Universität Stuttgart

Institut für Navigation

Direktor
Prof. Dr. techn. Thomas Hobiger

Ansprechpartner/in

Institut für Navigation • Breitscheidstr. 2 • 70174 Stuttgart

Wrocław University of Environmental and Life Sciences
Discipline Council of Civil Engineering, Geodesy and Transport
Grunwaldzka 55
50-357 Wrocław
Poland

Kontakt
Institut für Navigation
Breitscheidstr. 2
70174 Stuttgart

T 0711 685-83400
F 0711 685-82755

E-Mail:
thomas.hobiger@ins.uni-stuttgart.de

URL:
www.ins.uni-stuttgart.de

Review report on the PhD thesis

GNSS troposphere tomography as a part of weather forecasting systems

submitted by Estera Trzcina.

This document summarizes the evaluation of the PhD thesis "GNSS troposphere tomography as a part of weather forecasting systems" which has been submitted by Mrs. Estera Trzcina (hereafter abbreviated as ET) in April 2023. In the following, the thesis, which is written in cumulative form will be analyzed section-by-section before a general evaluation of the work is performed.

Evaluation of the written thesis

Chapter 1 – Introduction

This chapter starts with an overview on the motivation behind this work in which ET puts her research in perspective to studies from the past or ongoing research activities at other institutes. The high spatial and temporal variability of humidity, resp. water vapor, in the lower atmosphere is briefly discussed and then used to motivate the need for monitoring of this atmospheric constituent. In doing so, ET sets the focus on slant wet delays from GNSS and aims to utilize this observation type to improve the understanding about the 4D structure of wet refractivity fields by assimilating GNSS observations into different numerical weather prediction (NWP) models.

In section 1.2 ET explains the basic physics that cause refraction of electromagnetic signals in the troposphere before she discusses how this effect relates to GNSS observations. The section closes with a discussion

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about mapping functions, which are used to convert zenith delays into slant delays at arbitrary elevation angles.

In the next section (1.3) the concept of GNSS troposphere tomography is introduced, starting the with basic principles of inversion and the challenges of ill-posed inversion problems. As for the latter, ET discusses several methods (SVD, regularization, Kalman filtering and ART) which have been used in the past to overcome the fact that one has to deal with an under-determined equation system which cannot be solved by means of classical least-squares estimation. The section is then concluded by a rather brief discussion about how to parametrize the wet refractivity field. Here voxel- and node-based parameterizations are presented, whereas a more in-depth discussion is carried out for the latter one.

In section 1.4 ET is then introducing the main idea of her PhD research, i.e., direct assimilation of GNSS data into NWP models. She presents a general overview about numerical weather prediction before briefly discussing dynamic models which allow to map physical models into a mathematical framework which can then be used to analyze and predict atmospheric conditions. The question of proper choice of initial conditions is then addressed in greater detail since their values determine the goodness/correctness of an NWP model run to some great extent. A longer subsection is then dedicated to data assimilation. Here ET discusses empirical and stochastic methods which make it possible to consider measurement/observational data in NWP and thus improve the quality of such models. Particle filters are briefly mentioned, but since their complexity grow exponentially with the size of the state, it is concluded that this approach might not be applicable and ET focuses more on Gaussian approximations, which implicitly restrict the representation of stochastic parameters to a single type of probability density function, namely classical Gaussian normal distributions. ET discusses then the first and second moment, i.e., mean/expectation value und variance, of such a distribution, which is sufficient to describe the assimilation process in which model states are updated/corrected by external data/observations. Thereafter, a discussion about state-of-the-art NWP data assimilation of GNSS delays, including a very good literature overview, is made. The section concludes with a description of the methodology which has been developed and applied in the three papers. Here ET focuses on the aspects of near-real time applicability, the actual assimilation into NWP models and the question on how to parameterize the atmosphere in the tomographic domain.

Overall, the chapter appears to contain all the crucial information that is necessary to understand the basics of ET's research work and comprehend the content of the related scientific papers which were published by her.

Chapter 2 – Content of Publications

This chapter briefly summarizes the three peer-reviewed papers which form the base of this cumulative dissertation. The chapter is kept rather short, which makes sense, since the papers are available appendices A-C anyway. The contribution from ET to all three papers are explicitly stated, which helps to evaluate how and to which extent ET provided an original solution to a particular scientific problem and how well show gained an overview on a broader research topic.

Chapter 3 – Conclusions
In this short chapter, the main findings, which are documented in the three peer-reviewed papers, are summarized for the reader. ET lists seven main findings concerning the potential of GNSS to provide wet refractivity fields, the use of GNSS for operational weather forecast, the choice of a proper operator for assimilation or the selection of the model geometry, just to mention a few. The chapter ends with an outlook on what can be done in the future. ET explains that the sparsity of GNSS observations might need to be addressed better by the grid structure and that boundary conditions or the limitation of the model domain should be addressed properly. Finally, the question of moving GNSS receivers for weather forecasting is briefly mentioned.

References
The list of references appears to be complete and the reader should be able to find all proper sources of formulas, theories or methods which are mentioned in Chapters 1-3. However, only two of the three papers from ET, which are forming the base of this dissertation, are listed in the references section. This might be addressed when revising the dissertation after the oral defense.

Appendices A-C
The three appendices are dedicated to the three peer-reviewed scientific papers which form the base of this dissertation. Since all three papers are peer-reviewed and have already been published they have undergone already a thorough review process, from a formal and scientific point of view, respectively. Therefore, no detailed review is given here, but the overall scientific contribution from ES is evaluated in the following.

Scientific evaluation
In order to evaluate the thesis from a scientific point of view one needs to consider that ES succeeded already in publishing three paper, which are part of this thesis (appendices 1-3), in renowned peer-reviewed international journals. ET has clearly demonstrated that she is capable to work on a high-level scientific problem, identify the risks and advantages that come with novel approaches and develop a solution that aims to provide more precise and accurate results which will allow us to gain a better understanding of our planet. She has mastered the underlying theoretical framework of numerical weather prediction, studied how GNSS observations can be assimilated into such models and developed a suitable operator that serves this purpose. ET has tested her approaches on real observations and carefully evaluated the impact of GNSS data in NWP. In doing so, she studied how her approach quantitatively and qualitatively improves NWP. ET also reflects about the proper choice of the grid model, respectively the way how spatial information in the 3D/4D domain can be represented, so that it is possible to consider physical characteristics of the atmosphere in a suitable way while keeping the state space manageable. In addition to that, it can be stated that ET works in a very controlled fashion. This means she is not only comparing her results against independently obtained solutions, but she also reflects on the formal errors that are provided together with the estimates from the filter or critically scrutinizes her own results.

Overall evaluation

Judging the thesis from a more holistic view I would say that ES has demonstrated that she is clearly able to define and limit scientific issues within her specialist field and then work according to an established plan towards achieving an established goal. Based on the evaluation of her thesis I am confident that ET has been trained, and achieved a good understanding of, scientific research methodology. Which means that she learned to understand the relevance of her research results, within and outside the discipline in question, and its significance to the human being and society. I would state that ET is able to critically evaluate her own research results and the work of other researchers as well as she has demonstrated to be able to work effectively in inter-disciplinary research groups by adopting an open approach to other scientific fields.

Recommendation

Based on the evaluation carried out in this review I think that Mrs. Estera Trzcina has gained all the necessary skills, has demonstrated enough scientific maturity and communicated her findings to a large scientific community. Therefore, I recommend to continue the with the process of the dissertation process and evaluate her thesis as

positive with honors

since he has really demonstrated outstanding work in her discipline. In order to comply with the university's regulations, her positive evaluation is expressed by the following sentence.

In my opinion, this doctoral dissertation fulfills the requirements for a doctoral degree in particular under Article 13 of the Act of March 14, 2003 Ustawa o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (tekst jedn. Dz.U. z 2017 poz. 1789).

I am looking forward to Mrs. Trzcina's PhD defence. Corrections and suggestions for very minor improvements on her dissertation will be communicated with her directly.

Yours sincerely,

Thomas Hobiger