dr hab. inż. Krzysztof Kroszczyński,
Professor of the Military University of Technology
Military University of Technology
Faculty of Civil Engineering and Geodesy

Warsaw, November 23, 2018

Review

of the PhD thesis by

M.Sc. Andrè Garcia Vieira de Sá

for granting the PhD degree
in the field of Technical Sciences in the discipline of Geodesy and Cartography,
realized under the direction of dr. hab. inż. Witold Rohm, professor of the Wrocław University of Environmental and Life Sciences

1. Documents and materials constituting the basis for the review:

1. A letter from prof. dr hab. inż. Bernard Kontny, the Dean of the Faculty of Environmental Engineering and Geodesy of the Wrocław University of Environmental and Life Sciences, of October 2, 2018.

2. Act of Law of March 14, 2003 on scientific degrees and titles (Dz.U. z 2016 r. poz. 882 i poz. 1311), Order of the Minister of Science and High Education of September 1, 2011 on the criteria of assessment of achievements of a person applying for PhD degree (Dz.U. z 2011 r. nr 196 poz. 1165), Order of the Minister of Science and High Education of September 26, 2016 on the mode and conditions of PhD proceedings (Dz.U. z 2016 r. poz. 1586).

3. Scientific achievement, according to the Act of Law of March 14, 2003 on scientific degrees and titles (Dz.U. z 2016 r. poz. 882 ze zm.), in the form of the PhD thesis entitled:

„*Tomographic determination of the spatial distribution of Water Vapour using GNSS observations for real time applications*".

2. The thesis content and factual remarks

The PhD thesis of M.Sc. Andrè Garcia Vieira de Sá concerns the issues related with application of the technology of the Global Navigation Satellite System (GNSS) signal delays to tomography of the atmosphere. Nowadays, it is even spoken of GNSS meteorology which is developed in numerous all-European scientific and research projects, e.g.: the E-GVAP (The EUMETNET EIG GNSS water vapour programme) that provides the EUMETNET (The Network of European Meteorological Services) members with the GNSS signal delays and water vapour estimates for operational meteorology. The thesis Author took part in a few such projects including the COST ES1206 - GNSS4SWEC programme (European Cooperation in Science and Technology Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate). He presented the results of his work on 15 thematic conferences. He co-authored a few papers including two in the Bulletin of the American Meteorological Society. His work has been cited 16 times and his h-index equals 1.

The research issues presented in the thesis concern an important from theoretical and practical point of view problem of real time determination of spatial and temporal distribution of water vapour (humidity field) in the atmosphere by means of the tomography methods. Water vapour plays a key role in development of many weather phenomena. It is related with occurrence of precipitation. Delivering about half of the amount of energy to the atmosphere, water vapour has an important impact on its dynamics. It is also the dominating greenhouse effect gas. Knowing the distribution of water vapour is important for proper weather forecasting, i.e.: it influences the quality of numerical weather prediction models. It's also of special importance for hazardous weather phenomena forecasting and nowcasting. The research presented by the Author is very important because the meteorological observing systems based on the synoptic and upper air sounding stations networks do not provide sufficient spatial and temporal density of humidity measurements. This is one of the causes, according to meteorologists, that the numerical weather prediction models are usually too humid or too dry.

The Author studies the behaviour of the solutions of the tomographic models of the atmosphere. The solutions are spatial and temporal distributions of humidity that are generated using GNSS pseudo observations – slant delays determined in real time. It is worth mentioning that it is a complicated and difficult task because, although numerous aspects of the GNSS tomography have already been studied, it is still in its experimental phase. The causes of the status are related with still insufficient density of observations (density of the GNSS stations) with respect to the sizes of the analyzed areas of the atmosphere, quick changes in the water vapour distribution, distribution of the GNSS stations and quick changes of the satellites constellation. There is hope for a change of the situation in the near future due to improvement of the quality and speed of GNSS data processing and the determined delays as well as of the availability of the GLONASS, BeiDou, Galileo and other tropospheric products. Another important role in the Author's study is played by the realized search for and investigating of the properties of numerical algorithms of the solutions of tomographic systems that can manage great variability of their observations (operators) matrices. The Author showed that the standard techniques applied so far are not optimum with respect to this.

The complexity of the discussed problems is first of all the result of the mathematical formulation of the tomographic model. In order to reconstruct the humidity field, the Author uses a tomographic model based on the signals delays being functions of the parameters of the atmosphere including the water content on the GNSS signal path. That is why it is a difficult to solve incorrectly posed inverse problem. It usually means the lack of an accurate solution, bad conditions of the problem or sensibility to disturbances of input data.

The selection of the tomographic reconstruction methods is also very important. The Author chose iterative models for the purposes of his thesis, i.e.: for improving the effectiveness of the tomographic analysis by means of application of the Algebraic Reconstruction Technique (ART) and the Simultaneous Algebraic Reconstruction Technique (SART) type methods to determination of high frequency distribution of water vapour in the troposphere and to studying the ART models' properties in comparison with other tomographic, meteorological and upper air sounding models. The models are the basic part of the SWART-UBI (SEGAL GNSS Water Vapour Reconstruction Software) software developed by the Space and Earth Analysis Laboratory (SEGAL) of the University of Beira Interior (UBI).

The thesis indicates that solving the tomographic problem (inversing the tomographic operator) is related with numerous issues. These include: the methods of the slant delays determination, constructing grids for spatial discretization of the atmosphere, the modelling, initialization (i.e.: defining the initial condition), selection of methods of inversion of the tomographic operator (i.e.: solving the inverse problem) or constructing limitations for the solutions.

Important information concerning computing the GPS delays which are pseudo observations and, at the same time, free terms of the tomographic system are presented in chapters 3 (Global Navigation Satellite Systems characteristics) and 4 (GPS and tropospheric water vapour).

Wet refractivity resulting from the interaction between the magnetic field of the GPS signal and the dipole moments of water vapour molecules are defined in chapter 3. The refractivity and the density of water vapour are the main unknowns of the discussed tomographic problem.

The products estimated in the procedure of the GPS signals processing that are used in tropospheric tomography are discussed in detail in the following chapter. They include first of all the Zenith Total Delay (ZTD) and the slant delays: Slant Total Delay (STD), Slant Hydrostatic Delay (SHD) and Slant Wet Delay (SWD). It is important that the discussion included the impact of simplifications on the determination of the Slant Wet Delay related with tropospheric anisotropy, i.e. the usage of mapping functions and gradients of mapping functions. It is important because the co-existence of a number of weather phenomena in an area of the troposphere studied by means of tomography may lead to relatively large changes of the slant delays values being a function of the observation azimuth. The reviewer is the author of a (papers and monograph) concerning anisotropy of the tropospheric delays related with similar cases. In general, neglecting to take into account the gradients may increase the errors of slant delays and, due to the sensibility of the tomographic problem to input data disturbances, it may lead to a different solution from the real one. It is also necessary to mention, it is perceived by the thesis' Author and the reviewer, that the estimation of the anisotropy of the mapping functions using GNSS data is still insufficiently studied. In the reviewer's opinion, the presented in the thesis strategies of slant delays determination implemented in routine programmes like the Gipsy-Oasis, Bernese or Gamit (network solution) are in a way perverse because the measured slant delays are first of all used to determine the Zenith Total Delay (ZTD). This way of proceeding is justified and it is related with the reduction of the number of unknowns. The zenith delays are then in turn mapped by means of the probably previously used mapping functions into the directions of the satellites. The Vienna Mapping Function - VMF1 was used for the purpose in the thesis. The functions are computed in the process of raytracing using the ECMWF (European Centre for Medium-Range Weather Forecasts) meteorological model data. This way of proceeding smoothes the disturbances of the field of slant delays because they are the result of a specific process of averaging applied for determining ZTD and of the smoothness of the mapping functions. The following question might be asked here: does this way lead to losses of valuable information concerning the state of the atmosphere? The Slant Integrated Water Vapour (SIWV) is also defined in chapter 4. Like the Slant Wet Delay (SWD), SIWV is a basic input data for the tomographic model. A relation indicating that SIWV is proportional to SWD is quoted in the thesis. The proportion coefficient depends on the average temperature of the troposphere. The thesis' Author states that the coefficient results from the linear correlation between the zenith delay (ZWD) and the water vapour content in the column of the troposphere. In the reviewer's opinion, it may not be the case even when the local climatic conditions and seasonal variability are taken into account. The authors of some recently published papers concerning the tomography of the atmosphere define the parameter for every layer of the tomographic model. It may pose a significant problem because the information has to be acquired from an external source, i.e.: upper air sounding data, microwave radiometers or numerical weather prediction models.

In chapter 5, GNSS Tomography, the thesis' Author presents the linear model of tomography of the troposphere applied in his research. It maps the spatial distribution of the refractivity or density of the water vapour into the slant delays determined in the process of GNSS analysis. The discrete linear operator of the tomographic system is modelled by means of a matrix of constant coefficients related with the length of paths defined by the time the GNSS signal takes in the voxels of the tomographic grid. Finally, the matrix elements define the participation of each cell of the grid in a certain slant delay - SWD. Due to this, such a model is of geometric nature. In reality (in the reviewer's opinion) it should be of physical nature related with the time of the GNSS signal interaction with each cell of the grid. In case of the application of an iterative method to the solution, besides the unknown values of the voxels' refractivity, the coefficients of the observation matrix of the tomographic system of equations should also be the subject of changes. The discrete character of the inverse problem is rather in favour of large errors resulting in disturbances of the structure of the tomographic operator and at the same time in favour of errors in reconstruction of the spatial distributions. The greater the dimensions of the voxels of the model's grid, the greater the errors. Grids of the horizontal dimensions of 30-50 km (i.e.: of the angular dimension of 0.5°x0.5°) and the vertical dimensions of 500 m at the Earth's surface and up to 2 through 4 km at higher levels of the troposphere are applied in the thesis. Such dimensions of the cells, determined among others by the average distance between the GNSS stations, lead to discontinuity of the reconstructed fields of humidity. The discontinuities are visible in the plots of the distributions of the reconstructed fields of water vapour density in the troposphere presented in the thesis. I think it is worth here to bring the attention to the relation between the cells of the global model of weather forecasting and the tomographic model with respect to the capability of humidity fields assimilation. Currently, the Global Forecast System (GFS) forecasting model of the National Centers for Environmental Prediction (NCEP) is run on a grid with the horizontal resolution of 13km and 64 sigma pressure hybrid vertical levels. NCEP plan to upgrade GFS to 128 levels. The Global Data Assimilation System (GDAS) used by GFS provides data with a quarter of a degree spatial resolution (0.25° by 0.25°) at standard pressure levels: 1013.25 hPa - 0.0 m, 1000 hPa - 111 m, 975 hPa - 989 m, 950 hPa - 540 m, 925 hPa - 766 m, 900 hPa - 989 m, 850 - 1457 m, ... The information indicates that in the boundary layer of the atmosphere (~1000m) of the GDAS system there are a few computation levels while in the GFS model there are even several. For this reason, the vertical dimension of the cells in the layer should be smaller than the one used in the thesis, i.e. 1000 m or 500 m. This issue is partially discussed in the thesis. A test of resolution in which the vertical dimension of the cells was increased to 2000 m is presented in chapter 8. A stabilized solution was achieved this way, however, at the cost of degradation of the humidity field resolution. The role of additional constraints and of observations other than GNSS in the process of tomographic inversion is presented in chapter 5. It may be stated that applying them results in stabilizing the solution i.e.: it helps to maintain the results within meteorologically reasonable range and to reduce artefacts.

The described in chapter 6 of the thesis Algebraic Reconstruction Techniques (ART) and Simultaneous Iterative Reconstruction Techniques (SIRT) are based on iterative methods. The Simultaneous Algebraic Reconstruction Techniques (SART), combinations of ART and SIRT, were applied in the research. They are relatively simple, i.e. algorithmically straightforward and fast. The efficiency of the algorithms was additionally increased by means of paralleling them using the Open Multi-Processing (OpenMP) and the linear algebra Eigen3 libraries. Paralleling the computations enables to use the GNSS tomography products in near real time applications.

The functional elements of the applied and severely tested SWART tomographic software are described in chapter 7 - GNSS tomography system implementation and description. The algorithms of the software used in the research were positively validated. The standard Shepp-Logan test used for assessment of the quality of images reconstruction was applied for the purpose. The issue of determination of the 5-minute tomographic solutions for near real time applications was also discussed.

The SWART software results were compared with the results obtained by means of the Kalman version of the LOFT_K French software for tropospheric tomography in chapter 8 - SWART GNSS Tomography Validation. Synthetic slant wet delays (SWD) were used in the research. Practically consistent results of the reconstruction were obtained in both cases. There were differences that occurred in the outer grid where the GNSS stations density is lower, i.e.: there are fewer intersections of the voxels. The issue of convergence of the SWART iterative algorithms was also studied. The number of iterations depends in this case on the data quality and the „divergence" of the initial condition from the stable solution. For the synthetic data, the solution stabilized after 300 iterations and it was practically the same as after 5000 iterations. The SWART software was positively tested for the synthetic data. The data provided appropriate relations between the number of delays and the vertical and horizontal resolution of the voxel grid for achieving stable solutions. Tests with real data were also conducted. The impact of the tomographic model's grid resolution, noise and iterations number on the stability of the inverse problem was also studied. Disturbing the synthetic observations with noise showed its great impact on the obtained solutions. Changes of voxels exceeding 50% were observed. In this case, the „incorrectness" of the tomographic problem is fully manifested, i.e.: small disturbances are usually accompanied by large changes of the solutions. It was indicated that this result may be caused by susceptibility of the inverse methods to coarse errors of the input data and, consequently, that the application of initial filtering of slant delays (e.g.: incorrectly operating stations and the slants leaving model from the side faces) is needed. I think that the research is important for comprehending the level of difficulty of inverse methods application (i.e.: tomography of the atmosphere) in case of real data.

Two case studies of tomography based on the Continuously Operating Reference Stations (CORS) system data for an area in the Victoria State in the southern part of Australia and in the area of Poland are presented in chapter 9 - Case studies. In the first case study the research was focussed on comparing the fields of water vapour density obtained from the SWART-UBI model with the fields obtained from the BIRA model of the Belgium Institute for Space Aeronomy and the TOMO2-WUELS model of the Wrocław University of Environmental and Life Sciences. The models use various techniques for solving the inverse problem, i.e. Singular Value Decomposition (SVD), weighted and damped LS (Least Square) adjustment (BIRA), Kalman filter with SVD (TOMO2) and SART (Simultaneous Algebraic Reconstruction Technique). The same set of GNSS measurements processed using double difference technique with Bernese 5.0 software was used for computations. The Slant Integrated Water Vapour (SIWV) delays were the input data for the tomographic models. Unfor-

tunately, the specific computational methods applied in the computations to determine them (e.g.: network and PPP) were not described in detail. The obtained results were referenced to data of independent upper air soundings. They were also compared with data of the Australian Community Climate and Earth-System Simulator (ACCESS-A) weather model and radio-occultation profiles. In order to validate the SWART model, numerous thorough tests were conducted that took into account various combinations of the initialization process, data stacking and including pseudo observations into computations. It was concluded that the SWART model yields better or comparable results for the lower layers of the tomographic model
as compared with the BIRA and TOMO2 models. These are the 0.2 – 1.5 km and 1.5 – 4 km layers. It is also the case for the ACCESS-A weather model up to the altitude of 4 km while for the WRF model (in the second phase of tomography) – up to 6 km. In the layer between 8 and 13 km the SWART tomographic model significantly overestimates the values of the water vapour density which is related with neglecting to apply the condition that assumes the density to be zero above the tropopause. With respect to this, the BIRA model is the best of the studied tomographic models.

The research showed that the SWART model yields the best results in the layer between 0 and 8 km when data stacking is applied. It also occurred that including pseudo observations into the computations does not improve the obtained solutions. Actually, it may have been anticipated because pseudo observations do not provide any real information concerning the state of the atmosphere. The Author's research indicates also that an appropriate initialization of the tomographic model is a very important issue. The ACCESS-A and WRF models data were used for the purpose. It may be noticed that the quality of the tomographic reconstruction depends to a significant degree on the quality of analyses and forecasts of the numerical weather prediction models. The speed of processing the analyses for nowcasting purposes was also analyzed as a function of the number of observations. These analyses indicate that the SWART tomographic model used in the tests has very good computational efficiency.

It is important for models operated in near real time. The computation time of a system of equations of a 6000x1800 matrix for the SWART model is 35 seconds while it is 130 minutes for the BIRA model.

In summary, on the basis of the obtained results it may be concluded that the aim of the thesis has been achieved. In a number of tests and analyses, numerous important aspects of functioning of the SWART model of the GNSS tomography of the troposphere were studied. The model uses fast iterative Simultaneous Algebraic Reconstruction Technique (SART) algorithms to determine four dimensional field of water vapour density in the atmosphere in near real time.

3. Editorial remarks

I have to make the following editorial remarks:

1. The ACCESS-A acronym is not explained (no such entry in the acronym list).
2. On page 28, the text line proceeding formula 2.4. It is: Water Vapour WV [kg m^{-3}]. In the reviewer's opinion it should state: density of Water Vapour.
3. The capital letter K is used for the coefficient in formula 4.11 (page 53). In the text it is represented by *k*.
4. On page 60, in line 9 from the bottom. It is: I_{NM}. It should be: d_{MN} as in the design matrix of the 5.2 equation system.
5. Pages 64 and 65. In my opinion, the final paragraph of subsection 5.3 should be moved to a different part of the thesis.

6. Page 69 and others. The Author uses the term: "single value decomposition". I think it should be: "singular value decomposition".
7. The colour palettes of the figures might be chosen more carefully. For example, figures 15 and 16 on pages 73, 91 and 92 of the Shepp-Lodan test are illegible (unlike figure 10). The same remark concerns figures presenting the cross sections of the water vapour density fields.
8. Page 85. The OMP acronym is used (no such entry in the acronym list). It should be: OpenMP, as on page 84.
9. I think that the tables should include additional rows containing e.g.: information about the stacking time. It would facilitate interpretation of the presented results. Some of the tables should have the landscape format.
10. Page 134. The refractivity parameter is written in two forms: Nw and N_w.

The editorial remarks do not in any way change the high mark for the thesis.

Moving to the next topic of the review

4. Issues to explain – questions to the thesis Author

You are kindly requested to explain the following:

1. Why aren't the directly measured slant delays used in GNSS tomography?
2. What are the factors limiting the minimum dimension of the tomographic model cell?
3. What is the current possibility to assimilate humidity fields obtained by means of the GNSS tomography methods into global and mesoscale weather prediction models?
4. Why doesn't the studied tomographic model use limitations including the upper and lower boundary conditions?

5. Summary and final conclusion

The presented PhD thesis includes a number of realized numerical experiments related with the issues of solving an incorrectly posed inverse problem of GNSS tomography. The input of work of M.Sc. Andrè Garcia Vieira de Sá concerning preparing the experiments as well as processing, analyzing and interpreting the results proves the Author's capability to do research independently. It also confirms the Author's vast interdisciplinary knowledge in the fields of satellite geodesy, numerical methods and meteorology. The important and original elements of the thesis include thorough multi-variant research validating the SWART-UBI model using the results of computations made by means of the BIRA and TOMO2-WUELS tomographic models and the ACCESS-A and WRF weather prediction models data as well as upper air sounding data and occultation data. The research is very important because practically there are no direct comparative analyses functioning on the basis of various strategies of inverting tomographic models. The obtained results indicate their large potential of applicability.

The scientific achievement of M.Sc. Andrè Garcia Vieira de Sá in the form of the presented for assessment thesis and the research achievements to date constitute an important contribution to the development of the discipline of geodesy and cartography.

I ultimately state that the reviewed PhD thesis by M.Sc. Andrè Garcia Vieira de Sá contains original results of scientific research and meets the requirements of the Act of Law of March 14, 2003 on scientific degrees and titles. I put forward a motion to admit M.Sc. Andrè Garcia Vieira de Sá to publically defend the PhD thesis.