PHD THESIS REVIEW

PhD candidate: Mr. André Garcia Vieira de Sá
Thesis title: Tomographic determination of the spatial distribution of Water Vapour using GNSS observations for real-time applications

Review by: Assoc. prof. dr. Guergana Guerova
Organisation: Sofia University "St. Kliment Ohridski", Sofia, Bulgaria

Developed to provide accurate Positioning, Navigation and Timing services Global Navigation Satellite Systems (GNSS) is today an established atmospheric observing system, which can accurately measure the most abundant greenhouse gas - water vapour. Currently in Europe tropospheric product (Zenith Total Delay and Integrated Water Vapour) from over 2 500 GNSS stations are available for validation and assimilation in the state-of-art Numerical Weather Prediction (NWP) models used by the National Meteorological Services. However, water vapour is still under-sampled for severe weather events with high spatio-temporal resolution like intense precipitation, thunder and hail storm, which are associated with large economic losses. Thus obtaining accurate 3-D/4-D refractivity or humidity fields through tomographic reconstruction of GNSS signal delay has a potential to provide valuable input for advancing severe weather monitoring and forecasting. And is currently a prominent area of research within Europe.

This thesis addresses tomographic reconstruction of atmospheric water vapour with GNSS and has the following objectives: 1) to compare the inversion techniques and identifying strengths and weaknesses in the tomography processing; 2) to develop tomography with low latency by applying multi-thread libraries to the algebraic reconstruction technique (ART); 3) to conduct Observing System Experiments (OSE) with selected tomography method and evaluate it for case studies in Australia and Poland.

The thesis starts with introducing the context and the motivation. However, the motivation of the work can be better presented. Application of tomographic technique for tropospheric monitoring was suggested in 1999 and since then has been developed by several groups. In a recent review of the state-of-the-art of GNSS meteorology in Europe the following summary is given: "Today, after more than 15 years of experience, the networks are enlarged up to nationwide dimensions and numerous inversion strategies have been tested but GNSS tomography is still in an experimental phase." (Guerova et al., 2016). Thus this thesis contribution is towards further development of the technique by addressing the above mentioned objectives, which are both valid and valuable.

Chapter 2, 3 and 4 provide the well known basics of: 1) GNSS, 2) GNSS signal characteristics and propagation, 3) GNSS processing and 4) GNSS monitoring of the atmosphere. In addition, water vapor measurement techniques are compared and the the status of meteorology in Portugal is given. However, a significant level of detail of those chapters makes them unfocused. In particular, section "3.2 GNSS signal characteristics" will be necessary if the focus is the GNSS processing but this is not the case for this thesis. In section "4.3 GPS tropospheric parameters/products" a review of history of the mapping function development is given. It is not clear why this review is important and how it relates with the GNSS tomography reconstruction. Shortening and focusing of those sections will likely contribute to the thesis's readability.

Chapter 5 presents the theoretical background and reviews the the state-of-the-art of GNSS tomography. The-state-of-the-art description of tomography provides accurate review of the various software developed in the last 18 years and their strengths and limitations. Further it is suggested that: "The reason why the 4D information of the water vapor supplied by the GNSS tomography has not yet been used in meteorological institutes, for example through the development of methods for assimilation of 3D moisture information in its NWP models, may be due to a set of limitations in the performance of the technique." This statement is true for tomography products however, to the best of my knowledge two Meteorological Services (DWD and KNMI) are currently developing Slanth Delay assimilation for their operational NWP models. Observing System Experiment (OSE) with Slant Delay assimilation are reported by Kawabata et al., (2013)[1] and conducted by M. Bender (DWD COSMO model, reported at GNSS4SWEC). In this chapter is given, in addition, description of the input data but missing is information about the NWP model set-up used in chapter 8 and 9.

In chapter 6 Algebraic Reconstruction Technique (ART) for solving linear inverse problem is described. The original new results of the thesis are outlined in section 6.3.4. "Parallelizing Algebraic Reconstruction". Conducted are performance experiments for ART parallelisation by using 4 different algebra libraries. The performance experiments include: 1) usability, 2) reliability and 3) production speed. The best performing library was identified to be Eigen3 and was selected for the algebraic operations for SEGAL GNSS Water Vapor Reconstruction Image Software (SWART). A

[1] Kawabata et al., 2013, "A numerical study on a mesoscale convective system over a subtropical island with 4D-Var assimilation of GPS slant total delays" J. Meteor. Soc. Japan, 91, 705-721.

summary of Eigen3 library is given but the other 3 libraries are not described. Regretfully, no results from the experiments are presented.

Chapter 7 presents SWART tomography system components, implementation and evaluation using the Shepp-Logan phantom image test. In this section 7.1 "SEGAL GNSS Water Vapor Reconstruction Image Software (SWART) description" the motivation to implement ART is outlined namely: 1) high numerical stability, 2) possibility to handle large data input, 3) extensive grid cell configuration and 4) computational efficiency. The first SWART evaluation experiment shows that the lack of initial input data and/or its small perturbations can lead to a different results and/or unstable solution. This led to implementation of criteria ensuring convergence and optimal number of iterations. Furthermore definition of initial condition state is proposed by using a-priori data from various type. Section 7.2 presents the results from Shepp-Logan phantom image. Compared are the solution of ART with two other algorithms and the resulted standard deviation is 0.116, 0.122 and 0.199, respectively. For evaluation of the performance of the three algorithms it will be helpful to provide not the absolute values but the improvement percentage.

In chapter 8 the SWART algorithm is evaluated using synthetic and GNSS data. Section 8.1 presents SWART comparison with developed in France tomographic software (LOFTT_K) using synthetic data. The results from the comparion show: 1) absolute differences mainly below 4000 m and 2) large differences in the grid cells close to the boundary of the tomography region. Further evaluations for the number of iterations (section 8.2) and the initial state (section 8.3) conclude that less iterations are needed provided the initial state is well defined. Section 8.4 presents SWART evaluation of: 1) vertical resolution (1 vs 2 km), 2) introduction of noise (±3%) in the GNSS data and 3) number of iterations (300 - 1 000 000) for Australia. The evaluation concludes that: 1) better results are obtained for vertical resolution of 2 km and 2) noise introduction results in differences higher than 50% for some voxels. The number of iteration evaluation leads to the conclusion that the iterations alone could not provide satisfactory results without appropriate initial conditions. Interestingly all evaluations are with course horizontal resolution (200 km) and no evaluation of the horizontal resolution is considered. From the performed in this chapter evaluation it can be concluded that initial state and the quality of the Slant Delays are of essential importance for tomographic reconstruction with SWART.

In my opinion chapter 9 "Case studies" is excellent and very detailed. Section 9.1 presents a very well designed OSE (OSE1) for multimodel tomography inter-comparison covering 6 days in March 2010. The a-priori profiles are from NWP

ACCESS-A model with initialisations every 6 hours or at the start of the period. Three tomography models (SWART, BIRA and TOMO2) are computed and compared for solutions every 6 h or every 30 min. Tested is also the impact of observation staking for 30 min, 1 h and 2 h for both initial and pseudo-observations. The tomography results are evaluated versus the radiosonde and GNSS-RO profiles. The tomography intercomparison show that with ACCESS-A model initialisation every 6 h the best results are obtained for the layers below 4 km for all models but for the layer 4 to 8 km BIRA results are accurate while SWART and TOMO2 overestimate. Degradation of all tomography models is reported with ACCESS-A model initialisation at the start of the period. The degradation is most prominent for the layers 8 to 13 km. Further intercomparisons with GNSS observation staking and introduction of pseudo-observations are carried out. Reported is that "overall results seem to improve with longer stacking periods, however, when considering normalized RMS (Table 12), longer stacking periods (7b) improve considerably for BIRA for layers above 4 km." For the intercomparison of pseudo-observations it is concluded that adding pseudo-observations to ACCESS-A initialisation every 6 h gives the best results. Very interesting and promising results are obtained for the GNSS-RO intecomarison (section 9.1.6). To the best of my knowledge this is the first work, which considers sinergetic use of ground based and RO GNSS profiles and this is to be commented. Further in section 9.1.7 it is demonstrated that the SWART processing time is under 1 min, which makes it very suitable for real-time application for short range forecasting. In section 9.2 the second OSE (OSE2) is conducted covering 56 day period in May-June 2013 for Poland. This period was selected for a benchmark campaign of COST Action GNSS4SWEC and extensive evaluation of the GNSS tropospheric products has been carried out. In this thesis simulations are conducted with tomography domain with realistic horizontal resolution for the existing operational station density namely 50x80 km and the total number of voxels about 800. For OSE2 the a-priori profiles are from NWP WRF model and experiments are conducted with initialisation 1 h and 24 h. The results can be summaries as: "no interesting improvement from 24-hour to 1-hour was observed, as opposed to what was verified in the first case study (i.e. inter-comparison study regarding time resolution)." Suggested is that "the initialization field of WRF is not as determining as in the previous case study... and better results from 24h initializations are still obtained when comparing SWART retrievals from 1h initialization in some layers". This is an interesting finding and its interpretation, in may opinion, will require further investigation. Namely, the NWP model set-up in particular data assimilation, is likely to be critical for the quality of the used a-priori profiles. Thus this aspect of the WRF model needs to be carefully addressed in this section. A second aspect and difference to OSE1 is the use of "extensive validation of line-of-sight tropospheric slant total delays". In conclusion, it is not advisable to compare the OSE1 and OSE2 as the a-priori NWP models and their setup are different and so are the quality of the GNSS observations.

The last chapter gives summary and recommendations for future work.

As outlined in Guerova et al. (2016): "The future prospects of GNSS tomography, however, are encouraging.... Real-time humidity fields might be available in the future on a national or even a European scale if efforts are made to densify GNSS networks and to process SPDs in a consistent manner." This thesis addresses an important part of real-time provision of humidity profiles using the state-of-the-art GNSS station density in a realistic real-time tomography setup thus it is a valuable advancement in GNSS tomography field. **The dissertation fulfils the conditions set out in Article 13.1 of the Act on Academic Degrees and Titles, and on degrees and title in the field of art - OJ 2003 No. 65, item 595, as amended and I recommend Council of the Faculty of Environmental Engineering and Geodesy to accept it.**

QUESTIONS

1) Figure 3 (page 34) presents the PWV map for Portugal. However, PWV dependents of the station altitude thus the question is how are the shown values to be compared?
2) Please provide comparison and comment the differences of the NWP model set-up of ACCESS-A and WRF. Are the NWP models evaluated against GNSS ZTD/IWV for the OSE1 and OSE2?
3) In chapter 6 a parallelisation of the ART is conducted. What is the achieved production speed with and without parallelisation?
4) Why are the tomography results degraded for OSE1 when the ACCESS-A model initialisation is at the start of the period?
5) Please explain how are re-calculate profiles obtained (figure 52)?
6) How is the quality of the Slant Delays influencing the OSE2 tomography results? If possible provide quantitative estimation?

REMARKS

The thesis is well written and the presentation is mostly clear. Still, I would like to recommend some changes, which in my opinion will improve it.

1) Thesis structure and formatting:

a) Please consider shortening chapter 2, 3 and 4. They provide a well known basic knowledge and are too extensive.
b) Check the thesis formatting and ensure that only new chapters start with new page.
c) Check the figures for missing x or y-axis labels (figure 45,47, 48 but also others).

2) Thesis title:
The thesis title "Tomographic determination of the spatial distribution of Water Vapour using GNSS observations for real-time applications" in my opinion needs to specify is it about real-time applications in Geodesy or Meteorology.

3) Abstract:
a) The following text is, in my opinion, too strong and/or biased "Water vapor plays a crucial role in most atmospheric processes, however, it is not currently observed by the meteorological sensors with the desired spatial resolution. This is a knowledge gap and an important source of errors in numerical weather forecast model, particularly errors related to severe weather phenomena." Please revise or provide supporting citation from respected source.
b) The summary of the results is too short. This is the best part of a thesis and needs more than two sentences thus it is suggested to be revised.

4) Introduction:
   a) It is stated that water vapour variability "creates a fundamental problem for climate and atmospheric modeling", "water vapor monitoring is a prerequisite for model validations" and "the monitoring of water vapor could be a main contributor to explain and predict severe weather events". The statements are not convincing without a reference.
   b) The summary of GNSS tomography work includes developments after 2010 while the technique is first proposed in 1999 and developed since then. Thus it can be recommended to revise the paragraph to agree with the state-of-the-art in chapter 5.

5) Chapter 2, 3 and 4:
   a) The level of detail of those chapters can be reduced significantly as the main focus of the thesis is tomography. Suggested is to keep only the tomography relevant part of the chapters.
   b) Further example is:
   c) Revision of section "3.3 Propagation of electromagnetic signal in the atmosphere" is recommended.
   d) In section 4.3 the following is written: " Hordyniec et al (2015) shows the importance of collocated pressure and temperature sensors and the negative impact from indirect observations (meteorological

models/numerical weather models). When not collocated, the interpolation (nearest neighbor) affects the meteorological parameters by additional uncertainties, adding 1.18 mm bias to ZHD." This citation gives suggests that all NWP models have the above ZHD bias. However, it only concerns the specific NWP model. Thus this type of conclusion is misleading and the proper citation of the NWP model and set-up is required.

6) <u>Chapter 5</u>:
   a) Suggested is to include in this section review of Slant Total Delay assimilation OSE.
   b) It is appropriate to include a section with the NWP model setup used in chapter 8 and 9 namely ACCESS-A and WRF. This information is essential for interpretation of the OSE discussed in chapter 9.
7) <u>Chapter 6</u>:
   Adding a table with comparison of performance experiments with the 4 algebra libraries will strengthen chapter 6.
8) <u>Chapter 7</u>:
   Consider adding in table 4 also the relative values of std, z(min) and z(max).
9) <u>Chapter 9</u>:
   a) Consider changing the name from "Case studies" to "SWART water vapour reconstruction for Australia and Poland".
   b) Consider moving the acknowledgement on page 131 to the the beginning of the thesis where other acknowledgements are found.
10) <u>Chapter 10</u>:
   The following recommendation: "A good approach to decide the time resolution of the a priori data of other models instead of the last tomographic retrieval could be given by establishing a comparison between the available sources of IWV and a reference model and then checking the performance of each source. Whenever the performance of the source being considered as an a priori source is lower than the GNSS IWV, the decision should be to decrease the a priori source time resolution or the a priori should be less weighed." is not clear and as it concerns an important aspect of possible future work it is suggested to be revised.
11) <u>Minor changes:</u>
   Suggested is to improve readability of the following sentences:
   • page 8: "gratitude to all who that to some extent contributed to the elaboration of this thesis".
   • page 17: "developed from scratch" is not acceptable for scientific publication/thesis
   • page 18: replace "verified" with "achieved"

• page 18: Please specify "lower" it can be 10 m, 100 m, 1000 m, 5000 m.

• page 22: Please explain the difference between "field of meteorology and atmospheric monitoring (i.e now-casting and forecasting)"

• page 25: Suggest to replace "The largest gaps occur over oceans where most atmospheric conditions originate" with "The largest gaps occur over oceans where most of the evaporation takes place"

• page 26: Remove the vertical line.

• page 27: Replace "meteorological situations" with "weather conditions"

• page 27: Please replace: "NWP focuses on taking current observations of weather and processing these data with computer models to forecast the future state of weather." with "NWP employs a set of governing equations, numerical methods, and parameterizations of physical processes which combined with initial and boundary conditions are solved over a defined model domain (https://www.weather.gov/media/ajk/brochures/NumericalWeatherPrediction.pdf).
"

• page 27: Please replace: "Current weather observations serve as input to the numerical computer models through a process known as data assimilation to produce outputs of temperature, precipitation, and hundreds of other meteorological elements from the oceans to the top of the atmosphere" with "NWP is an initial value problem, the quality of the initial state is of crucial importance to the quality of the forecasts. The procedure of finding the initial state is called data assimilation (Guerove et al., 2016)."

• page 28: Please revise: "L = 2.5 ∗106 J "

• page 28: Please change: "T [k]" with "T [K]" and check on the same page that the capital letter is used for temperature unit.

• page 35: Please revise: "This information is disseminated in the form of electromagnetic signals in the frequency of the microwave, being mainly used for navigation, which was popularized by the American system"

• page 36: Please remove: "The major difference (Galileo) to existing systems is to ensure the provision of services irrespective of the existence of possible military crisis that could lead to an interruption or temporary coding signal from Russia or the USA because of its military character of origin."

• page 36: Typo " tridimensional"

• page 36: Please revise: "The categorization of the electromagnetic signal of the carrier wave (carrier beat phase) emitted by the GPS system in the frequency of the micro waveband L can be subdivided into several types of Pseudorandom Noise (PRN), which indicate the nature of the signal code."

• page 40: The following sentence needs attention "The electromagnetic signal interacts in different ways with the different atmospheric layers, so it is important to understand this behavior from the point of view of the estimation of atmospheric water vapor. With this in mind, a simple division depending on the signal behavior along its route is considered, which comprises only two layers, the troposphere and the ionosphere."

- page 43: Replace "N along" with "N in"
- page 43: Replace "solid portion" with " ice part"
- page 45: Check english: "due to its presence"
- page 45: Check "ephemeris and orbits"
- page 45: Check english: "The expression for the pseudo-distance observable differs from equation 4.1 only not to include the term for the integer phase ambiguity."
- page 46: Check english: "the refractivity N of the middle characteristics"
- page 49: Please revise by citing the exact NWP model and the reference paper: "Regarding the numerical weather models it was found that they can produce systematic errors larger than 5.5 mm in ZHD."
- page 50: Replace "rate of variation with the altitude" with "temperature decrease with altitude"
- page 50: Replace "delay under atmospheric conditions referred to MSL (Mean Sea Level)" with "at mean sea level pressure"
- page 52: Check english: "The integral of water vapor in a vertical profile of the troposphere in the zenith direction, which is a unit widely used in meteorology"
- page 53: Replace "3 kg/m2 " with "3 mm"
- page 65: Please explain "damped least squares"
- page 69: Revise: "Perler et al. (2011) proposed an improved version of his software (Troller et al., 2006b)"
- page 77: Revise: "in only one pass through all the equations in (equation 6.3) and"
- page 79: Revise: "What distinguishes the various methods is the order in which row is processed"
- page 81: Check english: "Also define the diagonally matrix S"
- page 87: Check english: "According to the diagram (see Annex 1), a brief description about SWART and it´s components is here provided."
- page 88: Check english: "in the ASCII market format"
- page 88: Check english: "Weather Refractivity (Nw)."
- page 108: Change "8.4.4" with "8.4.3"
- page 133: Table 16 is incomplete. Please provide also the type of orbit and clock products used.
- page 136: Table 18 caption is incomplete and does not show that this concerns the wet refractivity. Please revise.

• page 141: Contradictory information in the text and figure 60. It is not clear which tomography model is used SWART or TOMO?
• page 141: Replace "sharp events" with "case studies".

6 November 2018 Signature:

/Assoc. prof. G. Guerova/