Optimizing GNSS Tomographic Nodes' Distribution Using Signal Geometry for Enhanced Tropospheric Sensing

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THE IDEA

Global Navigation Satellite Systems (GNSS) tomography enables high-resolution tropospheric sensing, but its accuracy is **limited by conventional node distribution** methods that overlook GNSS signal geometry. This study introduces an optimized node placement approach that **accounts for the spatial distribution of GNSS signals** using a four-step algorithm. The method employs node-based parameterization with natural cubic spline interpolation of wet refractivity. The proposed algorithm was evaluated against both voxel-based and node-based models for a dense network of low-cost GNSS receivers in Wrocław, Poland. Evaluation against WRF model outputs and radiosonde data demonstrates **improved accuracy, particularly at altitudes between 0.5 and 2.0 km**. Results show a reduction in RMSE of estimated wet refractivity by 0.5–2.0 ppm, confirming the **benefits of geometry-aware node distribution in GNSS tomography**.

METHODOLOGY

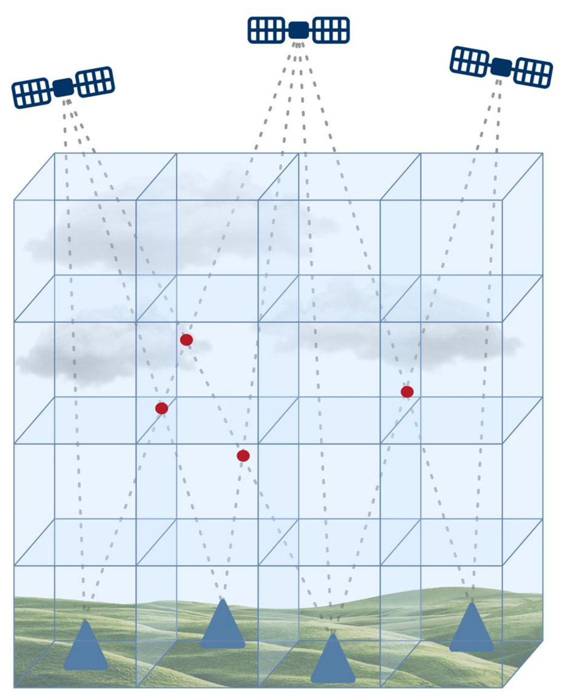
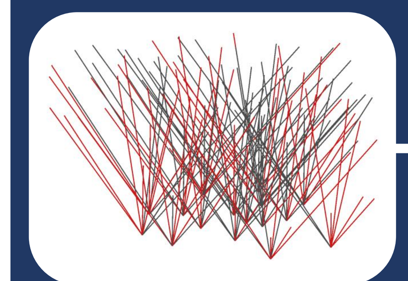


Figure 1. Schematic representation of a tomographic model domain utilizing slant wet delay (SWD) observations along GNSS rays (dashed lines) to estimate wet refractivity for particular voxels (blue cubes) or their nodes. Red points denote the proposed locations of additional tomographic nodes to enhance refractivity estimation near GNSS signal intersections.

- **GNSS troposphere tomography** uses the inverse Radon transform to reconstruct 3D humidity-related fields by analyzing delays in GNSS signals passing through the troposphere
- **Conventionally**, the model domain is divided into a regular grid to estimate wet refractivity at predefined voxels or nodes (Fig. 1). In contrast, this study proposes a novel approach that first analyzes the distribution of GNSS rays within the domain to identify optimal spots for refractivity estimation.
- **The proposed algorithm** operates in a four-step approach, outlined below. First, the most valuable observations are extracted (Step 1), and intersections of the GNSS rays are identified (Step 2). Next, the intersections are clustered using the DBSCAN method to avoid small inter-node distances (Step 3). In Step 4, regular nodes are incorporated.

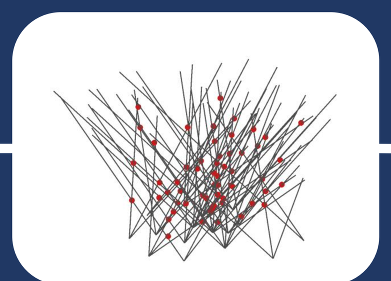
STEP 1



SELECT INTERSECTING RAYS

to use the most valuable observations

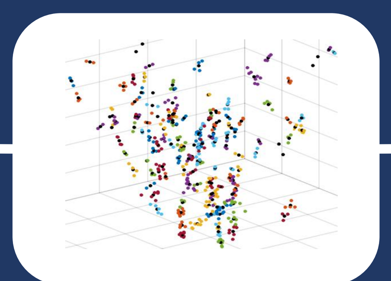
STEP 2



IDENTIFY POINTS OF INTERSECTIONS

to identify spots with the most GNSS information

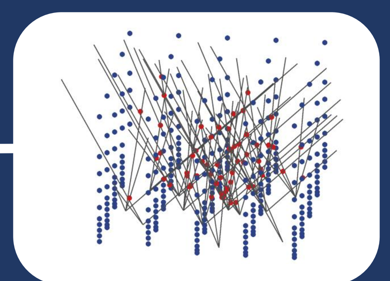
STEP 3



CLUSTER INTERSECTIONS

to avoid small interdistances between the nodes

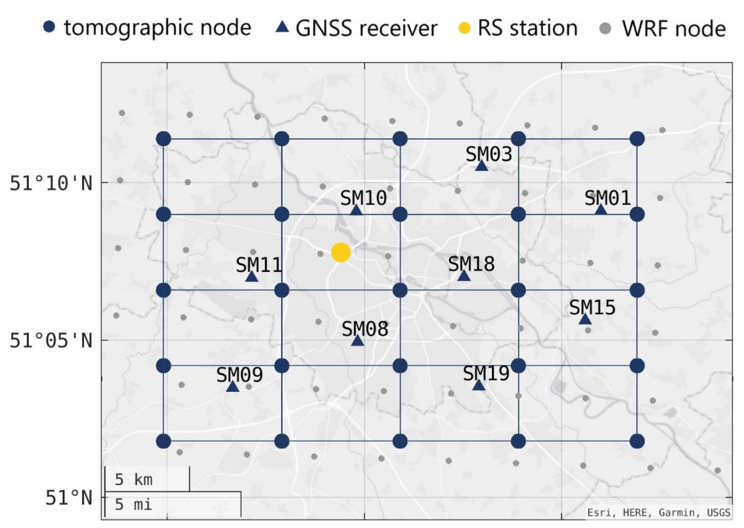
STEP 4



ADD REGULAR NODES

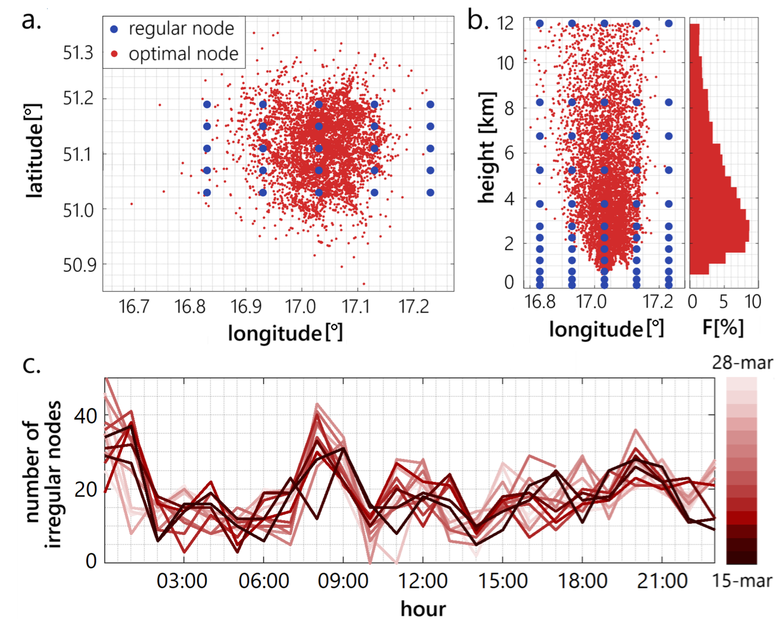
for proper modeling of the SWD

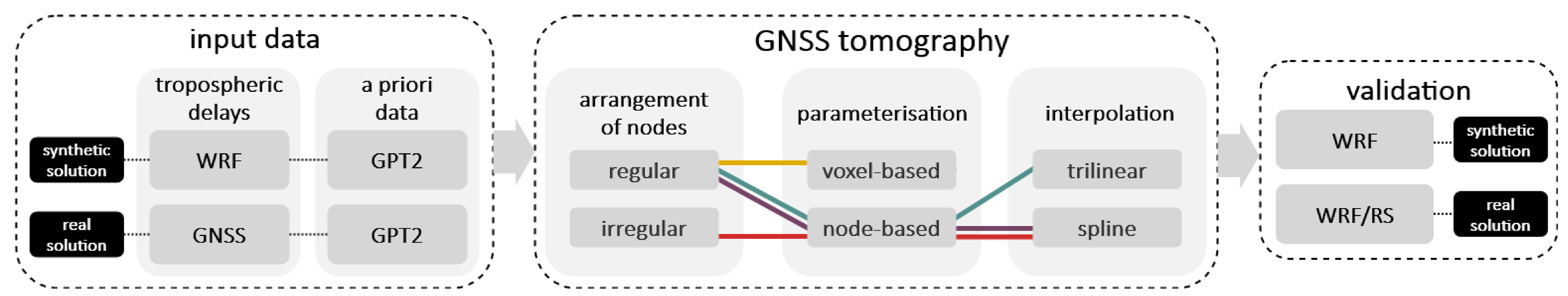
CASE STUDY



The case study was conducted using a **network of 16 low-cost multi-GNSS receivers** located in the urban area of Wrocław and its suburbs. In the conventional approach, tomography was based on the voxel structure with a horizontal resolution of 5 km, in 11 vertical levels. Wet refractivity (N_w) estimates were validated using radiosonde (RS) observations and the Weather Research and Forecasting (WRF) model.

The optimization algorithm was applied to two weeks of observations (15–28 March 2021). The **spatio-temporal distribution** of the resulting nodes was analyzed. Horizontally, the optimal nodes are regularly distributed (a), while vertically, they **concentrate at 1–3 km altitudes** (b), where GNSS ray intersections are most frequent. Temporal variability (c) shows a **sidereal pattern** linked to GPS constellation geometry.





To evaluate the optimization algorithm, an experiment was conducted involving four tomographic runs with different parameterization approaches: voxel-based (yellow), node-based with trilinear interpolation (green), node-based with spline interpolation (purple), and the proposed method (red).

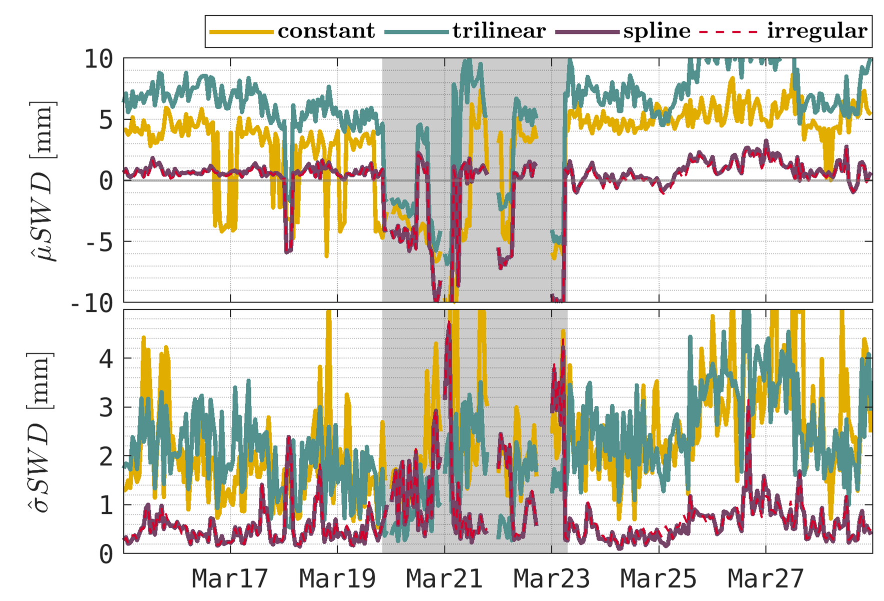


Figure 2. SWD statistics from TOMO2 vs. a priori model over time for different parameterizations ($\hat{\mu}$ denotes bias, $\hat{\sigma}$ is standard deviation).

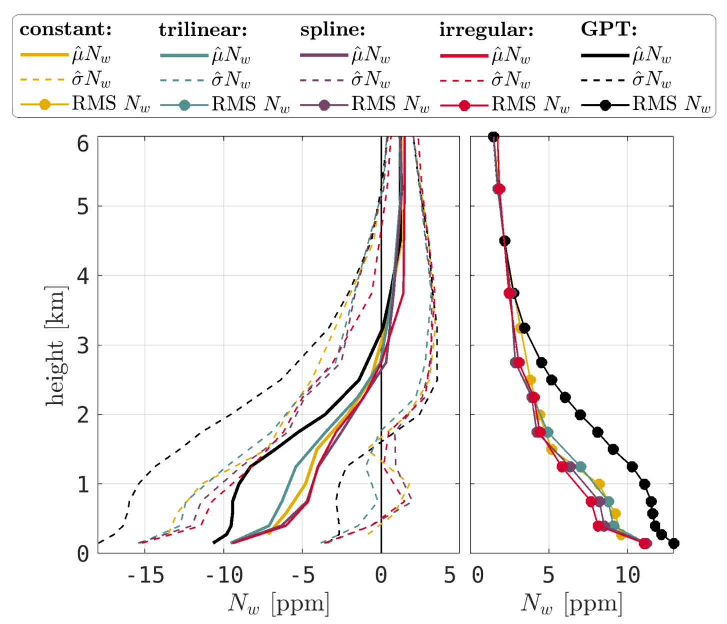
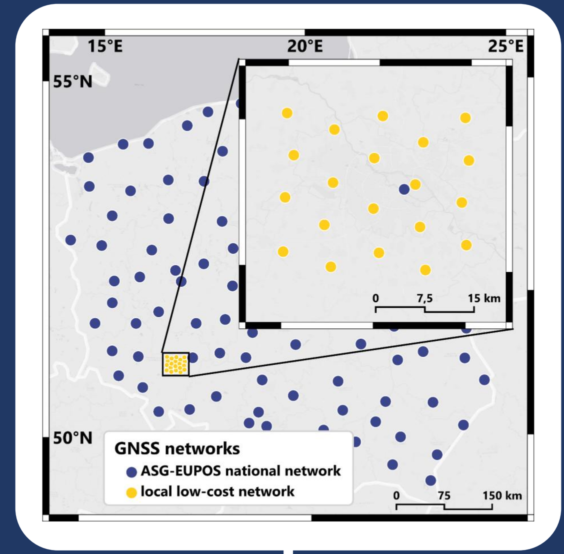


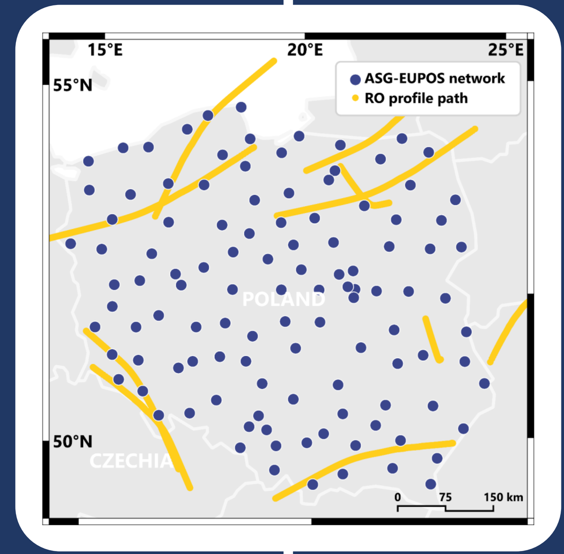
Figure 3. Statistics of the reconstructed N_w fields from TOMO2 vs. WRF model for different parameterisations.

FUTURE APPLICATIONS

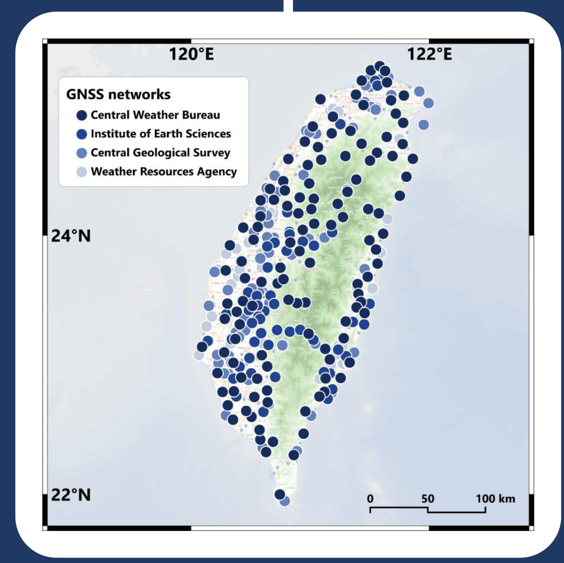
A.



B.



C.



This study confirms the benefits of using geometry-aware node distribution in GNSS tomography. While the improvement in humidity fields estimation is relatively modest, the impact could be more substantial when applied to tomographic models with specific observational geometries:

A. Dense networks of low-cost receivers

Integrating dense networks of low-cost receivers (<10 km) with national-scale GNSS networks (~80 km) offers the potential to enhance the resolution of humidity retrievals. Map A illustrates an example of such networks in Poland. However, aligning tomographic grid spacing with the heterogeneous distribution of stations is not feasible using conventional methods. In this context, the applied optimization algorithm may enable effective utilization of both dense and standard observational data.

B. GNSS tomography with RO observations

GNSS radio occultation (RO) profiles can improve tomographic models by introducing a new observation geometry (Cegla et al., 2024). Map B shows the distribution of RO profiles during a 2-day heavy precipitation event over Poland. As RO observations are more horizontally oriented and independent of GNSS station spacing, standard tomographic grid definitions are suboptimal. The proposed algorithm can be adapted to integrated tomography to emphasize the impact of RO data on humidity field estimation.

C. Non-uniform distribution of GNSS stations due to orography

Performing GNSS tropospheric tomography in regions with specific environmental characteristics can pose challenges for defining an appropriate grid. In such cases, regular grid spacing is suboptimal. Map C shows an example from Taiwan, which is covered by several GNSS networks (over 200 stations). However, due to the mountainous terrain in the island's center, high-resolution estimation of N_w is not feasible across the entire domain. Therefore, identifying optimal grid node locations based on signal geometry is essential for obtaining high-quality three-dimensional humidity fields.

FIND OUT MORE

Initial results highlight the significance of the geometry-aware algorithm in designing tomographic nodes. The greatest impovement was observed at altitudes with the highest density of the GNSS signal intersections. This approach holds even greater potential when applied to more complex observational geometries. Full details are provided in the following paper:

Trzcina, E., Rohm, W., & Smolak, K. (2023). Parameterisation of the GNSS troposphere tomography domain with optimisation of the nodes' distribution. Journal of Geodesy, 97(1), 2.

Acknowledgements

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