Synergy of GNSS Tomography and Radio Occultation: Methods for Assimilating Refined Water Vapor Fields

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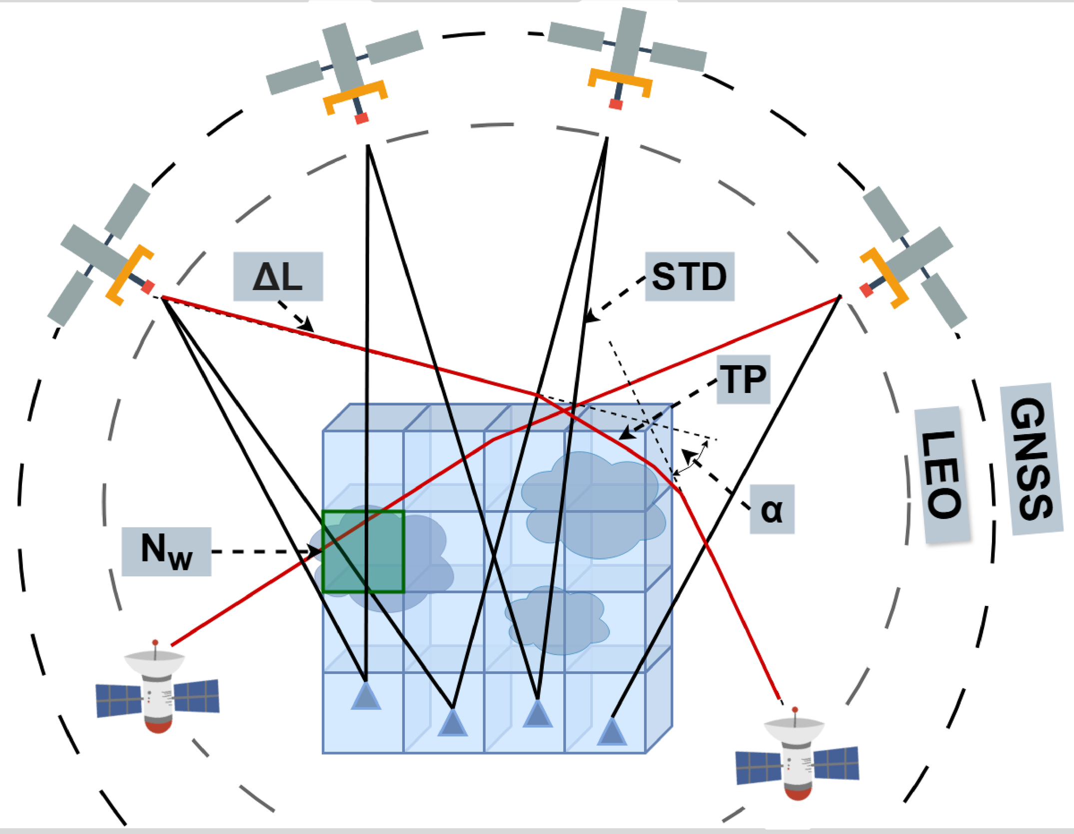
INTRODUCTION

Global Navigation Satellite Systems (GNSS) tomography is a rapidly developing method in meteorology that provides 3D grid-based information about water vapour distribution in the lower troposphere. The standard tomographic solutions are derived by processing signal delays between satellites and ground-based GNSS receiver networks. As the technique has advanced, additional observational data sources have been integrated into the process, enhancing its accuracy and applicability. Low Earth orbit (LEO) satellites can provide signal delays similar to those from ground-based networks by tracking GNSS signals. This technique is known as GNSS radio occultation (RO) and relies on radio transmissions from GNSS satellites, where signals pass through the atmosphere and undergo refraction. The degree of refraction is influenced by atmospheric temperature and water vapor concentration. With the exponential increase of the LEOs satellites number over the past 30 years, this technique has been a cornerstone for atmospheric measurements. It is widely used in meteorological offices as a tool for weather forecasting and shows strong potential for improving tomographic applications. The Weather Research and Forecasting (WRF) Model, equipped with its tomographic operator tomoref, facilitates the integration of tomographic products into meteorological fields. In recent years, several studies have explored available practices for tomographic data assimilation. In this work, we present two variants for assimilating combined RO and tomographic solutions. With further fine-tuning, the presented methodology for assimilating tomographic products demonstrates significant potential for future testing in meteorological centres.

1. GNSS tomography: Space- and ground-based



GNSS Satellite Signals passing the troposphere

- **Velocity and trajectory changes**, leading to:
  - Excess phase (ΔL)
  - Slant total delay (STD)

GNSS RO

- Based on analyzing the bending of GNSS signals caused by the atmosphere.
- Observations are made between a GNSS satellite and a receiver onboard a low Earth orbiting (LEO) satellite.
- The **tangent point (TP)** moves nearly vertically through the atmosphere.
- **Output:** A **time series of bending angles (α)** OR **vertical profile of atmospheric refractivity**, which can be used for weather forecasting, climate studies, and atmospheric research.

Ground-based GNSS

- ZTDs are calculated based on the dual-frequency code and carrier phase measurements from a network of ground-based GNSS receivers.
- To separate ZTDs into wet (ZWD) and hydrostatic parts (ZHD), Saastamoinen formula is used.

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

2. Tomography: Integration methods

Integrated tomographic processing solves the basic tomography equation, depending on the input data:

- Ground-based observations: SWD values are recalculated from the ZWDs (Zenith Wet Delays) obtained from GNSS processing;
- Space-based observations: $N_{w,RO}$ (RO wet refractivity profiles) OR ΔL_{w} (RO wet excess phase);
- $N_{w,apr}$ is the a priori wet refractivity fields derived from NWM data (e.g., ERA5 reanalysis).

2.1. RO Profiles

$$\begin{bmatrix} SWD \\ N_{w,RO} \\ N_{w,apr} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{GNSS} \\ \boldsymbol{A}_{RO} \\ \boldsymbol{A}_{apr} \end{bmatrix} \cdot N_w \Rightarrow b = \boldsymbol{A} N_w$$

$\boldsymbol{A}_{GNSS}$ are the ray lengths in each voxel. $\boldsymbol{A}_{RO}$ and $\boldsymbol{A}_{apr}$ are binary matrices with values 0 or 1, where 1 means the a priori information from NWM field is considered in the processing and 0 means no a priori information is available in the voxel.

Processing: Software package ATom for Atmospheric TOMography; see Möller (2017) and Hanna and Weber (2023).

2.2. RO Excess phase

$$\begin{bmatrix} SWD \\ \Delta L_{w} \\ N_{w,apr} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{GNSS} \\ \boldsymbol{A}_{RO} \\ \boldsymbol{A}_{apr} \end{bmatrix} \cdot N_w \Rightarrow b = \boldsymbol{A} N_w$$

$\boldsymbol{A}_{GNSS}$ and $\boldsymbol{A}_{RO}$ are matrices with the values of integrands from mixed bilinear/spline interpolation corresponding to each node from ground- and space-based observations, respectively (Trzcina et al., 2023). $\boldsymbol{A}_{apr}$ is a binary matrix.

Processing: Integrated GNSS tomography tool (INTOMO); see Cegla et al. (2024) AND EGU25-12037 (Wed).

Resulting 3D wet refractivity field can serve as an input to the Numerical Weather Prediction (NWP) models.

3. Assimilation: TOMOREF operator

A function that is used to calculate equivalents of N_w observations based on the NWP model variables. In the TOMOREF, this is derived as follows (Trzcina et al., 2020):

$$N_w = \mathcal{H}(p, m, T)$$

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

Where p is the atmospheric pressure in Pa, m is the water vapour mixing ratio in $\mathrm{kg \cdot kg^{-1}}$, T is the temperature in K. The empirical constants $k_2' = 2.21 \cdot 10^{-1} \mathrm{K \cdot Pa^{-1}}$ and $k_3 = 3.73 \cdot 10^{3}\ \mathrm{K^2 \cdot Pa^{-1}}$ are given by Bevis et al. (1994). The ratio between gas constants of dry air and water vapor $\epsilon = 0.622$ is used.

3.1. Observation errors

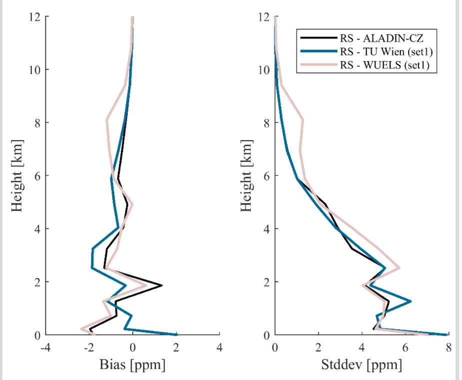


Fig 2. GNSS Tomography vs. Radiosonde profiles.

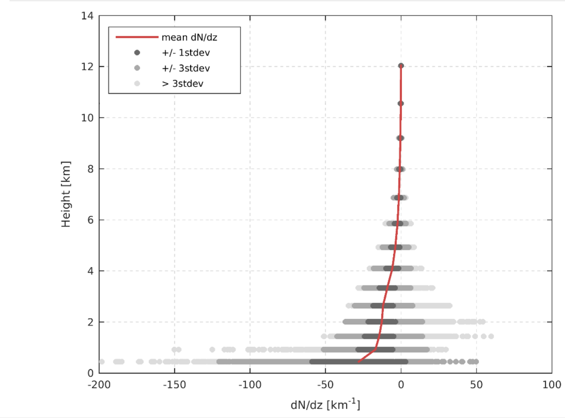
Height [km]	Nw error [ppm]
< 1.5	$0.1 \cdot N_w$
1.5 – 5.5	$0.2 \cdot N_w$
5.5 – 8.0	3.0
8.0 – 10.0	2.0
> 10.0	0.2

3.2. Quality control

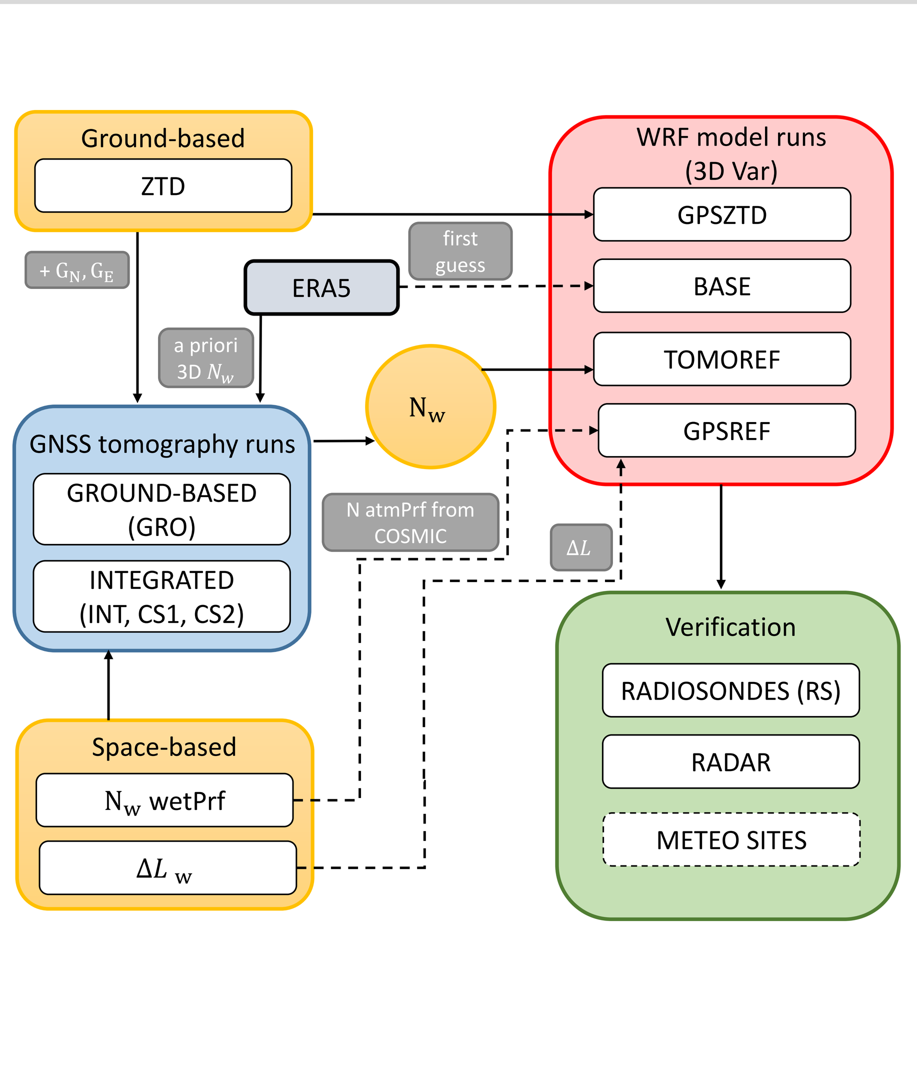
Based on the percent error $\left|\frac{O-B}{(O+B)/2}\right|$

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

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



4. Assimilation scheme



5. Results: Asimilation of various tropospheric products

5.1. STUDY CASE 1: RO profiles

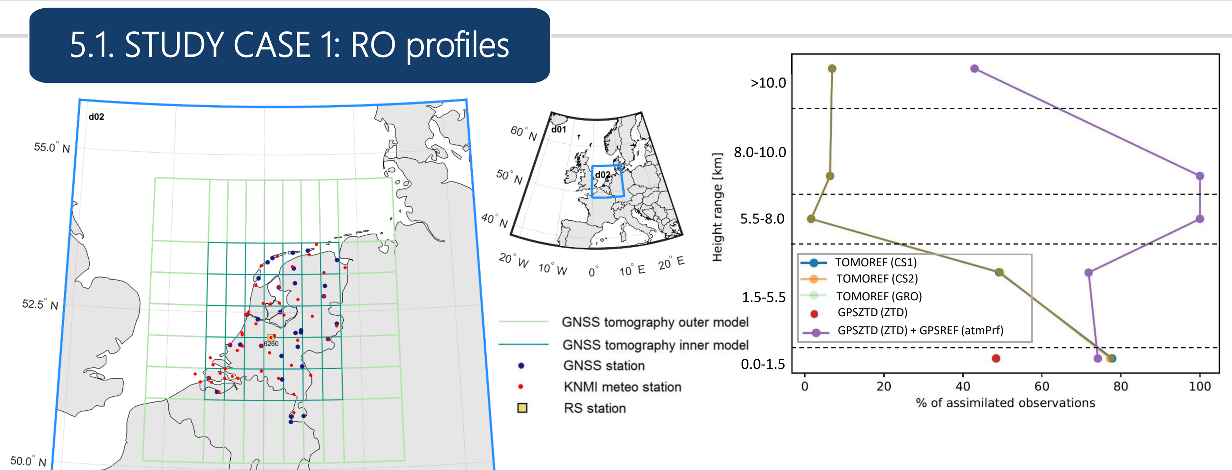


Fig. 3. Tomographic domain (left) & Percentage number of assimilated observations (right). ZTDs are considered point observations at the height of GNSS station (2018-02-02 00:00:00).

In the analyzed case, the wet refractivity fields derived from ground-based and space-based solutions differ by up to 2 ppm within the voxels intersected by the RO profile. The combination of observations reduces the bias between the tomographic solution and meteorological station measurements, achieving improvements of up to 1 ppm at the locations of the reference KNMI stations. However, under calm weather conditions, particular WRF model assimilation runs do not significantly improve forecast parameters. When compared with RS-derived specific humidity observations, all model runs yield a correlation coefficient of approximately 0.99.

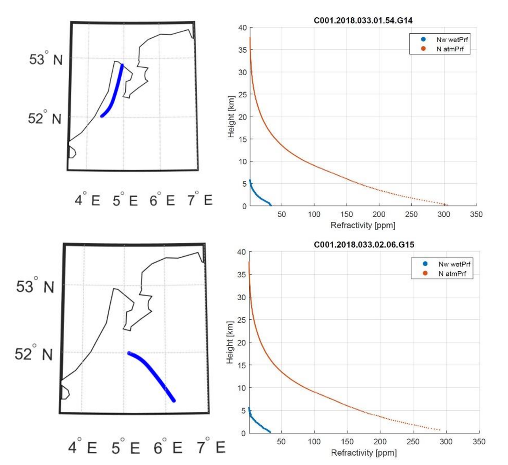


Fig. 4. COSMIC RO wet refractivity profiles identified in the domain area on 2018-02-02 at 02:00 UTC.

5.2. STUDY CASE 2: RO excess phase

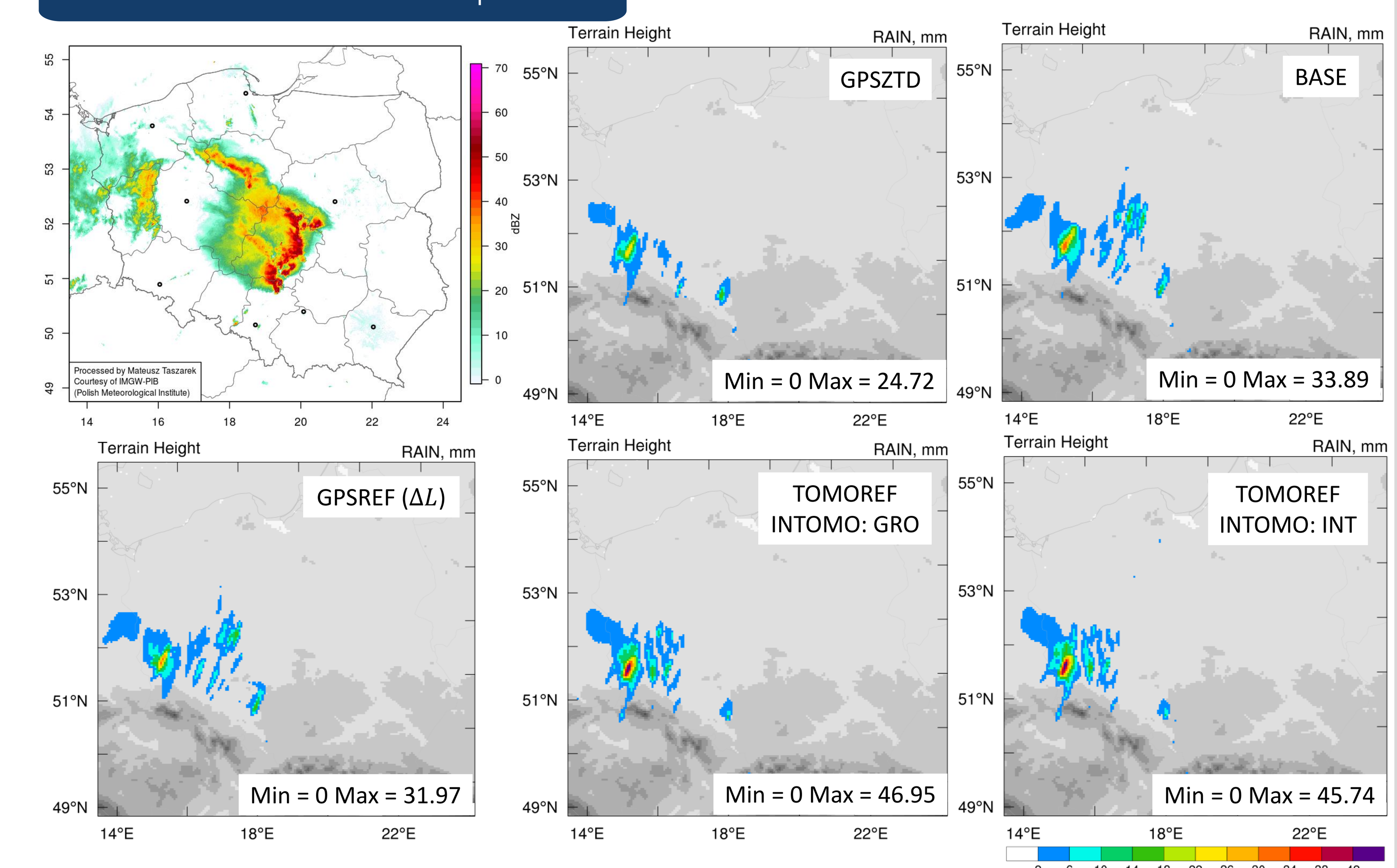


Fig 5. Radar data vs. Hourly rain [mm/h] (2021-06-24 00:00:00 +6 hr).

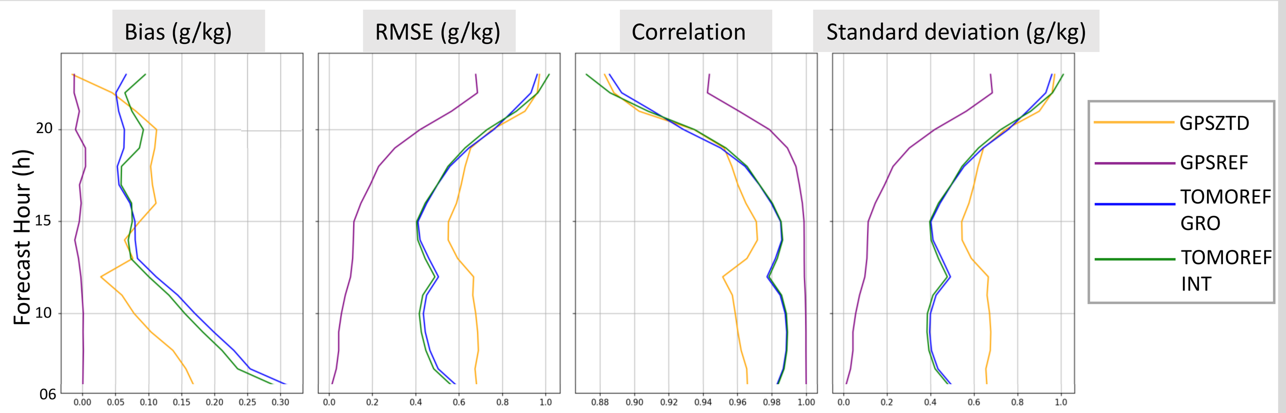


Fig 6. QVAPOR: WRF assimilation vs. BASE run (2021-06-23 18:00:00).

6. Conclusions & Outlook

The integration of ground- and space-based observations at various product levels enables the use of the tomographic 3D refractivity field as a complementary data source for numerical weather prediction (NWP) models, with particular potential to improve forecasts of humidity-related parameters.

Challenges:

- Limited availability of open-access RO data, despite the growing number of commercial data providers.
- Real-time tomographic processing over larger domains, constrained by the need for precise time-synchronization between space- and ground-based observations and by significant computational demands.
- Towards 4DVar assimilation (currently based on 3DVar), where operational implementation entails considerably higher computational costs for a given assimilation window.

More details of the tomographic studies can be found in the following reasearch:

Möller, G. (2017). Reconstruction of 3D wet refractivity fields in the lower atmosphere along bended GNSS signal paths (Doctoral dissertation, Technische Universität Wien).

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.

Hanna, N., & Weber, R. (2023, May). Tropospheric tomography-integration of ground-and space-based GNSS observations. In EGU General Assembly Conference Abstracts (pp. EGU-9910).

Cegla, A., Moeller, G., Rohm, W., Kryza, M., & Taszarek, M. (2024). Application of integrated GNSS tomography in observation study over the area of southern Poland. Advances in Space Research, 74(8), 3654-3667.

Acknowledgments: This work was funded by the National Science Centre (NCN) Poland, by the Grant: UMO-2020/37/B/ST10/03703. Radar data were obtained through a license agreement from OPERA. We thank SPIRE Global for delivering RO data. We also thank the Wroclaw Center of Networking and Supercomputing computational grant using MATLAB Software License No: 101979 (https://www.wcss.wroc.pl) and License No: 173, thanks to which the WRF-based weather models were calculated.

EGU General Assembly 2025