditions in the Netherlands in February 2018, focusing mainly on wind parameters forecasting.

1. GNSS tomography principles

GNSS troposphere tomography obtains **3-D field of wet refractivity** in the lower atmosphere, based on the GNSS signal delays. Slant Wet Delay (SWD) can be modeled as an integral of the wet refractivity (N_w) along the ray path (Fig. 1). The inversion of a set of equations leads to estimation of the wet refractivity distribution.

1.1. Tomographic domain

$$SWD = 10^{-6} \int_s N_w(s)\,ds$$

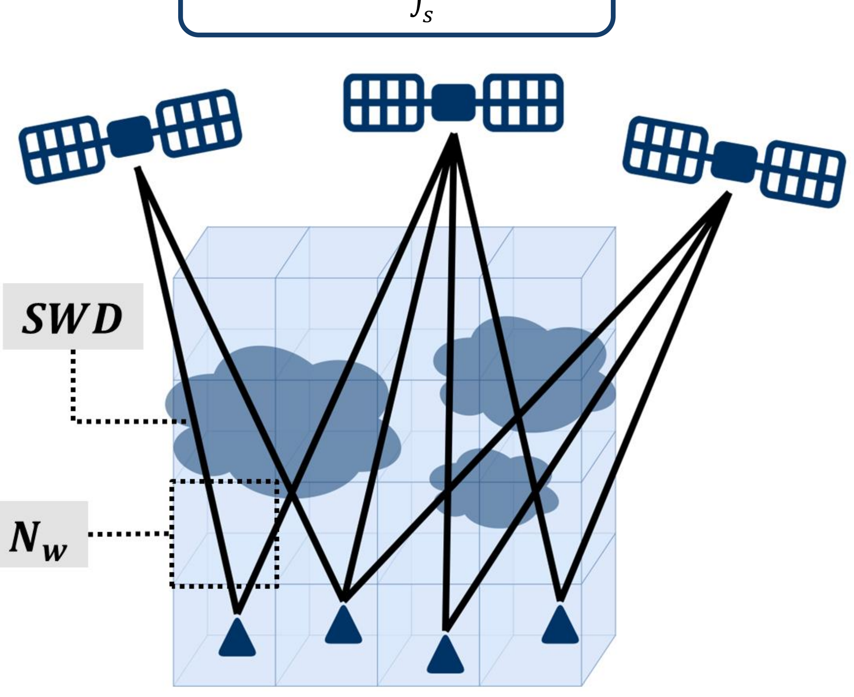


Figure 1. Scheme of the GNSS rays in the tomographic domain.

1.2. System of equations

$$\overline{SWD} = A \cdot \overline{N_w}$$

observed — projection matrix — estimated

$$\overline{SWD} = \begin{bmatrix} SWD_1 \\ SWD_2 \\ \vdots \\ SWD_l \end{bmatrix} \quad A = \begin{bmatrix} \frac{\partial SWD_1}{\partial N_{w1}} & \frac{\partial SWD_1}{\partial N_{w2}} & \cdots & \frac{\partial SWD_1}{\partial N_{wm}} \\ \frac{\partial SWD_2}{\partial N_{w1}} & \frac{\partial SWD_2}{\partial N_{w2}} & \cdots & \frac{\partial SWD_2}{\partial N_{wm}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial SWD_l}{\partial N_{w1}} & \frac{\partial SWD_l}{\partial N_{w2}} & \cdots & \frac{\partial SWD_l}{\partial N_{wm}} \end{bmatrix} \quad \overline{N_w} = \begin{bmatrix} N_{w1} \\ N_{w2} \\ \vdots \\ N_{wm} \end{bmatrix}$$

1.3. Tomographic solution – inversion

$$\overline{N_w} = inv(A) \cdot \overline{SWD}$$

The estimated 3-D fields of wet refractivity depend on humidity in the troposphere, thus they have a great potential to be used as a source of data for the **weather prediction**.

2. TOMOREF operator

TOMOREF operator was developed **to assimilate GNSS-derived 3-D fields of wet refractivity** directly into the Weather Research and Forecasting (WRF) model. The operator was designed as a module of the WRF Data Assimilation (WRFDA) system.

2.1. Wet refractivity and meteorological parameters

Wet refractivity values can be expressed in terms of **pressure (p), humidity (q), and temperature (T)**.

$$N_w = k_1 \frac{pq}{0.622\,T} + k_2 \frac{pq}{0.622\,T^2}$$

The TOMOREF operator consists of three parts:

Operator	
forward operator – calculate N_w based on the model variables	p, q, T → N_w
tangent linear operator – calculate increments of N_w based on model increments	$\delta p, \delta q, \delta T$ → δN_w
adjoint operator – calculate impact of δN_w on the meteorological parameters	δN_w → $\delta p, \delta q, \delta T$

2.2. Quality control

step 1 Check consistency with the **background data**. If ε is larger than a treshold, the outlier is rejected.

$$\varepsilon = \left|\frac{O - B}{(O + B)/2}\right| \qquad O - \text{observation}, \; B - \text{background}$$

step 2 Check **inner consistency** of the assimilated data based on wet refractivity gradients.

2.3. Observation errors

The observation errors of assimilated wet refractivity fields are assigned based on validation with the **radiosonde data**.

3. Heavy precipitation 2013

3.1. Assimilation domain

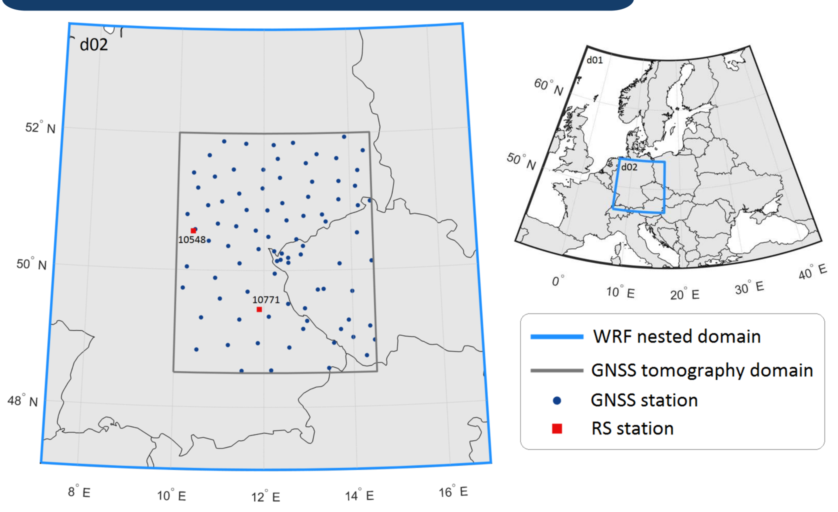
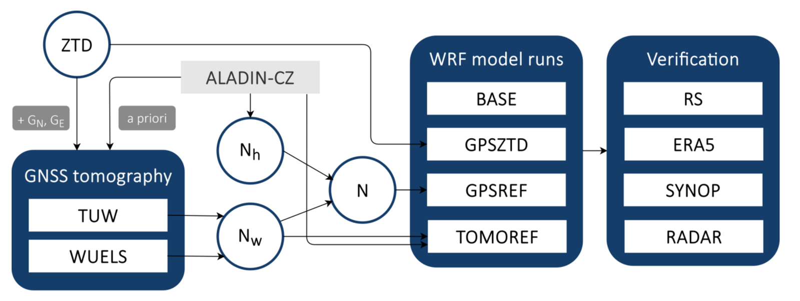


Figure 2. The assimilation domain, GNSS stations and the tomogrpahic model area.

The assimilation experiment was performed for the area of Germany and Czech Republic, in the period of the **heavy precipitation** event in 2013.

3.2. Assimilation scheme

The tomography data from **2 models** (TUW, WUELS) were assimilated into the WRF model. Two observation operators were examined: **GPSREF** (dedicated to assimilation of total refractivity from radiooccultation observations) and **TOMOREF** (a new tool for direct assimilation of the wet refractivity fields). Also, zenith total delays (ZTD) were assimilated using **GPSZTD** operator to check the impact of ZTD on the weather forecasts.



3.3. Forecast verification

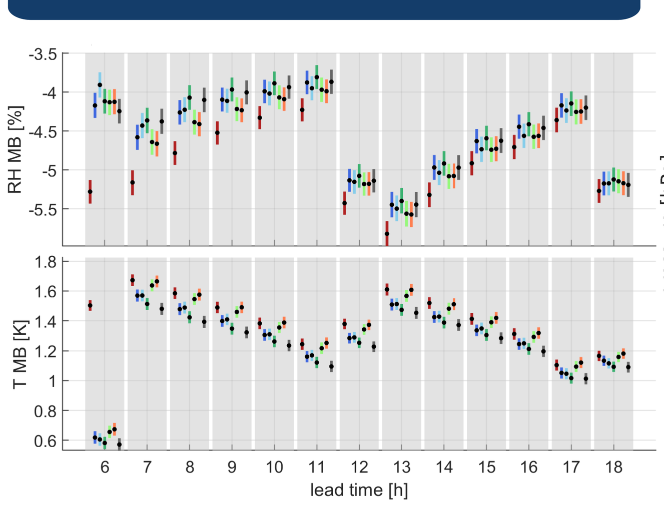


Figure 3. Verification with synoptic observations.

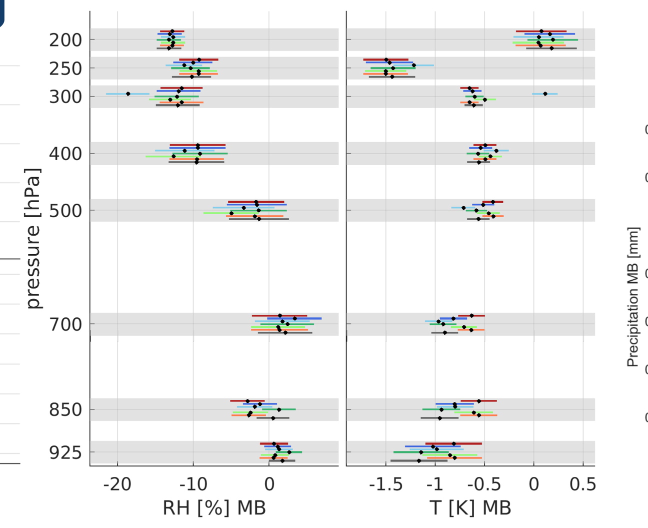


Figure 4. Verification with radiosonde observations.

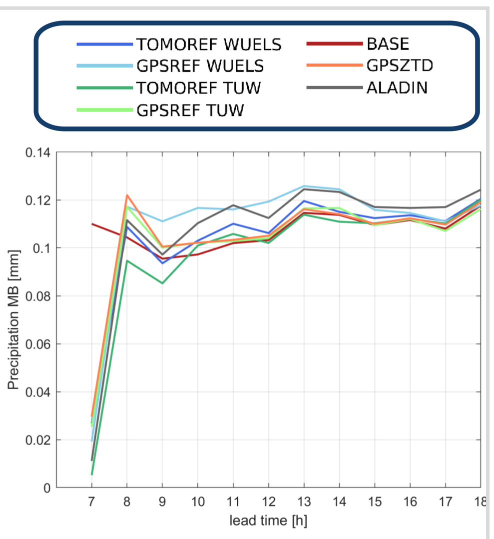


Figure 5. Verification with radar data.

Validation with **synoptic observations** (Fig. 3) shows improvement of relative humidity (RH) and temperature (T) forecasts for all assimilation runs, comparing to the base run (without assimilation). The largest impact of the assimilation is noticed for TOMOREF operator in 9-14 h lead time. Verification based on **radiosonde observations** (Fig. 4) shows that differences between particular model runs are not significant. Assimilation improves forecast of **precipitation** (Fig. 5) in the first hour, for all model runs.

4. Wind forecasting 2018

4.1. Assimilation domain

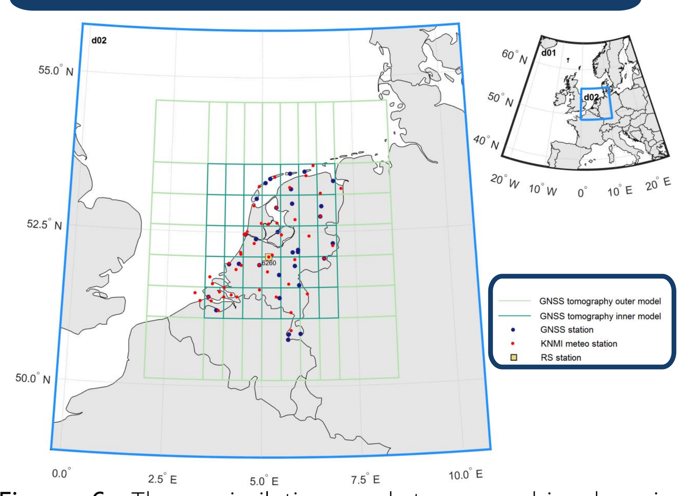


Figure 6. The assimilation and tomographic domains; GNSS, radiosonde, and meteorological stations.

The assimilation experiment was performed for the area of the Netherlands in February 2018.

4.2. Assimilation results

The tomography data from the **TUW model** were assimilated into the WRF model (3DVAR) using the **TOMOREF** operator. Additionally, zenith total delays (ZTDs) were assimilated using **GPSZTD** operator.

Table 1. Statistics for wind speed (WS) validated against radiosonde data at the assimilation time.

WS [m/s]	TOMOREF	GPSZTD	BASE
Bias	0.320	0.278	0.310
Stdev	2.055	2.079	2.054
RMS	2.206	2.230	2.203

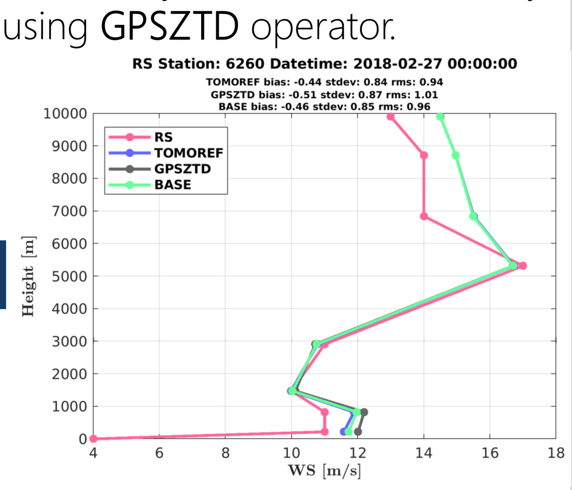


Figure 7. Vertical profiles of WS derived from WRF runs at the assimilation time and radiosonde lanuch, as obtained for the 27th of February 2018, 00 UTC.

4.3. Forecast verification

Validation with **synoptic observations** was performed in terms of wind speed (WS) and relative humidity (RH) (Fig. 8). Apart from the analysis time (6h lead time), the assimilation of tomography data (TOMOREF run) does not improve forecast of WS and RH significantly, comparing to the GPSZTD run.

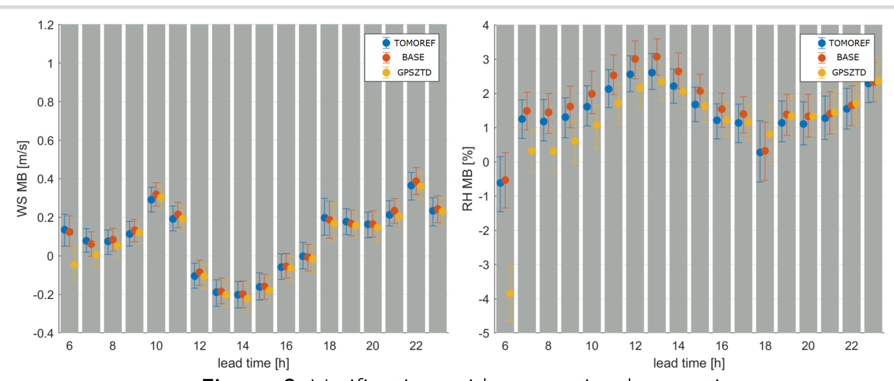


Figure 8. Verification with synoptic observations.

5. Conclusions and outlook

- assimilation of the GNSS tomography wet refractivity field is enabled by the use of the new observation operator TOMOREF, which was developed in this study for the WRF DA system
- assimilation of the 3-D wet refractivity fields gives better results than ZTD data assimilation, especially in terms of temperature and precipitation forecasting
- assimilation of the tomographic data shows the significant improvement of WS and RH forecasts at the assimilation time when compared to ZTDs data assimilation; however, this impact vanishes in time

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More results of the study can be found in the following paper:

Trzcina, E., Hanna, N., Kryza, M., & Rohm, W. (2020). TOMOREF operator for assimilation of GNSS tomography wet refractivity fields in WRF DA system. Journal of Geophysical Research: Atmospheres, 125(17), e2020JD032451.

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