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GNSS Meteorology

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ABSTRACT: GNSS meteorology is the remote sensing of the atmosphere (troposphere) using Global Navigation Satellite Systems (GNSS) to derive information about its state. The most interesting information is a delay of the signal propagation due to the water vapor content - the Slant Wet Delay (SWD). The inverse modeling technique being concern here is the tomography. It is the transformation of the slant integrated observation of state of the atmosphere (SWD), to the three dimensional distribution of the water vapor. Over past six years the studies on GNSS tomography were performed in the Wroclaw University of Environmental and Life Sciences on the GNSS tomography. Since 2008 the new national permanent GNSS network ASG-EUPOS (about 130 GNSS reference stations) has been established in Poland (www.asgeupos.pl). This paper presents the issues of the Near Real Time troposphere model construction, characteristic of GNSS and meteorological data and the building of the required IT infrastructure.

1 INTRODUCTION

Global Navigation Satellite System is designed for positioning, navigation, amongst other possible applications it can also be used to derive information about the state of the atmosphere, what is now recognized as GNSS meteorology. Particularly GNSS meteorology is the remote sensing of the atmosphere from satellite platform (GNSS radio occultation meteorology) (Pavelyev et al. 2010) and ground permanent stations (ground based GNSS meteorology) (Bender et al. 2010). Continuous observations from GNSS receivers provide an excellent tool for studying the earth atmosphere. There are many GNSS meteorology applications: climatology, nowcasting and 4D monitoring.

The ground based GNSS meteorology is based on the tropospheric delay, one of the results of GNSS data processing . 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 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 (Kleijer 2004):

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

where R_w is the specific gas constant for water vapor, k'_2, k_3 are refraction constants (Boudouris 1963) and T_M is weighted mean water vapor temperature of the atmosphere (Kleijer 2004).

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

$$IPWV = \frac{IWV}{\rho_w} \tag{3}$$

where ρ_w is the water density (Mendes 1999).

The *IPWV* is delivered according to equations (2 and 3) from *ZWD* and gives 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). Since 2005 EPN analysis centres ASI, BKG, GOP and LPT delivers Near Real Time *ZTD* for meteorological applications in the frame of international project E-GVAP (EUMETNET 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 signal

Slant Wet Delays SWD, which are the results of the GNSS data processing, the meteorological observations from synoptic stations and the Numerical Weather Prediction (NWP) models data. The NWP models data are also used for GNSS data verification and calibration of the tomography model (Rohm and Bosy 2010). The STD can be separated like (1) into hydrostatic SHD and wet SWD components 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 (Niell 1996; Boehm et al. 2006).

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

$$SWD = A \cdot N_w \quad (5)$$

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 (5) 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 (ART) developed by Kaczmarz (Bender et al. 2009). The method presented in this paper uses the minimum constraint conditions imposed on the system of observation equations (5) (Rohm and Bosy 2009; Rohm and Bosy 2010).

The wet refractivity N_w is estimated from equation (5) and finally the water vapour distribution in the troposphere (4D) represented by the water vapour partial pressure e and the temperature T is extracted from the formula:

$$N_w = \left(k_2' \frac{e}{T} + k_3 \frac{e}{T^2} \right) Z_v^{-1} \quad (6)$$

where Z_v^{-1} is an inverse empirical compressibility factor (Owens 1967).

The new Polish national permanent GNSS network (Ground Base Augmentation System) 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 consists (including foreign stations) of about 130 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*. The paper presents in the second section the methodology of NRT atmosphere models construction procedures. The second section encloses proposal of the method of water vapor distribution in space and time (4DWVD) using GNSS tomography technique. The third section includes the ASGEUPOS system description and sources of GNSS and meteorological data, localization and accuracies. The fourth section contains the specification of IT infrastructure for NRT data streaming and processing. The paper is closed in fifth section with conclusions.

2 NEAR REAL TIME 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 1 shows the diagram of NRT ZTD and NRT ZWD models construction (Bosy et al. 2010).

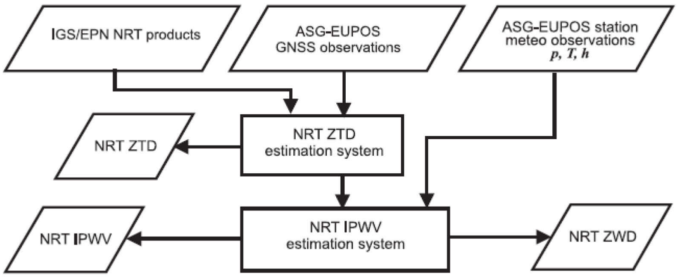


Figure 1: The diagram of NRT ZTD, ZWD and IPWV models construction on the base of GNSS and meteorological data from ASG-EUPOS reference stations

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 (Bosy et al. 2010).

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 2 (Bosy et al. 2010).

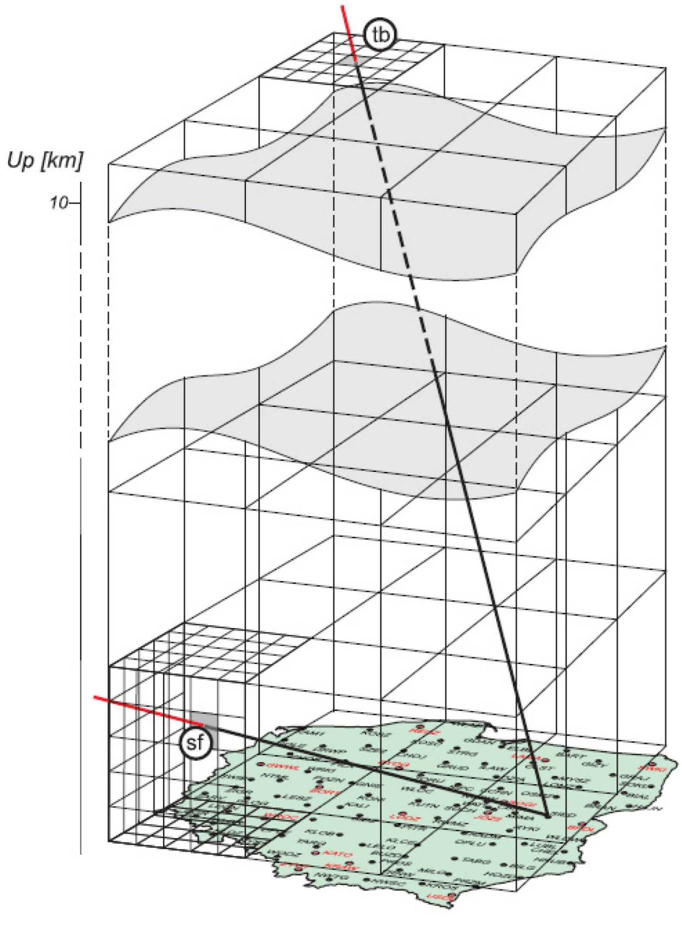


Figure 2: The ray path in consecutive voxels. Two cases are considered, the first when the ray is coming out of the model's side face (sf), and the second, when ray is comming out of the model top bounduary (tb)

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. The quality and quantity of the GNSS observations is strongly correlated with the GNSS satellites constellation, 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 (5). One of the method to resolution of equation (5) is the authors method (Rohm and Bosy 2009; Rohm and Bosy 2010) presented briefly below.

To find the voxels' (Fig. 2) refractivities one needs to invert the equation (5), which in theory might be solved by the means of the least squares method:

$$N_w = \left(A^T \cdot P \cdot A\right)^{-1} \cdot A^T \cdot P \cdot SWD^T \tag{7}$$

where the A is design matrix (5) and P is a weighting matrix. The weighting matrix P is constructed as an inversion of covarince matrix of observations *SWD* given by the formula:

$$P = C_{SWD}{}^{-1} \tag{8}$$

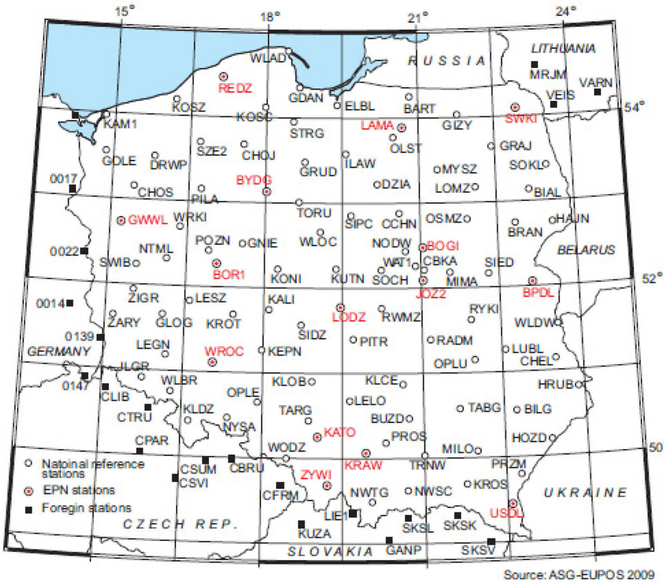
To get 3D picture of the wet refractivity N_w the Singular Value Decomposition (*SVD*) technique is used. The *SVD* technique is the pseudo inverting of system (5) on the base of factorization of the variancecovariance matrix in the equation (7).

$$\left(A^T \cdot P \cdot A\right)^{+} = V \cdot S^{+} \cdot U^T \tag{9}$$

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 ASG-EUPOS GNSS AND METEOROLOGICAL DATA

The GNSS data are currently available from the GNSS permanent stations operated in the frame of national networks. In Poland the national permanent GNSS network ASG-EUPOS has been established since 2008. 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 (3). 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. 3) (Bosy et al. 2008).



Source: ASG-EUPOS 2009

Figure 3: Reference stations included of ASG-EUPOS system (www.asgeupos.pl)

The reference stations of ASG-EUPOS system (Fig. 3) are equipped with themodern GNSS receivers and the antennas with absolute calibrations. 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.

Meteorological observations from ASG-EUPOS stations (Bosy et al. 2010) will be used for *ZHD* extraction from equation (1), to compute *ZWD* and finally *SWD* (4). The external meteorological observations from Institute of Meteorology and Water Management (IMGW) synoptic stations, radiosoundings observations and NWP COAMPS model outputs will be used also for verification of GNSS tomography model (Rohm and Bosy 2010).

4 IT INFRASTRUCTURE

Meteorological data from stations dispersed on the area of study are collected with GNSS data and put into ASG-EUPOS caster. Then using the NTRIP (Networked Transport of RTCM via Internet Protocol), data are transferred to the center that deals with NRT (Near Real Time) processing. The Internet is particularly well suited to transmit data between different providers over long distances. However, the servers required must be tied to the Internet via interconnected broadcasters with sufficient bandwidth. In order to secure resources the infrastructure must be equipped with firewall and IDS (Intrusion Detection System) / IPS (Intrusion Prevention System) elements (Fig. 4).

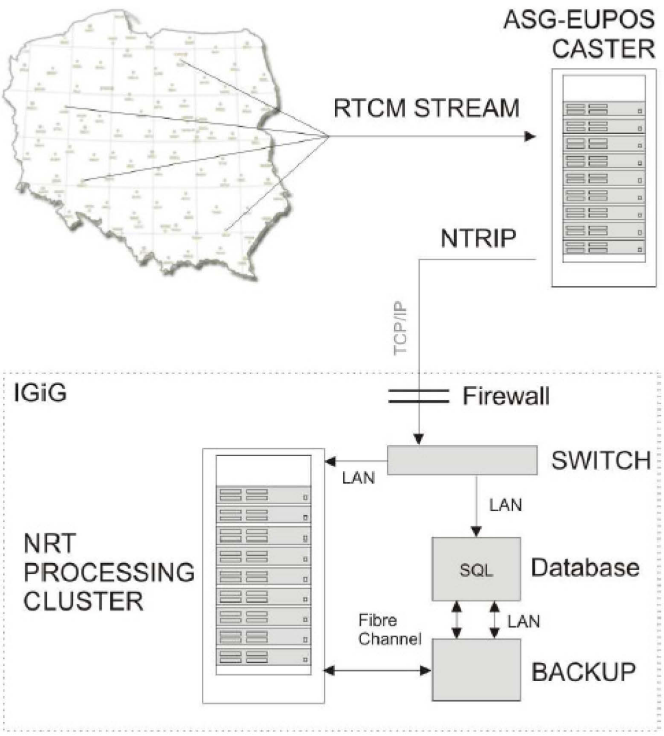


Figure 4: IT infrastructure for data streaming and processing

The GNSS and meteorological data from Management Centre (MC) of ASG-EUPOS are decoded and sent both to compute clusters and database (Fig. 4). Despite the effectiveness of the algorithms computations require compute clusters. That is why one needs such computer cluster, which enables parallel computations. NRT processing should be equipped with back-up system, which connects with other devices through dedicated high-speed fiber channel network. The above presented conception is still very general and will be detailed during tests and the project realization.

5 CONCLUSIONS

Ground based GNSS meteorology currently utilizes the height resolution GBAS networks like ASGEUPOS, where reference stations are equipped with GNSS and meteorological sensors. The NRT troposphere model based on the GNSS and meteorological data of GBAS system could be used as well as in meteorological applications, in the real-time and post-processing positioning services of ASGEUPOS system. The model created from meteorological and GNSS data, could be competitive to Numerical Weather Prediction models, 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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