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Expert report on doctoral thesis

„Modeling of Troposphere Parameters from GNSS Observations to Ground-Based Stations and Low-Earth Orbiters"

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1. Background

The usage of ground and satellite based GNSS data for atmospheric remote sensing on regional and global scales has developed into an established meteorological observation technique during the recent two decades. It is operationally applied by numerous national and international weather centers based on data from several regional and global ground networks and satellite missions with Radio Occultation (RO) receivers. The corresponding atmospheric data products are continuously used to improve the day-by-day regional and global weather forecasts. In addition, there are many applications in atmosphere, ionosphere and climate research.

The PhD thesis of Paweł Hordyniec focuses on both GNSS observation techniques, ground based sounding and radio occultation. This combination makes the thesis of him unique, compared to the majority of theses in that field. Especially innovative is the investigation of the influence of liquid water, ice and clouds on the atmospheric GNSS data products, the tropospheric delays and the vertical bending angle profiles. The influence of these hydrometeors is usually neglected in the data analysis. Only very few publications are available on this topic. These investigations would allow new future atmospheric GNSS data products (e.g. cloud occurrence).

From my point of view the topic and the content of the PhD is very appropriate as an important scientific contribution on highest international level of recent cutting-edge GNSS remote sensing research.

2. Content of the doctoral thesis

The PhD is a cumulative thesis. Four papers with Paweł Hordyniec as first author form the thesis core. The papers are connected by the identical research field: GNSS based atmospheric remote sensing. Three of the publications (I-III, numbering see below) are already printed, one (IV) is accepted, i.e. all papers passed successfully a critical review process by internationally leading scientists. The candidate gives the background and framework of these four papers within three chapters, which are in front of the publication reprints. The candidate contributed during his PhD period to four other papers as co-author, which are not part of the thesis. This quite extensive publication work indicates that he is an active member of the international scientific community in that field already in the early career stage as PhD student.

The **Introduction** is the **first chapter**. It contains an appropriate short description of the scientific motivation and the background of the thesis. The ground and satellite based GNSS remote sensing techniques are introduced with focus on the usage for the improvement of operational weather forecasts. Basics of the atmospheric refraction are given, before the ground and space based GNSS sounding techniques are introduced briefly and descriptively. This first chapter ends with the characterization of the methodology, which was used by the candidate to reach his scientific goals.

The required description of the content of the four „core" papers (see below) of the PhD is comprehensively and briefly given in the **second chapter**: **Content of publications**. The candidate successfully summarizes in a brief manner the most important results of his scientific work.

The short **third chapter** contains the **conclusions and prospects**.

The major scientific part of the thesis are four ISI listed publications, which are listed below including a short summary from my prospective.

Paper I: Assessment of Errors in Precipitable Water Data Derived from Global Navigation Satellite System Observations (Journal of Atmospheric and Solar-Terrestrial Physics, 2015)

This paper addresses uncertainties in precipitable water vapor (PW) data, derived from Zenith Total Delay GNSS observations. The uncertainties are broadly evaluated. A major result of the study is the fact, that the usage of numerical weather models instead of empirical models significantly reduces the PW errors. The reduction itself depends mainly on the horizontal resolution of the used model. This result is of special importance for the usage of PW data from stations without in-situ atmospheric data. There the information must be taken from the analyses.

Paper II: Residuals of Tropospheric Delays from GNSS Data and Ray-Tracing as a Potential Indicator of Rain and Clouds (Remote Sensing, 2018)

This study demonstrates that a non-negligible GNSS propagation delay can be introduced by atmospheric particles. This can be potentially used to provide information on the presence of these particles. The investigations are based on extensive ray-tracing calculations to identify the non-particle induced propagation delay from the total one to isolate the particle-induced delay. The work contributes significantly to the potential provision of additional information from GNSS atmosphere observations compared to the current products, which focus on the gaseous phase of water.

Paper III: Simulation of Liquid Water and Ice Contributions to Bending Angle Profiles in the Radio Occultation Technique (Advances in Space Research, 2018)

The paper reports on extensive numerical simulation calculations to investigate the impact of liquid water and ice (clouds) to vertical bending angle profiles, derived from GNSS radio occultation data. Data from the Global Forecast System throughout 2016 were utilized to simulate the effect of the clouds on the retrieved profiles. One finding is, that the liquid water effect could reach ~10% (bending angle) for unusual weather phenomena with strong atmospheric inhomogeneities. The effect is much smaller for ice clouds (~2%).

Paper IV: GNSS Radio Occultation Profiles in the Neutral Atmosphere from Inversion of Excess Phase Data (accepted manuscript for Terrestrial, Atmospheric and Oceanic Sciences. 2019).

The paper describes results of quite complex software developments for GNSS radio occultation data analysis. The retrieval starts at the processing level of atmospheric phase delays. It covers the mathematical/physical inversion, including wave optics based algorithms for the handling of the lower troposphere, which exhibits strong vertical refractivity gradients. These gradients make the GNSS tracking and the retrieval of atmospheric parameters difficult. Mr. Hordyniec developed the retrieval software by himself. He compared his results with those from the official U.S. CDAAC analysis center, which has long-term experience of more than two decades in GNSS RO data processing. The agreement of the retrievals is in general satisfying. Especially in the lower troposphere and above the UTLS region however in part significant deviations were observed. The comparison results are discussed in detail to improve the retrieval software of Mr. Hordyniec for future use.

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3. Evaluation

The thesis is a complex scientific contribution at the cutting edge of current research in GNSS atmosphere sounding. The most remarkable and unique fact for me is, that both, ground and satellite based observation methods, are focused in parallel in this thesis. Due to the complexity and differences of the related data analysis for both techniques, this task is quite challenging, but the candidate excellently handled it. In addition, for both methods, the impact of hydrometeors on the GNSS observations was focused, a challenging topic, which is in the majority of the GNSS data analysis centers neglected due to its complexity.

Mr. Hordyniec successfully published his scientific results as first author of four ISI listed papers. A critical review process by international experts in the field is part of this publication process.

In addition to my very positive evaluation of the thesis I had several times the chance to be personally convinced on the high quality of the presentation capabilities (posters, but also scientific talks) of Mr. Hordyniec at international conferences. The audience always very well received his scientific messages.

The publications and the introducing chapters of this thesis are very carefully written. They are factually and methodologically correct. Several results are included, which are on the cutting edge of the research in this field. They document the excellent scientific abilities of Mr. Hordyniec and the excellent handling of the selected PhD topic. The current scientific knowledge is clearly referred at each page. I do not see any reason to doubt on the scientific creditability of the thesis.

I recommend without any reservation to accept the present thesis of Paweł Hordyniec as PhD work. In case a mark is required, I would rank the quality of the work without any limitation with the grade:

"With highest honors"

I wish Mr. Hordyniec highest success for his future scientific career and good luck for his personal life. I like to thank the Wrocław University of Environmental and Life Sciences for the selection as reviewer of this excellent doctoral thesis.

Prof. Dr. Jens Wickert