THE NEAR REAL TIME ATMOSPHERE MODEL BASED ON THE GNSS AND THE METEOROLOGICAL DATA FROM THE GROUND BASE AUGMENTATION SYSTEM ASG-EUPOS

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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 few years. Continuous observations from GNSS receivers provide an excellent tool for studying the earths 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 and preliminary results of the integrated investigations for NRT atmosphere model construction based on the GNSS and meteorological observations from ASG-EUPOS stations.

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 Numerical Weather Prediction (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:

$$ZTD = ZHD + ZWD \qquad (1)$$

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 given by the equation (Bevis et al., 1992, Bevis et al., 1994, Kleijer, 2004):

$$IWV = \frac{ZWD}{10^{-6} \cdot R_w} \left(k_2' + \frac{k_3}{T_M} \right)^{-1} \qquad (2)$$

where $R_w = 461.525 \pm 0.003 [Jkg^{-1}K^{-1}]$ is the specific gas constant for water vapor, $k_2' = 24 \pm 11 \ [K \ hPa^{-1}]$, $k_3 = 3.75 \pm 0.03 \ [10^5 K^2 \ hPa^{-1}]$ are refraction constants (Boudouris, 1963) and $T_M \approx 50.2 \pm 0.72 \cdot T_0$ is weighted mean water vapor temperature of the atmosphere, T_0 is the surface temperature (Mendes, 1999, Kleijer, 2004).

The $IPWV$ (Integrated Precipitable Water Vapor) is computed $IPWV$ according to relation:

$$IPWV = \frac{IWV}{\rho_w} \qquad (3)$$

where ρ_w is the water density (Mendes, 1999).

The $IPWV$ is delivered according to equations (2 and 3) from ZWD and give the information about contents of water vapor (2D model) above GNSS stations. The EUREF Permanent Network (EPN: *www.epncb.oma.be*) is the base of determination of IPWV in Europe (Vedel and Huang, 2004). Some of the Analysis Centers (AC) of EPN and International GNSS Service (IGS: *igscb.jpl.nasa.gov*) process GNSS data in NRT mode (e.g. Geodetic Observatory Pecn GOP: *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) (Dousa, 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 (EU-METNET GPS Water Vapour Programme) (Dousa, 2010).

The spatial structure and temporal behavior of the water vapor in the troposphere (4D model) can be modeled by using the GNSS tomography method. The input data of GNSS tomography are the delay on the way between the satellite and the receiver (Slant Troposphere Delay: STD) from GNSS stations. The STD can be separated like (1) into hydrostatic SHD and wet SWD compo-

nents and represented by the well known relation:

$$STD = SHD + SWD$$
$$= m_d(\varepsilon)ZHD + m_w(\varepsilon)ZWD \quad (4)$$

where ε is the satellite elevation angle and $m_d(\varepsilon)$ and $m_w(\varepsilon)$ are the mapping functions. The mapping functions are currently used for SWD computation based on the Marini formula (Marini, 1972):

$$m_{d,w}(\varepsilon) = \cfrac{1 + \cfrac{a}{1 + \cfrac{b}{1+c}}}{\sin(\varepsilon) + \cfrac{a}{\sin(\varepsilon) + \cfrac{b}{\sin(\varepsilon)+c}}} \quad (5)$$

The coefficients a, b and c which are the functions of meteorological parameters, are computed separately for hydrostatic (d) and wet (w) component. The most popular mapping functions based on the (5) are the following: NMF: Niell Mapping Functions (Niell, 1996), VMF1: Vienna Mapping Functions 1 (Boehm et al., 2006b) and GMF: Global Mapping Functions (Boehm et al., 2006a)

In the GNSS tomography SWD extracted from (4) is linked with the wet refractivity N_w by the given equation:

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

where A is the design matrix.

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), the second is to use a Kalman filter with the same equation system (Flores et al., 2000), the third is to find the solution directly from the GNSS phase measurement equation (Nilsson and Gradinarsky, 2006) and another is algebraic reconstruction technique (Bender et al., 2009, Jin et al., 2006, Jin and Park, 2007). The method presented in this paper uses the minimum constraint conditions imposed on the system of observation equations (6) (Rohm and Bosy, 2009, Rohm and Bosy, 2010).

The wet refractivity N_w is estimated from equation (6) and finally the water vapour distribution in the troposphere (4D) represented by the water vapour partial pressure e is extracted from the formula:

$$N_w = \left(k_2' \frac{e}{T} + k_3 \frac{e}{T^2}\right) Z_v^{-1} \quad (7)$$

where Z_v^{-1} is an inverse empirical compressibility factor and given by formula (Owens, 1967):

$$\begin{aligned}
Z_v^{-1} &= 1 + e[1 + (3.7 \cdot 10^{-4})e] \cdot \\
&\quad [-2.37321 \cdot 10^{-3} + 2.23366 \cdot T^{-1} - 710.792 \\
&\quad T^{-2} + 7.75141 \cdot 10^4 \cdot T^{-3}]
\end{aligned} \quad (8)$$

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., 2007, 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.

Since 2010 the idea of integrated researches based on the GNSS and meteorological observations from ASG-EUPOS stations is realized in the frame of research project entitled *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 paper presents in first section the ASG-EUPOS system description and sources of GNSS and meteorological data, localization and accuracies. The next section contains proposal of NRT ZTD processing strategy and ZWD and $IPWV$ models construction procedures. Then the proposal of NRT 4DWVD and NRT 4DTPD models construction procedure is described. In this section is described the proposal of the method of water vapor distribution in space and time (4DWVD) using GNSS tomography technique and also preliminary results are presented. For comparision of above models the Coupled Ocean / Atmosphere Mesoscale Prediction System (COAMPS) model 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).

2 ASG-EUPOS 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 (1). 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).
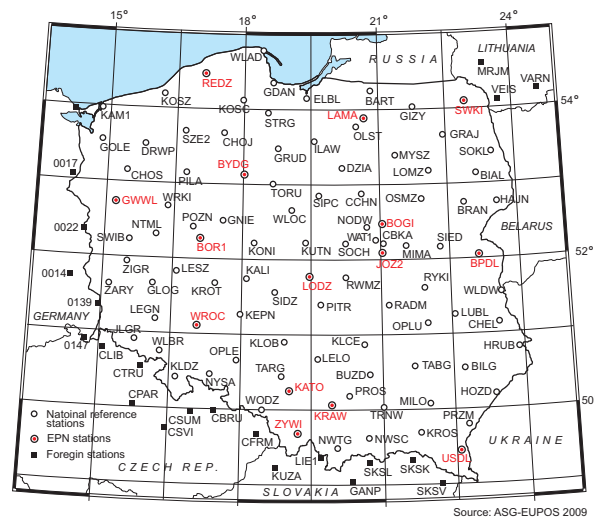

Figure 1: Reference stations included in ASG-EUPOS (www.asgeupos.pl).

The reference stations are equipped with the modern GNSS receivers and the antennas with absolute calibrations. The Management Centre (MC) of ASG-EUPOS system processing GNSS data of ASG-EUPOS network and uses the same processing strategy that IGS and EPN Analyses Centers (AC) (Bruyninx et al., 2010). One of the results of GNSS data processing is a tropospheric delay, detail Zenith Total Delay ZTD (see Fig. 2)

The comparison of ZTD estimated in ASG-EUPOS MC and obtained form combined EPN network solution for common stations confirmed convergence of received results.
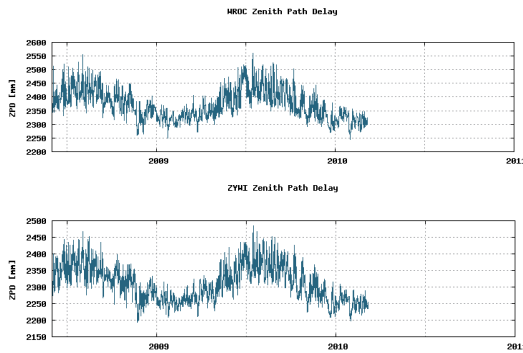
Figure 2: ZDT - the product of GNSS data processing for two selected ASG-EUPOS stations (*www.asgeupos.pl*)

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

- pressure with accuracy $\pm 0.08 hPa$ from 500 to 1100 hPa,

- temperature with accuracy $\pm 0.2^{o}C$ from -50 to +60 ^{o}C,

- relative humidity with accuracy $\pm 2\%$ from 0 to 100 %,

Figure 3 shows the example of meteorological observations: temperature, pressure and relative humidity from station WROC of ASG-EUPOS system equipped with Paroscientic, Inc. MET4A sensor.
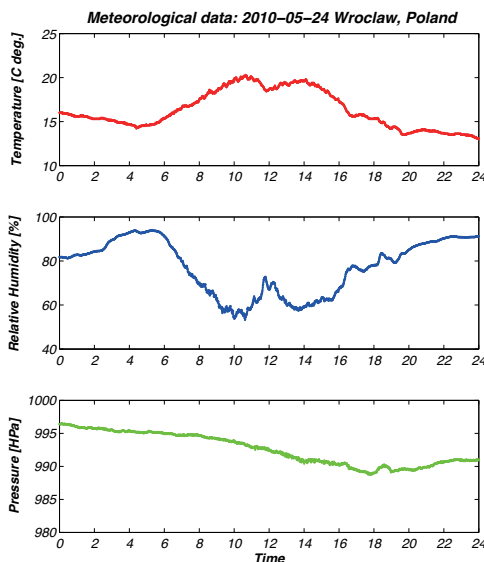

Figure 3: Meteorological observation form ASG-EUPOS station WROC equipped with MET4A sensor (www.igig.up.wroc.pl/spgnss).

The meteorological observations are also available from the Polish meteorological network, managed by Institute of Meteorology and Water Management (IMGW) and contains over 120 automatic weather stations: synoptical and climatological. 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 3 launching sites in Poland (Wroclaw, Leba and Legionowo), the second one is currently under construction - the network of radiometers (actually 3 radiometers are located also in Wroclaw, Leba and Legionowo). 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.

Because of data inhomogeneity, original methods of meteorological data validation based on the differential wavelet method will be used. The proposed method of the meteorological data validation leads to data reliability assessment as a measure of bias and random error. It is crucial to perform appropriate pressure measurements. Conditions for temperature measurements ease and more sensors meet the accuracy criteria. The recommendation is to sample the pressure as accurate as possible with homogeneous instruments and in the similar conditions (Bosy et al., 2010b).

3 NEAR REAL TIME ATMOSPHERE MODEL

3.1 Model construction methodology

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 4 shows the diagram of NRT ZTD and NRT ZWD models construction (Bosy et al., 2010a).
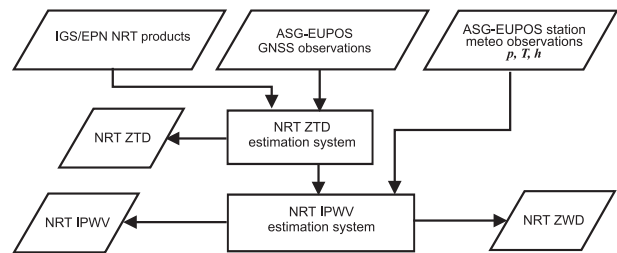

Figure 4: The diagram of NRT ZTD, ZWD and IPWV models construction on the base of GNSS and meteorological data from ASG-EUPOS reference stations

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 (Dousa, 2004, Dousa, 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 IWV and IPWV values above all ASG-EUPOS stations will be calculated from equations (2) and (3) and finally NRT ZWD and NRT IPWV models for Poland territory will be constructed.

The idea of water vapor NRT 4DWVD and meteorological parameters: temperature and pressure NRT 4DTPD in atmosphere models construction is presented in figure 5 (Bosy et al., 2010a).
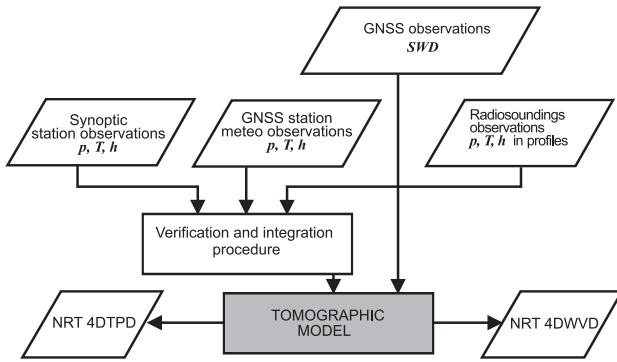
Figure 5: The diagram of NRT 4DWVD and NRT 4DTPD models construction

3.2 GNSS tomography model

The spatial structure and temporal behavior of the water vapour in the troposphere (4D) can be modeled using the GNSS tomography method. The GNSS signal delays due to the water vapour are evaluated for a large number of different views through the atmosphere (Bender and Raabe, 2007). The idea of GNSS tomography for Poland is presented in the figure 6 (Bosy et al., 2010a).
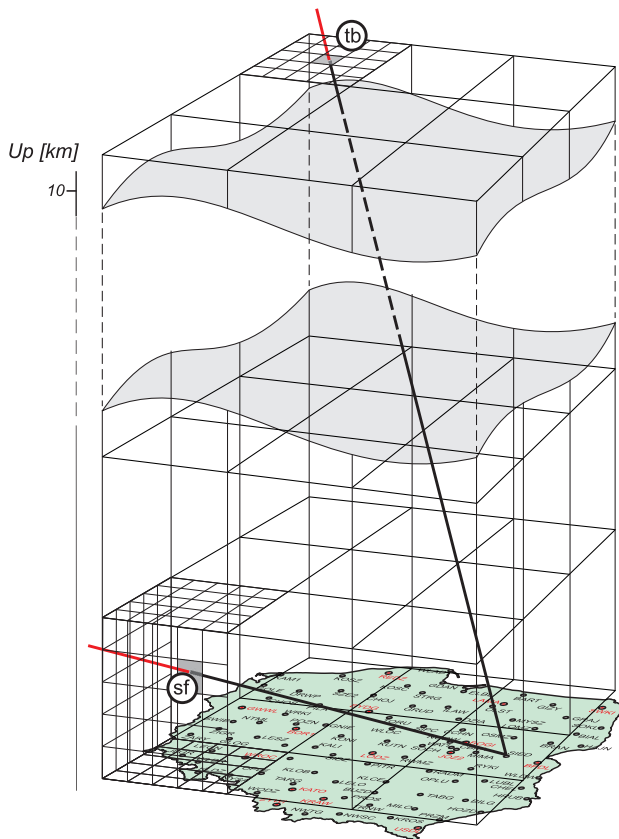

Figure 6: The ray path in consecutive voxels. Two cases are considered, the first when the ray is coming out of the model's side face (sf), and the second, when ray is comming out of the model top boundary (tb)

The input data of GNSS tomography are: the signal Slant Wet Delays SWD, which are the results of the GNSS data processing, the meteorological observations from ASG-EUPOS meteo stations and IMGW synoptic stations. The quality and quantity of the GNSS observations is strongly correlated with the GNSS satellites constelation, the number of the ground stations and inter-station distances. As a result of the GNSS data processing the cut off angle of SWD observations are set to 3 - 5 degrees of elevation. Moreover, the empirical results show that the angles are ranging from 5 to 85 degrees, but most of the observations are clustered between 10 and 15 degrees. In case of GNSS troposphere tomography it is typical condition (Bender and Raabe, 2007).

In the GNSS tomography SWD is linked with wet refractivity N_w by the equation (6). One of the method to resolution of equation (6) is the authors method uses the minimum constraint conditions imposed on the system of observation equations (6) (Rohm and Bosy, 2009, Rohm and Bosy, 2010).

The design matrix A has the form:

$$A = \begin{bmatrix} d_{11} & 0 & 0 & 0 & \cdots & d_{1m} \\ d_{21} & d_{22} & d_{23} & 0 & \cdots & d_{2m} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & 0 & d_{n4} & \cdots & d_{nm} \\ -1 & 1/w_{12} & 1/w_{13} & 1/w_{14} & \cdots & 1/w_{1m} \\ 1/w_{21} & -1 & 1/w_{23} & 1/w_{24} & \cdots & 1/w_{2m} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/w_{i1} & 1/w_{i2} & 1/w_{i3} & -1 & \cdots & 1/w_{im} \end{bmatrix} \quad (9)$$

where the elements d are the distances the rays travel through each voxel and the weights w are the inverse of the distance between the constrained voxel and all other voxels in the same layer (Fig. 6). The constrained voxel in matrix A (9) is the one that has assigned value -1, in the same time all voxels from this row have weights, which are distance dependend. The number of rows of A matrix varies, depending on the number of scanning rays in each epoch (SWD elements). The number of columns is fixed it's 250 as many as voxels in the model.

The constraint conditions added to the A matrix represent horizontal constraint equation, where each refractivity, for instance k voxel, is the weighted mean of the refractivities of the surrounding voxels (from the same layer):

$$0 = \frac{1}{w_{i1}} \cdot N_{w1} + \frac{1}{w_{i2}} \cdot N_{w2} + \ldots - 1 \cdot N_{wk} + \ldots$$
$$\ldots + \frac{1}{w_{im}} \cdot N_{wi} \quad (10)$$

To find the voxels' refractivities one needs to invert the equation (6), which in theory might be solved by the means of the least squares method:

$$N_w = (A^T \cdot P \cdot A)^{-1} \cdot A^T \cdot P \cdot SWD^T \quad (11)$$

where the P is a weighting matrix. The weighting matrix P is constructed as an inversion of covarince matrix of observations SWD given by the formula:

$$P = C_{SWD}^{-1}. \quad (12)$$

The closest approximation of the reference value is obtained by using the More-Penrose pseudoinverse ($^+$). The pseudoinverse is based on Singular Value Decomposition (SVD), which is the factorization of the variance-covariance matrix in the equation (11).

$$(A^T \cdot P \cdot A)^+ = V \cdot S^+ \cdot U^T \quad (13)$$

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.

3.3 Results

The proposed GNSS tomography model was tested for the real GNSS observations delivered from the GNSS network Karkonosze located in the Sudety mountains and compared with the NWP model (Rohm and Bosy, 2010). The data used in this case study comes from 48-hour GPS campaign in Karkonosze from 26th of August till 27th of August 2007 and 36 hours of the collocated run of COAMPS model. There were 48 epochs of GNSS tomography model, and 36 epochs of COMAPS models outputs. The first epoch of GNSS tomography model is epoch number 1, the last epoch is number 48. The first epoch of COMAPS model outputs is epoch number 12, the last epoch is number 48. Thus, there are 36 epochs of common observations.
The obtained SWD may be verified with the aid of COAMPS models data. The pressure p, the temperature T and the water vapour partial pressure e have been interpolated to the center points of the tomographic model grid (Fig. 6) using the procedure from (Bosy et al., 2010b). They were considered reference data. With the same raytracing technique as described in the paper of Rohm and Bosy (Rohm and Bosy, 2009), the reference SWD values from COAMPS model inside tomographic model were obtained. These were compared with SWDs obtained from GNSS and UNB3m model determinants (Leandro et al., 2008), the results are presented in figure 7 (Rohm and Bosy, 2010).
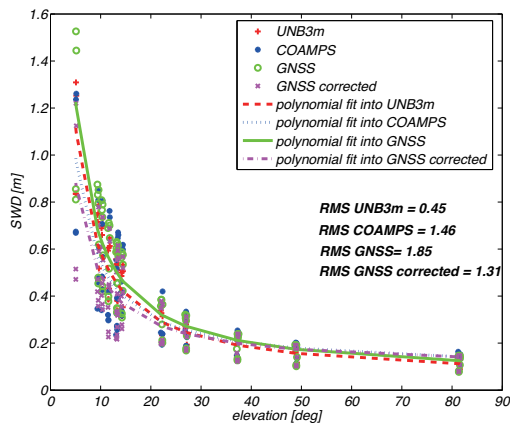

Figure 7: The SWD - elevation dependency epoch: 38, trends estimated from: UNB3m - red, COAMPS data line of sight - blue, GNSS observables - green, GNSS observables corrected - magenta, also goodness of fit has been presented in terms of RMS scatter

The blue line represents (Fig. 7) the integration of wet refractivities in the tomographic model derived from COAMPS as the reference data. Thus, it can be considered the reference SWD input to the tomographic model. The GNSS observables are affected by three main factors. Firstly, they are the estimate along the lines of sight from the antenna to the satellite and they may eventually leave the tomographic model through its side faces. Thus, some of the delay is caused by the part of atmosphere that is not included in the model (ray sf on the figure 6). This effect was minimalized with the help of the UNB3m model (Leandro et al., 2008) which was employed to determine the residual delay represented by the magenta line in the figure 7. The UNB3m model is a tool to obtain in given location (latitude, height) and direction (elevation angle) SWD. Here we calculated the SWD of the signal that leaves the tomographic model from the side face, then we subtracted this part from the SWD derived from GNSS observations (margenta color in the figure 7). The second accuracy limiting factor is that the pressure derived ZHD might be

biased and thus transfer the bias into ZWD. Finally, the third factor is non uniformity of the atmosphere around the receiver, which was not taken into account here (Rohm and Bosy, 2010).

In the case of GNSS tomography troposphere model verification the scanning rays path was calculated and all refractivity was summarized to get simulated Slant Wet Delays (SWD). 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. According to the equation (4), 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 (11) and (13) following the methodology presented in the Rohm and Bosy (Rohm and Bosy, 2009), the tomographic wet refractivities were obtained. The obtained accuracy of this simulated solution is between 0.2 to 0.6 mm/km (Rohm and Bosy, 2010, Bosy et al., 2010a).
The results of tomographic model solution feed with GNSS derived SWDs are presented in figure 8. The inputs for tomographic model (11) are: SWD - derived from GNSS data processing and corrections from UNB3m model and the d values obtained from the raytracing through the model (Fig. 6) (Rohm and Bosy, 2010).
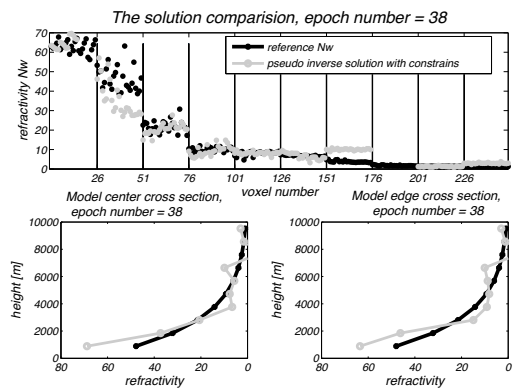

Figure 8: The tomographic solution from GNSS derived SWD (grey), against reference wet refractivity from the COAMPS at the center points of tomographic model (black), epoch:38

In case of the 38 epoch, the agreement between the obtained and the reference wet refractivities could be an evidence that proposed approach of including the flow parameters and correcting the SWD with the aid of UNB3m model improves the solution (Fig. 8). Nevertheless there are lots of epochs with lower accuracy - which is a consequence of the previously discussed discrepancy between GNSS-derived SWD and COAMPS-derived SWD. 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 (Rohm and Bosy, 2010, Bosy et al., 2010a) .

4 CONCLUSIONS AND FUTURE WORK

The GNSS tomography technique, produces high quality information concerning the state of water vapor in the atmosphere. The proposed model based on the minimum constraints solution is validated with the help of simulated weather conditions. The same model transformed into the near real time 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 near real time atmosphere model created from meteorological and GNSS data, could be competitive to Numerical Weather Prediction model, especially for nowcasting. The improvement in positioning is that tropospheric delays will be calculated directly from observations, not like now from deterministic models.

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