Review of PhD thesis

"GNSS troposphere tomography as a part of weather forecasting systems" by Estera Trzcina

Submitted to the Institute of Geodesy and Geoinformatics, The Faculty of Environmental Engineering and Geodesy, Wroclaw University of Environmental and Life Sciences, June 2023

The present thesis builds on work developed at Wroclaw University, within the group of Prof. Witold Rohm (the thesis supervisor) aiming to turn GNSS tomography into a relevant source of information for weather forecasting.

GNSS meteorology has been around for more than 20 years, but its progress has been slow, due to the need of developing innovative approaches to assimilate its data and of sufficiently high-resolution GNSS observations with adequate geometry and operational designs. The regional nature of ground based GNSS observations, only available over land and with a very heterogeneous density, have also made them less interesting for the leading weather forecast systems, such as ECMWF's and NCEP's. There is, however, great promise in these new datasets, obtained by cheap sensors that do not require calibration and do not drift in time, making the topic of the thesis of great significance.

The thesis takes benefit from a strong network of collaborative research at the European level set up by the Wroclaw group, and from the earlier development of a tomography model and of field observations. Its three main contributions led to three papers, already published, in top journals: Trzcina and Rohm (2019, Quarterly Journal of the Royal Meteorological Society), on the near real time assimilation of wet refractivity into NWP (Numerical Weather Prediction models), Trzcina et al. (2020, Journal of Geophysical Research), on the development of TOMOREF, a critical module for the assimilation of tomography into the WRF model, and Trzcina et al. (2023, Journal of Geodesy) on the optimization of the node location in tomographic models. Trzcina co-authored three other papers in associated topics, also in relevant journals. This is a strong set of published literature for a PhD candidate, easing the task of the reviewer.

GNSS tomography faces a number of challenges. The main challenge is the rank-deficiency of its observation equation system, meaning that it is an underdetermined linear problem. The standard response to that problem has been the inclusion of extra equations, not associated with GNSS. This is the approach that has also been followed by the Wroclaw model, although with some particularities. Such approaches make tomography dependent on those extra constraints, namely from NWP models, and may strongly reduce the added value of GNSS observations. Everyone is aware of that, and that limitation will remain with the use of the 4 GNSS constellations. A second challenge, not usually recognized and not discussed in the thesis, comes from the smoothness of GNSS observations resulting from the need to convert the data to the zenith prior to the decomposition between Hydrostatic and Wet components of the signal delay. That process implies the use of mapping functions, merging information from different elevations and azimuths, and leading to the GNSS effective inverted cone of observations. The production of Slant Integrated Water Vapor observations (SIWV, or their equivalent in refractivity variables) to assimilate into tomography, using estimated gradients, only partially compensates for that problem. Is there a way to recover SIWV observations not so strongly smoothed? Or do we need to live with smoothness and forget about mesoscale observations?

The previous question comes to my mind when I look at the main thesis results. The assimilation of tomography with the standard GPSREF module (developed for GPS-RO observations to be assimilated by WRF) led to quasi-neutral or slightly positive impacts in the forecast quality. The experiment, at 80 km horizontal resolution for the scale of Poland, suggests that the focus was on synoptic scale features, but the apparent lack of signal from GNSS raises the question of the amount of smoothness that was implied in the Slant observations and of how much of it is inevitable. A comparison with published results with InSAR data, that measures the same effects at a much higher effective horizontal resolution suggests that excessive smoothness may be to blame on the quasi-flat results of GNSS data assimilation.

The exercise shown in Trzcina et al. (2020), using a specially tailored data assimilation module, does indicate a positive impact of tomography but still at a very low level (0.5% in relative humidity) even if the case study concerned a heavy rain even. Again, this could be the result of the excessive smoothness in the Slants, or a consequence of the excessive weight of the external data added to the tomography. How could we check what is the case?

There is, however, the possibility that there is only that much room for improvement in current state-of-art models, which are in some cases very good. If that is the case it would imply the need for long assimilation experiments, not case studies, that could help to compute the significance of slight changes in the model performance across many different weather conditions, and maybe different climates. This is probably a way forward to make a stronger case for the inclusion of GNSS tomographic results into NWP, although it clearly requires a non-trivial long-term effort.

The third main paper (Trzcina et al. 2023) is of more technical nature, concerning the advantages of adaptive geometries in the design of the tomographic domain, taking into account the distribution of GNSS data, and compensating for regions which are void of data, namely at lower altitudes. This is a topic that has motivated a lot of recent studies, again with hints of possible improvements, but yet without a breakthrough. So, the work is clearly justified. In this case the problem is how to validate small scale water vapor features in these subsectors of the domain, near the surface, when all direct observations come from radiosondes which only probe the vertical structure of water vapor? This is a limitation of most (maybe all) studies of tomography, that compute 3D distributions of water vapor but only validate vertical profiles. New ideas, maybe merging unconventional data sources (InSAR?) are required.

The previous text highlighted what I think are the main limitations current applications of GNSS tomography, which are still mostly unsolved after the relevant contributions of E. Trzcina: (a) excessive dependency on first guess data from external sources, namely NWP; (b) excessive smoothness of slant observations coming from GNSS data processing required to compute wet delay; (c) limited size of the numerical experiments to support small but positive improvements in weather forecasts; (d) lack of validation of the horizontal water vapor distribution at the voxel level. Only limitation (c) is easy, but expensive, to overcome.

In spite of that, the present thesis clearly developed some advancements. Ground based GNSS water vapor observations can be assimilated at least in limited area models, improving the model forecast skill in an era where further improvements are increasingly more difficult. The required network of observations is cheap and easy to maintain.

GNSS meteorology is an area of research at the interface between Geodesy and Meteorology. These are rather different cultures, and I praise the candidate for the effort in exploring the literature of meteorology to be able to make a relevant contribution. I know (by my own experience in reading from Geodesy) that it can be a difficult task, and I only found a handful of imprecisions (not in the papers but in the Introduction) that are not at all relevant. In what concerns the Geodesy component, of which I am much less aware, I found the thesis very well explained, with a clear description of all mathematical steps required to develop a tomographic solution. In both components (Geodesy and Meteorology) I found the text very well supported by relevant references.

Besides the major comments described above, the thesis addresses many details that merit discussion. I will now look at some of those points.

The discussion of tomographic model in Trzcina and Rohm (2019) constrain the solution of the tomographic equation (6) with the addition of a priori values of the unknowns at some voxels (eq 7) but throw away a large number of observations to avoid the need to deal with rays crossing the wall boundaries (at low elevation). These two options, common in many tomographic approaches, appear to reduce the added value of GNSS observations and reinforce its dependency on haddock assumptions. While it is clear that a boundary condition is required in such cases, and it may not be trivial, this is a problem that needs a better solution.

The use of reanalysis data as an observation is often done, due to the lack of sufficient radiosondes. However, the water vapor density is not very well constrained in reanalysis, as it is a poorly observed variable, and not well mixed. Reanalysis is relatively low resolution, especially in the case of ERA-Interim at 75 km, implying that it can not represent the mesoscale features that characterize the water vapor field. In the case of the method used in that paper, there is also a dependency on Aladin model data, which may introduce another source of uncertainty.

The results in Trzcina and Rohm (2019) indicate really small improvements (cf page 1044) in relative humidity, and neutral impact in the main prognostic variables, sometimes even negative impacts on model skill. The lack of sufficient direct in-situ observations raises, however, some questions. Overall, Trzcina and Rohm (2019) showed the possibility of near real time GNSS tomography being assimilated into a forecast model with a reasonable latency, but with underwhelming results in its impact on forecast skill.

Trzcina et al. (2020) takes another step towards assimilation of the tomography fields, by developing a specific module for the WRFDA system, directly dealing with wet refractivity. The module is tested in one heavy precipitation event, again with a rather small, but positive, impact on the model representation of relative humidity and a very small impact on precipitation. The study does indicate a larger impact than that of assimilation of ZTD (zenith total delay, associated with the integrated water vapor column). For such low levels of impact, a more extended study is required to guarantee the relevance of adding a new data source to NWP. As in Trzcina and Rohm (2019) the tomographic model required NWP information from the ALADIN model, and it shares many of the same limitations.

The TOMOREF operator developed appears to have a potential for disseminating the assimilation of GNSS tomography by other groups, many with different tomographic approaches, as it builds on the most popular atmospheric research model, WRF. There is however some way to go, with a need for longer GNSS data assimilation experiments, with better validation of the regional water vapor fields, and better, less constrained tomographic models, capable to better use GNSS observations.

The third main paper of the thesis (Trzcina et al. 2023) explores the geometry of the tomographic model, aiming to optimize its node distribution as a function of available GNSS slant observations. This study looks at tomography at a much smaller horizontal scale, with a dense (3km) network of low-cost stations deployed at Wroclaw and attains some improvement in the estimation of low-level water vapor. The paper concludes for the need of densification of the GNSS network in order to be able to observe the low troposphere at high vertical resolution. It does not however validate the horizontal features of the water vapor field, a difficult but needed task in tomography. The topic of optimized geometries for tomography appears to be still wide open, and I am not sure it can have a significant impact on the field.

I believe there is still a lot of potential gain to be taken from GNSS tomography. For that we need sharper images of the low troposphere: denser networks, more independent rays, less smoothing, but also corresponding 3D observations that can be used to validate the tomographic results at mesoscale resolutions of a few km. Maybe GNSS needs to be used in combination with other observations, such as InSAR or multispectral optical retrievals. On the other hand, it is clear that a lot more data is needed from field experiments and data assimilation exercises, covering full annual cycles in different climates, to integrate the many small improvements that this specific data source can contribute for rather complex NWP models and their data assimilation systems, which have already attained a state where further improvements in skill come at a very high cost.

The PhD thesis by E. Trzcina made some significant contributions to the progress of the field of GNSS meteorology. It showed that GNSS tomography can be retrieved in near real time, can be assimilated by operational numerical weather prediction models and can improve the performance of those models. The fact that the found improvements are somewhat modest maybe a consequence of the current quality already attained by NWP systems, but I think is still largely the result of excessive smoothing in the tomography methods, coming from the GNSS data itself, from the incorporation of NWP fields in the inversion, and from a still inefficient use of slant observations. The progress in the field is also constrained by a lack of independent 3D high-resolution observations of water vapor, that can help verify the accuracy of different tomographic solutions, reducing the current overreliance on NWP products that we know are not good enough for this purpose (and that is why we need new data sources such as GNSS!).

Finally, I have to mention that there is always a lot of work in a PhD that is not easy to assess from the reading of the thesis. The development of a new data assimilation operator is not a standard task, and it carries a lot of careful mathematics and many numerical tests. The set up and operation of a field experiment has other completely different difficulties, where many things can go wrong. All these obstacles were clearly delt with, certainly with good teamwork at Wroclaw.

The fact that there is still some way to go in this research topic should motivate us to think about potential innovations that can be tested, and the need to reinforce this interaction between Geodesy and Meteorology to deliver better methods and explore larger datasets of observations.

A final comment on GNSS meteorology. The requirements for precise positioning (the main goal of GNSS) and of water vapor tomography (the opportunistic exploration of the “noise” in the GNSS signal) are somewhat contradictory. The former requires smoothing, the latter needs sharp images. Can we deliver both? Is there a way to get sharp slant observations while keeping the coherency of the signal? I hope this is a good question for a geodesist, an area where the mathematical rigor as always been a defining mark.

For many years, weather forecasting has been the testbed for new methods in data analysis. It offers us a new experiment everyday and at each location, if we are able to gather the required data at the relevant temporal and spatial scales. Its societal value justifies the gathering of efforts from different disciplines and from different teams. While it is a remarkably difficult problem there are still opportunities for relevant improvements, and GNSS meteorology may be an area where they can be obtained.

13 June 2023

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