Acta Geodyn. Geomater., Vol. 7, No. 3 (159), 253–261, 2010

THE CONCEPT OF THE NEAR REAL TIME ATMOSPHERE MODEL BASED ON THE GNSS AND THE METEOROLOGICAL DATA FROM THE ASG-EUPOS REFERENCE STATIONS

Jarosław BOSY *, Witold ROHM and Jan SIERNY

Wroclaw University of Environmental and Life Sciences,
Institute of Geodesy and Geoinformatics, Grunwaldzka 53, 50-357 Wroclaw, Poland
**Corresponding author's e-mail:* jaroslaw.bosy@up.wroc.pl

(*Received* February 2010*, accepted* March 2010)

ABSTRACT

GNSS meteorology is the remote sensing of the atmosphere (particularly troposphere) using Global Navigation Satellite Systems (GNSS) to deliver information about its state. The two currently available navigation satellite systems are the Global Positioning System (GPS) and the GLObal'naya NAvigatsionnaya Sputnikovaya Sistema (GLONASS) maintained by the United States and Russia, respectively. The Galileo navigation satellite system, which is under supervision of the European Space Agency (ESA), is expected to be completed within the time frame of a few years. Continuous observations from GNSS receivers provide an excellent tool for studying the earth's atmosphere. The GNSS meteorology has reached a point, where there is a need to improve methods not only to compute Integrated Water Vapor over the GNSS receiver, but also to investigate the water vapor distribution in space and time (4DWVD). Since 2008, the new national permanent GNSS network ASG-EUPOS (98 stations) has been established in Poland. 17 Polish stations equipped with GNSS receivers and uniform meteorological sensors work currently in the frame of the European Permanent Network. This paper presents the concept of the integrated investigations for NRT atmosphere model construction based on the GNSS and meteorological observations from ASG-EUPOS stations.

KEYWORDS: GNSS meteorology, tomography, troposphere model, GNSS permanent stations network, ASG-EUPOS

1. INTRODUCTION

GNSS meteorology is the remote sensing of the atmosphere using GNSS. The term GNSS meteorology relates to the utilization of the Global Navigation Satellite System's (GNSS) radio signals to deliver information about the state of the troposphere. Continuous observations from GNSS receivers provide an excellent tool for studying the earth atmosphere. There are many GNSS meteorology applications: climatology (large set of uniform and well spread stations, observation time span over 15 years), synoptic meteorology (Tropospheric Delay (*TD*) as an additional data input for NWP models), nowcasting (*TD* alone is a standard real time product used as synthetic measure of the state of the atmosphere) and 4D monitoring (*TD* is use to build the tomography model and gain spatial and temporal characteristics of the troposphere above the network of receivers).

The GNSS meteorology is based on the GNSS observations. One of the results of GNSS data processing (permanent or epoch observations) is a tropospheric delay. The tropospheric delay is represented by the Zenith Total Delay *ZTD*. The *ZTD* can be split into hydrostatic *ZHD* and wet *ZWD* component of the delay:

$$ZTD = ZHD + ZWD \tag{1}$$

The tropospheric delay on the way between the satellite and the receiver (Slant Troposphere Delay: *STD*) can be separated like (1) into hydrostatic *SHD* and wet *SWD* components and represented by the well known relation:

$$\begin{aligned} STD &= SHD + SWD = \\ &= m_d(\varepsilon)\cdot ZHD + m_w(\varepsilon)\cdot ZWD \end{aligned} \tag{2}$$

where ε is the satellite elevation angle and $m_d(\varepsilon)$ and $m_w(\varepsilon)$ are the mapping functions corresponding to hydrostatic and wet components (Niell, 1996; Boehm et al., 2006a, 2006b).

The wet component of Zenith Tropospheric Delay *ZWD* is the foundation for computing of water vapor content in the atmosphere. The relation between *ZWD* and the water vapor content in atmosphere is expressed by *IWV* (Integrated Water Vapor) and *IPWV* (Integrated Precipitable Water Vapor) and given by the equations (Bevis et al., 1992, 1994; Kleijer, 2004):

$$\frac{ZWD}{IWV} = 10^{-6}\cdot R_v \cdot \left(k_2^{'} + \frac{k_3}{T_M}\right) \tag{3}$$

$$IPWV = \frac{IWV}{\rho_w} \quad (4)$$

where $R_v = 461.525 \pm 0.003\ \mathrm{J\,kg^{-1}K^{-1}}$ is the gas constant, $k_2^{'}$ and k_3 are the empirical constants, T_M is a mean temperature of water vapor and ρ_w is the water density (Kleijer, 2004; Mendes, 1999). In this study an empirici formula after (Bevis et al., 1992) is given for the $T_M \approx 70.2 \pm 0.72 \cdot T_0$, where T_0 is a surface temperature.

The relation between water vapor partial pressure e, temperature T and wet refractivity N_w is given by the formula:

$$e = N_w \cdot Z_v \cdot \left(\frac{k_2^{'}}{T} + \frac{k_3}{T^2} \right)^{-1} \quad (5)$$

where Z_v is an empirical compressibility factor of the water vapor (Owens, 1967).

The GNSS meteorology has reached a point where there is a need to develop methods not only to compute Integrated Water Vapor (*IWV*) over the GNSS receiver but also to investigate the water vapor distribution in space and time (4DWVD) (de Haan et al., 2004; Vedel and Huang, 2004).

The *IPWV* is delivered according to equations (3 and 4) from *ZWD* and give the information about contents of water vapor (2D model) above GNSS stations. For mountains area like Switzerland and Sudety in Poland dense network of GNSS permanent stations can produce 4DWVD model (Morland and Mätzler, 2007) in the troposphere. The EUREF Permanent Network (EPN) is the base of determination of *IPWV* in Europe (Vedel and Huang, 2004). Some of the Analysis Centers (AC) of EPN and IGS process GNSS data in NRT mode (e.g. Geodetic Observatory Pecný GOP: *http://pecny.asu.cas.cz*). The GOP realizes NRT solution of GNSS data since 2001 in the frame of GNSS meteorological projects: COST Action 716 (2001-2003) and TOUGH (2003-2005) (Douša, 2004). Since 2005 EPN analysis centres ASI, BKG, GOP and LPT delivers NRT ZTD for meteorological applications in the frame of international project E-GVAP (EUMETNET GPS Water Vapour Programme) (Douša, 2010; Elgered et al., 2004).

The new polish national permanent GNSS network ASG-EUPOS has been established since 2008. 17 Polish stations equipped with GNSS receivers and uniform meteorological sensors work currently in the frame of the European Permanent Network (Bosy et al., 2008). The ASG-EUPOS network consist (including foreign stations) of about 120 GNSS reference stations located evenly on the country area and build network of greater density than EPN network. This guarantees that the 4D troposphere delay and water vapor models will be more representative for the territory of Poland.

The spatial structure and temporal behavior of the water vapor in the troposphere (4D) can be modeled by using the GNSS tomography method. The GNSS tomography is based on the signal slant delays, precisely Slant Wet Delays (*SWD*), result of the GNSS data processing (Flores et al., 2000; Hirahara, 2000; Rohm and Bosy, 2009).

The new concept of national integrated researches based on the GNSS and meteorological observations from ASG-EUPOS stations and NWP models will be presented. Since 2010 the idea is realized in the frame of research project "Near real Time atmosphere model based on the GNSS and the meteorological data from the ASG-EUPOS reference stations on the territory of Poland" founded by Ministry of Science and Higher Education.

The following section presents the sources of GNSS and meteorological data, localization and accuracies. The third section contains NRT ZTD processing strategy, and latest findings in the area of GNSS tomography technique. Also the comparative study between GNSS tomography model and NWP model is presented. In all validation studies the NWP Coupled Ocean/Atmosphere Mesoscale Prediction System COAMPS was used. The COAMPS model has been built and is constantly developed by the Naval Research Laboratory (NRL) of the Marine Meteorology Division (MMD) (Hodur, 1997). The COAMPS has been implemented in the Applied Geomatics Section of Military University of Technology in Warsaw. The COAMPS outputs used for comparative study were created with 1.44 km horizontal and 1h time resolution. The outputs of COAMPS model consist of temperature *(T)*, pressure *(p)*, water vapor partial pressure *(e)*, delivered on 31 terrain-following layers. Finally the conception of integration of meteorological and GNSS data in the GNSS tomography model for NRT water vapor, temperature and pressure 4D distribution studies is presented.

2. THE GNSS AND METEOROLOGICAL DATA

The receiving segment (ground control segment) consists of a network of GNSS reference stations located evenly on the whole territory of Poland. Comply with EUPOS and project of the ASG-EUPOS system standards distances between neighboring reference stations should be 70 km what gives number of stations 98 (Fig. 1) (*EUPOS, 2008*). According to rules of EUPOS organization (in the frame of cross-border data exchange) 3 reference stations from Lithuania (LITPOS), 6 stations from Germany (SAPOS), 7 stations from Czech Republic (CZEPOS) and 6 stations from Slovakia (SKPOS) were added (Fig. 1; Bosy et al., 2008).

The ASG-EUPOS network will define the European geodetic reference system ETRS89 in

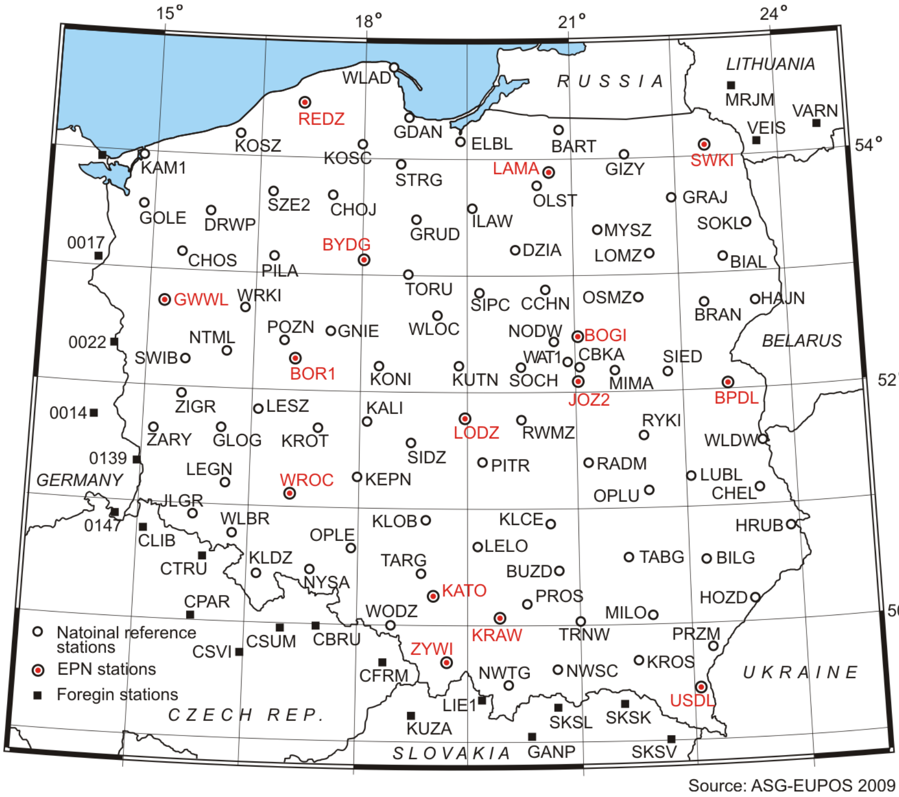


Fig. 1 Reference stations included in ASG-EUPOS (www.asgeupos.pl).

Table 1 GNSS equipment on the ASG-EUPOS reference stations.

Number of stations	Receiver	Antenna
72	Trimble NetRS	Trimble Zephyr Geodetic w/Radome (*TRM41249.00 TZGD*)
12	Ashtech Micro Z (*ASHTECH UZ-12*)	Ashtech L1/L2 Choke Ring SNOW (*ASH701945C M SNOW* - D/M element, REV.C, chokering with radome NGS)
8	Trimble NetR5	Trimble Zephyr GNSS Geodetic II w/Radome (*TRM55971.00 TZGD*)
4	Leica GRX1200 GG Pro	Leica L1/L2 Choke Ring, using DM-T style (*LEIAT504GG LEIS*)
1	Javad JPS E GGD	Ashtech L1/L2 Choke Ring SNOW (*ASH701945C M SNOW* - D/M element, REV.C, chokering with radome NGS)
1	Trimble NetRS	Dorne Margolin T Choke Ring (*AOAD/M T NONE*)

Poland. A close connection of the ASG-EUPOS stations and 15 of 17 stations of the EPN that are located in the territory of Poland will control the realization of the ETRS89 system at the Polish territory (Bosy et al., 2008).

The reference stations are equipped with the modern GNSS receivers and the antennas with absolute calibrations (ftp://igscb.jpl.nasa.gov/igscb/station/general/igs05.atx). The details are presented in Table 1.

In the 14 localizations of the EPN stations the new uniform meteorological infrastructure Paroscientic, Inc. MET4A sensors were installed. The EPN station Borowiec (BOR1) have the equivalent meteorological infrastructure: NAVI Ltd. HPTL.3A and Skye Instruments Ltd. sensors. In all stations the basic meteorological parameters:

- pressure with accuracy ±0.08 hPa from 500 to 1100 hPa,
- temperature with accuracy ±0.2 deg C from -50 to +60 deg C,
- relative humidity with accuracy ±2 % from 0 to 100 %,

are measured close to the GNSS antenna.

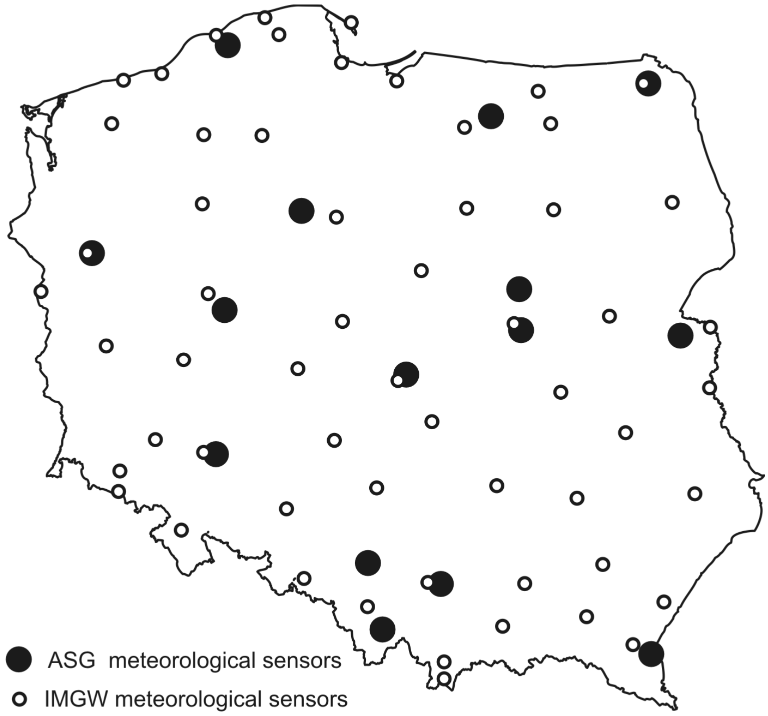


Fig. 2 The ASG-EUPOS and IMGW meteorological sensors location.

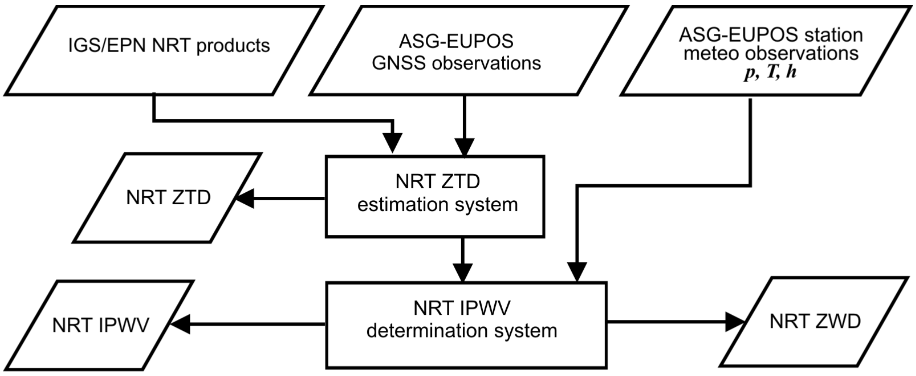


Fig. 3 The diagram of NRT ZTD, ZWD and IPWV models construction on the base of GNSS and meteorological data from ASG-EUPOS reference stations.

The Polish meteorological network is managed by Institute of Meteorology and Water Management (IMGW) and contains over 120 automatic weather stations: synoptical and climatological. The automatic weather stations are equipped with sensors based on Maws 301 and Milos 500 by Vaisala (*http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-94-TECO2006/P1(12)_Pietrzykowski_Poland.pdf*). Figure 2 show localization of ASG-EUPOS and IMGW meteorological sensors in Poland.

The distribution of the IMGW and the ASG-EUPOS meteorological stations is representative for the area of Poland. Two additional techniques are also present in the area of Poland, the first is the radio sounding - there are three launching sites in Poland (Wroclaw, Łeba and Legionowo), the second one is currently under construction – the network of radiometers. Both methods deliver the local vertical structure of the atmosphere. The combination of all these techniques will allow to verify and also to improve reliability of the model of the state of the atmosphere from GNSS observations.

3. THE NRT ATMOSPHERE MODEL

The GNSS and meteorological observations form ASG-EUPOS stations are the base of near real time models of tropospheric delay and water vapor (NRT ZTD and NRT ZWD) in atmosphere. Figure 3 shows the diagram of NRT ZTD and NRT ZWD models construction.

The NRT ZTD will be obtained from the NRT solution of ASG-EUPOS stations network. The strategy of NRT solution will be realized according to standards used for global IGS and regional EPN permanent GNSS networks and NRT solution strategy created in the frame of COST Action 716 (European Cooperation in the field of Scientific Technical Research—exploitation of ground-based GPS for climate and numerical weather prediction applications, 1998-2004), TOUGH (Targeting Optimal Use of GPS Humidity Data in Meteorology, http://tough.dmi.dk/, 2003–2006) and E-GVAP (The EUMETNET GPS Water Vapour Programme, http://egvap.dmi.dk, 2004–2008) projects (Douša, 2004, 2010).

The *ZHD* for all ASG-EUPOS stations will be estimated in NRT mode on the base of meteorological observation of Polish EPN stations equipped with meteorological sensors. Next according to relation (1) the values of *ZWD* will be computed. The *IPWV* values above all ASG-EUPOS stations will be calculated from equations (4) and (5) and finally *NRT ZWD* and *NRT IPWV* models for Poland territory will be constructed.

The spatial structure and temporal behavior of the water vapor in the troposphere (4D) can be modeled by using the GNSS tomography method. The idea of GNSS tomography is presented in Figure 4.

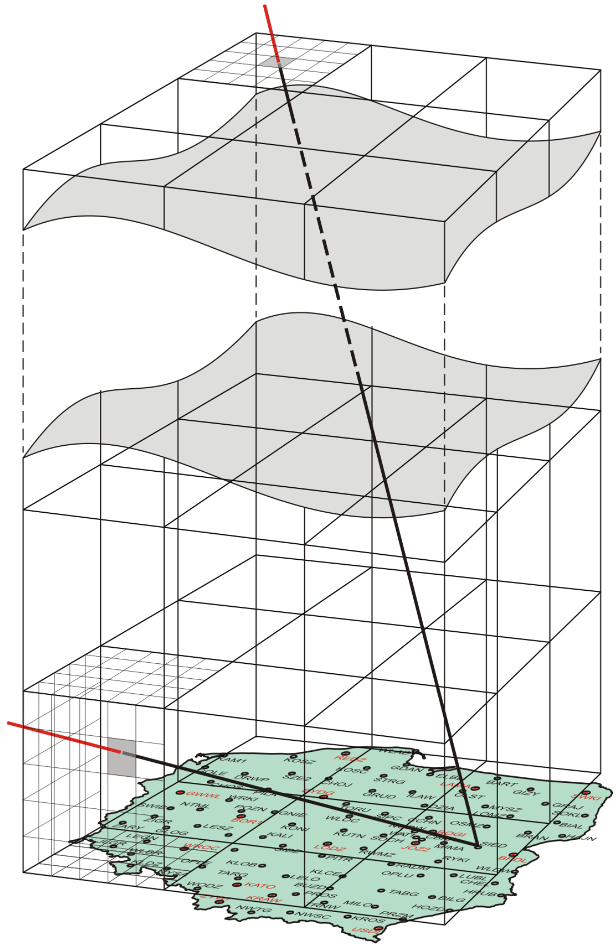


Fig. 4 The idea of GNSS tomography model for area of Poland.

The input data of GNSS tomography are the *SWD* form all ASG-EUPOS stations computed from equation (2). In the GNSS tomography *SWD* is linked with the wet refractivity N_w by the equation proposed by Flores (2000):

$$SWD = A \cdot N_w \quad (6)$$

where A is the design matrix. The basic information contained in the A matrix is a distance that signal travels through each voxel.

Currently several methods exist to solve the GNSS tomography model. The first is to add horizontal and vertical constraints into the system of equations (6) and then solve it (Hirahara, 2000). Another one is to use a Kalman filter with the same equation system (Flores et al., 2000), or to find the solution directly from the GNSS phase measurement equation (Nilsson and Gradinarsky, 2006). In this paper the original author's solution of equation (6) is applied (Rohm and Bosy, 2009, 2010). To find the voxels' refractivities one needs to invert the equation (6), using the More-Penrose pseudoinverse (+):

$$N_w = (A^T \cdot P \cdot A)^+ \cdot A^T \cdot P \cdot SWD^T \quad (7)$$

where the P is a weighting matrix. The weighting matrix P is constructed as an inversion of covariance matrix of observations $P = C_{SWD}^{-1}$. The design matrix A contains the distances and especially tuned horizontal constraints. The horizontal constraints impact together with model voxel's size has been studied in a Rohm and Bosy (2009). The A matrix was modified, according to latest findings in the field of flow analysis (Rohm and Bosy, 2010). The method presented in this paper uses the minimum constraint conditions imposed on the system of observation equations (6) and the design matrix A. The pseudoinverse of $(A^T \cdot P \cdot A)^+$ is based on Singular Value Decomposition (*SVD*):

$$(A^T \cdot P \cdot A)^+ = V \cdot S^+ \cdot U^T \quad (8)$$

where U is a $n \times n$ orthogonal matrix of left-singular vectors, V is a $m \times m$ orthogonal matrix of right singular vectors, S is a $n \times m$ diagonal matrix of singular values sorted in descending order (Anderson et al., 1999) and S+ is a pseudoinverse of the matrix S.

The results shows that the voxel height should be at least three to five times smaller than the horizontal size to solve the system with currently available GPS satellites. The usage of minimum horizontal constraints proved to be robust and sensitive. The summary of this study is presented in the figure (Fig. 5). All tests were performed on simulated data.

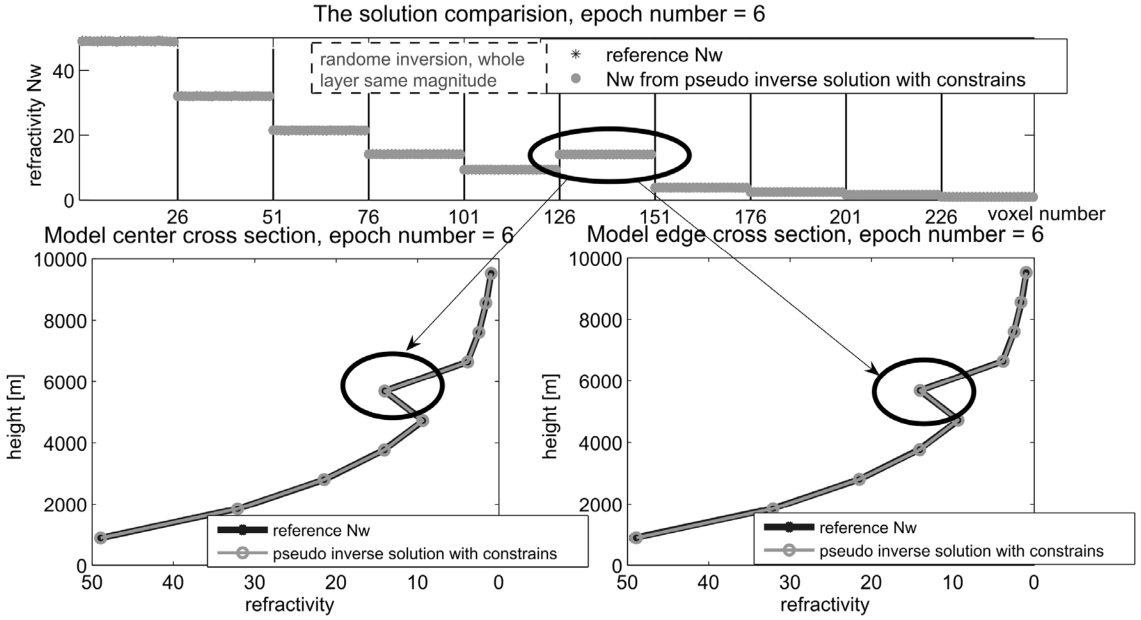
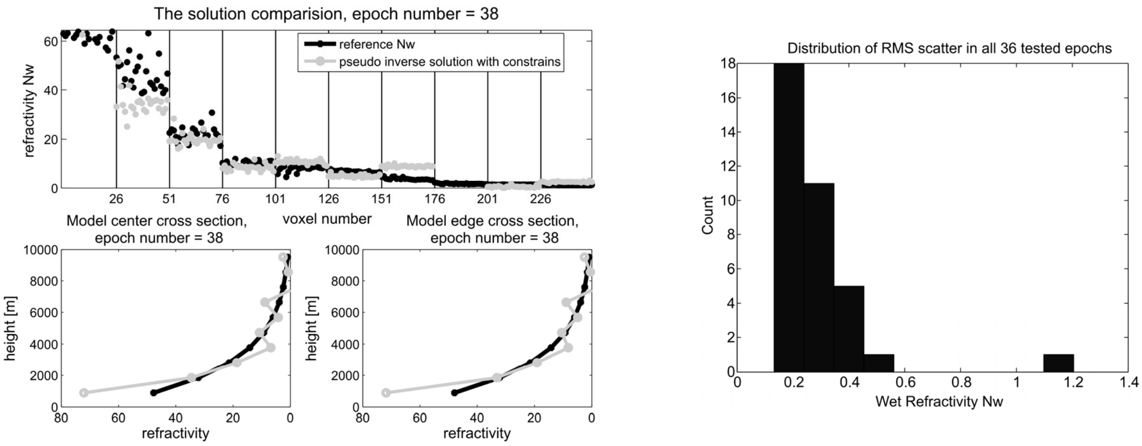


Fig. 5 The intersection through the model, simulated mean meteorological parameters were used. The mean profile was disturbed in the sixth layer to show the reliability of tomographic reconstruction (Rohm and Bosy, 2009).



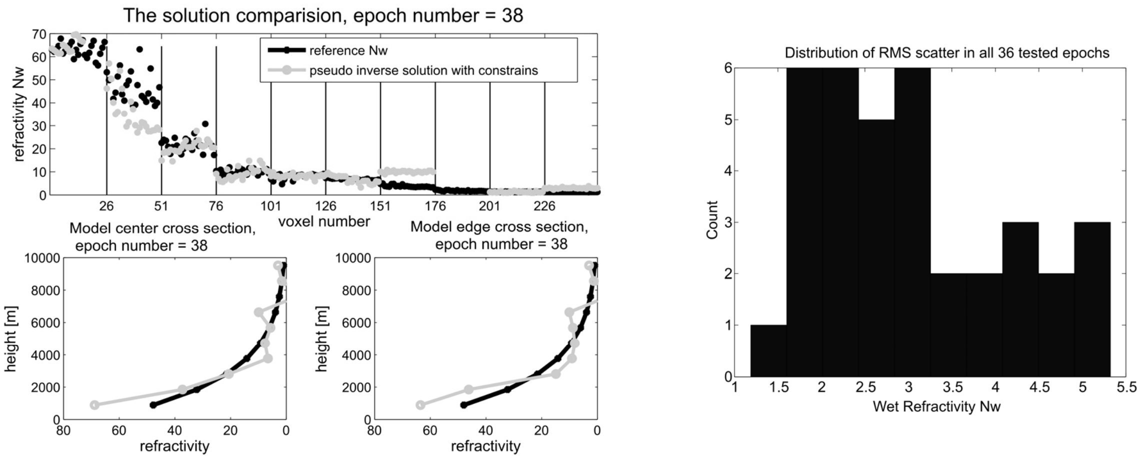
a) b)

Fig. 6 a) The intersection through the model, SWDs were COAMPS derived (grey line tomographic solution, black line reference COAMPS data),
b) The histogram of the RMS of the COAMPS simulated data solution (Rohm and Bosy, 2010).

Next the GNSS tomography model was modified, according to latest findings in the field of flow analysis (Rohm and Bosy, 2010). The analysis of the flow derived from radio sounding and NWP COAMPS model, shows that the actual correlation between consecutive voxels in the model is weaker in the bottom part and grows with increasing height. Thus, the model constraints scheme was changed to stick closer to the reality.

First solution with the new constraints scheme was applied with data from COAMPS model. The meteorological parameters were interpolated to the center of each voxel in the tomographic model. Then the wet refractivity of each voxel was calculated – it's reference data (black) in Figure 6a and Figure 6b.

Afterwards the scanning rays path was calculated and all refractivity was summarized to get simulated Slant Wet Delays (*SWD*). According to the equation (6), *SWD* were the observations, and the matrix *A* consist of the distances of rays in consecutive voxel and the constraints. When system was inverted according to equations (7) and (8)



a) **b)**

Fig. 7 a) The intersection through the model, real observed SWDs were used (tomographic solution - grey line, COAMPS reference data – black line),
b) The histogram of the RMS of the real data solution with respect to COAMPS reference data (Rohm and Bosy, 2010).

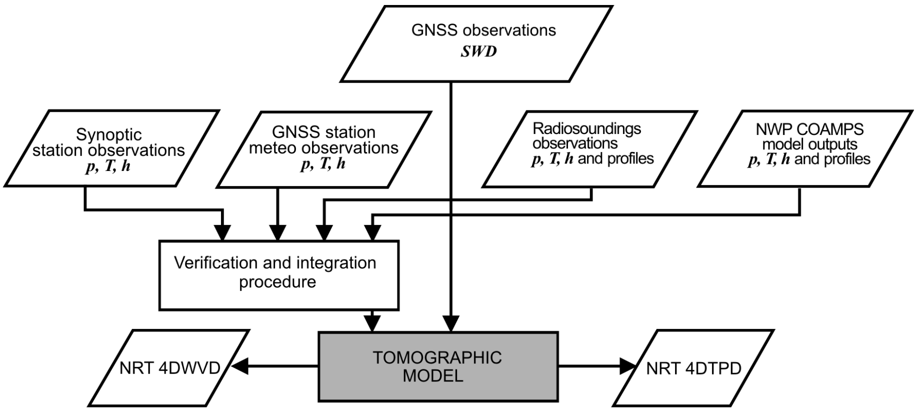


Fig. 8 The diagram of NRT 4DWVD and NRT 4DTPD models construction.

following the methodology presented in the Rohm and Bosy (2009), the tomographic wet refractivities were obtained (the grey line in Figure 6a). Comparison with the reference is presented in Figure 6b – the histogram of the solution accuracy. It shows superior accuracy of this simulated solution between 0.2 to 0.6 mm/km, the proof of method consistency.

The results of tomographic model solution feed with GNSS derived SWDs are presented in Figure 7. As a reference serves previously calculated refractivities from COAMPS model.

While, real *SWD's* were put into the equation (6) (the example solution is pictured in Figure 7) the higher discrepancy is observed. It is probably effect of the inaccurate trimming of the rays coming out of the faces of the model Figure 4. The solution is worse than the simulated by the factor of ten by the means of RMS error. There are test still pending in order to quantify and exclude the impact of this error.

The GNSS tomography method will be used to create of NRT models of water vapor *NRT 4DWVD* and meteorological parameters: temperature and pressure *NRT 4DTPD* in atmosphere according to Figure 8.

The input data for tomography model according to the diagram shown in Figure 8 are the meteorological observations from Polish EPN stations and IMGW synoptic stations (Fig. 2). Because of data inhomogeneity, original methods of meteorological data validation and NWP model calibration based on the differential wavelet method is proposed (Bosy et al., 2010). The results of analysis in paper

Bosy et al. (2010) shows that pressure should be measured as accurate as possible (uncertainty below 1.0hPa) with homogenous instruments while the temperature could be measured less accurately (uncertainty below 2.4K). The meteorological infrastructure of ASG-EUPOS and IMGW meet above conditions. Integration procedure of the COAMPS NWP model shows that the model output parameters are squaring with the meteorological observations from the synoptic stations.

Meteorological observations from ASG-EUPOS and IMGW synoptic stations after mutual validation and integration procedure will be used for *ZHD* extraction from equation (1), to compute *ZWD* and finally *SWD*. The above meteorological observations, radiosoundings observations and NWP COAMPS model outputs will be used also for verification of GNSS tomography model.

4. CONCLUSION

The GNSS tomography technique, produce high quality information concerning the state of water vapor in the atmosphere, which has been shown in previous papers (Rohm and Bosy, 2009; Bosy et al., 2010; Rohm and Bosy, 2010). The proposed model based on the minimum constraints solution is validated with the help of simulated weather conditions The same model transformed into the NRT operation mode and covering area of whole Poland, could also be established. Future works will utilize the integrated meteorological and GNSS data to obtain the real 4D structure of troposphere (temperature, pressure and water vapor). The obtained results could be used as well as in meteorological applications, in the real-time and post-processing positioning services of ASG-EUPOS system. The NRT atmosphere model created from meteorological and GNSS data, could be competitive to NWP model, especially for nowcasting. The improvement in positioning is that tropospheric delays will be calculated directly from observations, not like now from deterministic models.

ACKNOWLEDGMENT

This work has been supported by the Ministry of Science and Higher Education: research project No N N526 197238 and the Wroclaw Center of Networking and Supercomputing (http://www.wcss.wroc.pl/): computational grant using Matlab Software License No: 101979

REFERENCES

Anderson, E., Bai, Z., Bischof, C., Blackford, S., Demmel, J., Dongarra, J., Du Croz, J., Greenbaum, A., Hammarling, S., McKenney, A. and Sorensen, D.: 1999, LAPACK Users' Guide, Third Edition. Society for Industrial and Applied Mathematics.

Bevis, M.,S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and Ware, R.H.: 1992, GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system, Journal of Geophysical Research (D), 97, 15787–15801.

Bevis, M., Businger, S. Chiswell, S., Herring, T.A, Anthes, R., Rocken, C. and. Ware, R.H.: 1994, GPS meteorology: Mapping zenith wet delays onto precipitable water, Journal of Applied Meteorology, 33, 379–386.

Boehm, J., Niell, A., Tregoning, P. and Schuh, H.: 2006a, Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data. Geophys. Res. Lett. 33, 15–26.

Boehm, J., Werl, B. and Schuh, H.: 2006b, Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data. Journal of Geophysical Research-Solid Earth 111 (B2), B02406.

Bosy, J., Graszka, W. and Leończyk, M.: 2007, ASG-EUPOS. A multifunctional precise satellite positioning system in Poland, European Journal of Navigation, 5, (4), 2–6.

Bosy, J., Oruba, A., Graszka, W., Leończyk, M. and Ryczywolski, M.: 2008, ASG-EUPOS densification of EUREF Permanent Network on the territory of Poland, Reports on Geodesy, No. 2 (85), 105–112.

Bosy, J., Rohm, W., Borkowski, A., Figurski, M. and Kroszczyski, K.: 2010, Integration and verification of meteorological observations and NWP model data for the local GNSS tomography. Atmospheric Research, 96, 522–530, DOI: 10.1016/j.atmosres.2009.12.012.

Douša, J.: 2004, Evaluation of tropospheric parameters estimated in various routine GPS analysis. Physics and Chemistry of the Earth, Parts A/B/C 29 (2-3), 167–175.

Douša, J.: 2010, The impact of errors in predicted GPS orbits on zenith troposphere delay estimation. GPS Solutions (available on-line: http://www.springerlink.com/content/03j481297727h166/fulltext.pdf).

Elgered, G., Plag, H.-P., van der Marel, H., Barlag, S. and Nash, J. (Eds.): 2004, COST-716, 2004: Exploitation of Ground-Based GPS for Operational Numerical Weather Prediction and Climate Applications – Final Report. EUR 21639.

EUPOS: 2008, European Position Determination System Technical Standards, Revised 2nd Edition, 24 April 2008. Resolution of the International EUPOS® Steering Committee 13th Conference, Bucharest, Romania, 23 – 24 April 2008. http://www.eupos.org/images/eupos_files/eupos%20technical%20standards%20isc-r13_2.pdf

Flores, A., Ruffini, G. and Rius, A.: 2000, 4D tropospheric tomography using GPS slant wet delays. Annales Geophysicae 18 (2), 223–234.

de Haan, S., Barlag, S., Klein Baltink, H., Debie, F. and van der Marel, H.: 2004, Synergetic use of GPS water vapor and meteosat images for synoptic weather forecasting. Journal of Applied Meteorology 43, 514–518.

Hirahara, K.: 2000, Local GPS tropospheric tomography. Earth, Planets and Space 52 (11), 935–939.

Hodur, R.: 1997, The Naval Research Laboratorys Coupled Ocean/Atmospheric Mesoscale Prediction System. Monthly Weather Review (135), 1414–1430.

Kleijer, F.: 2004, Troposphere Modeling and Filtering for Precise GPS Leveling. Ph.D. thesis, Department of Mathematical Geodesy and Positioning, Delft University of Technology, Kluyverweg 1, P.O. Box 5058, 2600 GB DELFT, the Netherlands, 260 pp.

Mendes, V.B.: 1999, Modeling the neutral-atmosphere propagation delay in radiometric space techniques. Ph.D. thesis, Department of Geodesy and Geomatics Engineering Technical Reort No. 199, University of New Brunswick, Fredericton, New Brunswick, Canada.

Morland, J. and Mätzler, C.: 2007, Spatial interpolation of GPS integrated water vapour measurements made in the Swiss Alps. Meteorological Applications 14 (1), 15–26.

Niell, A.E.: 1996, Global mapping functions for the atmosphere delay at radio wavelenghs. Journal of Geophysical Research 101 (B2), 3227–3246.

Nilsson, T. and Gradinarsky, L.: 2006, Water vapor tomography using GPS phase observations: Simulation results. Geoscience and Remote Sensing, IEEE Transactions on 44 (10 Part 2), 2927–2941.

Owens J. C. (1967). Optical refractive index of air: Dependence on pressure, temperature and composition. Applied Optics 6 (1), 51–58.

Rohm, W. and Bosy, J.: 2009, Local tomography troposphere model over mountains area. Atmospheric Research 93 (4), 777–783, DOI: 10.1016/j.atmosres.2009.03.013.

Rohm, W. and Bosy, J.: 2010, The verification of GNSS tropospheric tomography model in a mountainous area. Advances in Space Research, DOI: 10.1016/j.asr.2010.04.017.

Vedel, H. and Huang, X.-Y.: 2004, Impact of ground based GPS data on numerical weather prediction. Journal of the Meteorological Society of Japan 82 (1B), 459–472.