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# Positioning and applications

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**Abstract:** The paper presents national report of Poland for IAG on positioning and applications. The selected research presented was carried out at leading Polish research institutions and concern precise multi-GNSS satellite positioning – relative and absolute – and also GNSS-based ionosphere and troposphere modelling and studies. The research resulted in noticeable advancements in these subjects confirmed by the development of new algorithms and methods. New and improved methods of precise GNSS positioning were developed, and also GNSS metrology was studied. New advanced troposphere models were presented and tested. In particular, these models allowed testing IPW variability on regional and global scales. Also, new regional ionosphere monitoring web-based services were developed and launched.

**Keywords:** precise positioning, troposphere, ionosphere, GPS, Galileo, GNSS

## 1. Introduction

The subject of positioning and applications covers important IAG activities. Therefore the IAG Commission 4 “Positioning and Applications” was established to promote research into the development of a number of geodetic tools that have practical applications to engineering and mapping (IAG C4 TOR). Recognizing the central role that Global Navigation Satellite Systems (GNSS) plays in many of these applications, the Commission’s work focuses on GNSS-based research in precise positioning, remote atmosphere sounding including InSAR and other space-geodetic techniques. This report presents summary of the selected research carried out at leading Polish research institutions, focusing on broad range of multi-GNSS systems applications, that is only a part of the broad research carried out in Poland on the subject. It starts from different aspects of positioning and continues into remote GNSS atmosphere sounding (in particular ionosphere and troposphere).

## 2. Positioning

### *2.1. Studies on Inter System Bias in multi-GNSS precise positioning*

In 2011–2015 extensive studies on relative precise positioning algorithms were carried out at the University of Warmia and Mazury in Olsztyn (UWM). A new methodology allowing for instantaneous (single epoch) precise positioning using medium to long baselines was developed. The most recent precise positioning model is developed to be applied in multi-GNSS relative positioning (Paziewski and Wielgosz, 2014). On the other hand this approach forces additional modelling of hardware biases which are introduced in tightly combined multi-GNSS model (Paziewski and Wielgosz, 2015).

Nowadays, combining observations from different GNSS systems often relies on the mathematical model requiring different reference satellites for each system. This approach can be referred to as loose combining and it is used when GNSS systems with different frequencies are applied. On the other hand, overlapping (i.e., the same) frequencies, like L1/E1 and L5/E5a in GPS and Galileo, support creating double-differences (DD) between satellites of different GNSS systems. This approach is known as tight combining, and the observational model assumes a single reference satellite for all the observations. However, when this approach is introduced, one must take into account not only time and coordinate system differences, but also the difference between the receiver hardware delays affecting the signals from different systems. This bias is termed as inter system bias (ISB). The ISB is caused by the correlation process within the GNSS receiver, thus it is present in both carrier phase and code data.

Figure 1 presents example estimates of the code and carrier phase ISBs obtained from single epoch solutions during the experiment conducted at UWM in 2014. In addition, the right hand plots in Figure 1 present Galileo satellite elevations during the experiment. The plots show that the estimated values of the ISB were stable. Higher noise of the code ISB at the beginning and at the end of the experiment coincides with the low elevations of the observed Galileo-IOV satellites.

The presented results show that in the tightly combined GPS+Galileo processing the receiver inter system bias is absent when a baseline is formed with receivers of the same type (including the same OEM boards and firmware versions, Javad Alpha#1 – Javad Alpha#2 in this example). For a baseline formed with receivers of different types (e.g., Javad Alpha#1 – Leica GR25), the ISB shows significant values that cannot be neglected. This indicates that the ISB is receiver-type dependent.

The phase and code ISBs also show high epoch-by-epoch repeatability during several hours of the experiment. The mean ISB estimated in the single-epoch solution is very close to values estimated in the 10-minute sessions. It was shown that the phase ISB can be estimated in the single epoch solution with 1–2 mm of noise. At the same

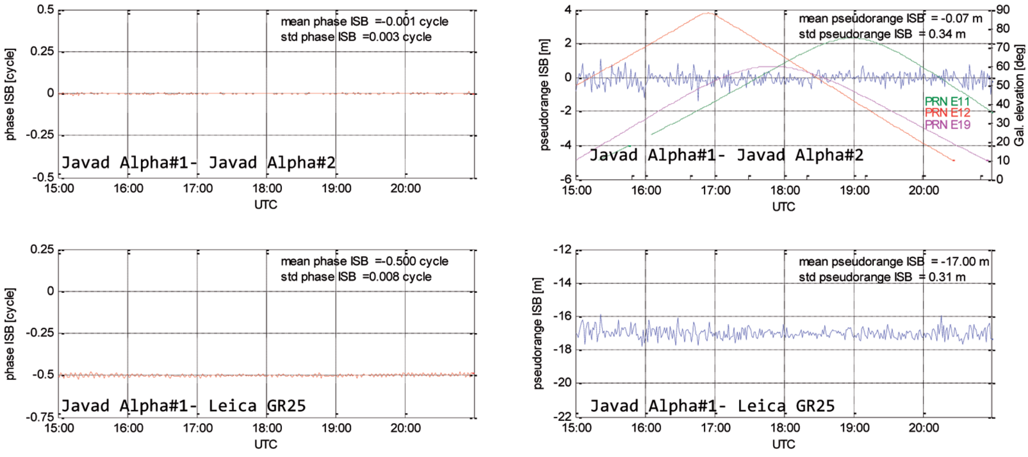

Fig. 1. Estimated carrier phase (left) and code (right) L1/E1 ISBs in the single-epoch solution for different receiver pairs (UWM experiment in 2014)

time, the accuracy of the instantaneous code ISB is at a decimetre level. The ISB values estimated as a single (constant) parameter in longer sessions show better repeatability than epoch-varying parameter in single-epoch solutions. These facts indicate that ISB parameters are rather stable in time and may be estimated as one parameter per session. The sum of the phase and code ISB in the triangle built of three receiver pairs equals zero. This means that one can directly compute ISB for, e.g. B–C receiver pair if ISBs for A–B and A–C pairs are known. It was also shown that the code and phase ISBs depend on signal frequency and differ for L1/E1 and L5/E5a signals. Also, the carrier phase and code ISBs for a particular receiver pair can be estimated once and introduced as a known correction in GPS+Galileo tightly combined processing. The positioning experiment showed that the introduction of the known ISB parameter had an advantage over the estimation of the ISB. The positive impact was also observed in the performance of the carrier phase ambiguity resolution. From more details see a paper by Paziewski and Wielgosz (2015).

### *2.2. Development of ambiguity function methods*

The MAFA method (Modified Ambiguity Function Approach) is the new strategy of carrier phase data processing developed at UWM in 2010. In this strategy the arrangement of computational process is different from the classical three-stage (float solution, integer ambiguity resolution, fixed solution) approach. The basic idea of this strategy relies on adding condition equations to a functional model of the adjustment. The ambiguities are not explicitly solved in this approach. However, due to condition equations, their integer nature is preserved in the final solutions. The functional model for the carrier phase adjustment is relatively weak. Therefore, different techniques of improving the efficiency of the MAFA method have been proposed. Three of them are the most important: cascade adjustment, integer de-correlation and search procedure (Cellmer, 2012; 2013) These procedures allow obtaining the correct solution, even if the a priori position is several meters away from the actual one. The tests performed show that the strategy is highly efficient and allows to obtain a precise position from a single epoch. An important advantage of the new strategy is its robustness to the "cycle slip" effect in subsequent observation epochs.

The general formula of the residual equations in the MAFA method is

$$\mathbf{v} = \frac{1}{\lambda}\mathbf{Ax} + \boldsymbol{\delta} \tag{1}$$

with

$$\boldsymbol{\delta} = \mathrm{round}(\boldsymbol{\Phi} - \frac{1}{\lambda}\boldsymbol{\rho}_0) - (\boldsymbol{\Phi} - \frac{1}{\lambda}\boldsymbol{\rho}_0) \tag{2}$$

where
$\mathbf{v}$ – vector of residuals ($n$×1),
$\mathbf{x}$ –vector of parameters (increments to a priori coordinates vector x0),
$\mathbf{A}$ – design matrix ($n$×3),
$\boldsymbol{\delta}$ – vector of misclosures ($n$×1),
$\boldsymbol{\Phi}$ – double differenced (DD) carrier phase observation,
$\boldsymbol{\rho}_0$ – DD geometric distance vector computed using a priori position and satellite coordinates,
round(.) – function rounding to the nearest integer.

Recently, the foundations for some validation techniques in the MAFA method have been elaborated. Each of them is based on forming the confidence region and then testing whether the final solution is inside it or not.

### *2.3. Studies on an advanced stochastic model*

The studies on an advanced stochastic model for precise positioning were carried out at the Warsaw University of Technology (WUT). The main goal was to improve the reliability of the position in carrier phase-based relative GNSS real-time kinematic technique that utilizes reference stations network, known as Network-based RTK method. The reliability of the rover positioning was defined as the resultant of two parameters: solution availability and accuracy. Solution availability describes the possibility of achieving the correct carrier-phase ambiguity fix, i.e. integer estimation of ambiguity as well as their acceptance in the validation test. It may be defined as a quantitative parameter on the basis of solution results as the ratio of the number of solutions for which correct ambiguities were obtained to the total number of solutions for a given period or as a parameter describing the potential probability of correct fixing of ambiguities for a given solution (epoch), i.e., Ambiguity Resolution Success Rate or

Probability of Correct Fix. The solution accuracy describes the accuracy of the rover position estimated for fixed baseline solution and its value can by determined using position variance estimations or the standard deviation for the given set of solutions.

In the reported studies a solution availability and accuracy were analysed using a new approach to account for the residual errors within the stochastic model of GNSS observations, called Network-Based Stochastic Model (NBSM) (Prochniewicz, 2014). This approach is based on the assumption that residual errors of observations remaining after applying network corrections can be described using the variances of those corrections. It is possible to utilize correction terms' variances in the stochastic modelling of the observations. The determination of the correction variances directly in the network solution together with the corrections allows to capture the current residual error values based on observations from a single epoch. This predisposes that new approach for application in instantaneous Network RTK positioning.

The schematic description of the Network-Based Stochastic Model is presented by the following equation

$$\mathbf{D}\{l\} = \mathbf{C}_l = \mathbf{C}_\varepsilon + \mathbf{C}_\delta \tag{3}$$

where $\mathbf{C}_l$ is the variance-covariance matrix of observations (observed-minus-computed values), the variance-covariance matrix $\mathbf{C}_\varepsilon$ describes the observations noise characteristic, and the variance-covariance matrix $\mathbf{C}_\delta$ the stochastic properties of correction terms; $\mathbf{D}\{l\}$ denotes the dispersion operator. Detailed mathematical formula and application algorithm of NBSM is presented in (Prochniewicz, 2014).

Determination of the correction variance based on the network solution results in the variance estimation being performed independently for ionospheric and geometric corrections for each observation (for each satellite or for each double-difference). From the point of view of GNSS models' classification, the NBSM is the Ionosphere-Weighted Troposphere-Weighted Model. On the other hand, neglecting the correction errors ($\mathbf{C}_\delta$) in Eq. (3) is referred as the Ionosphere-Fixed Troposphere-Fixed Model. The comparison of the non-zero elements of the variance-covariance matrix for the Ionosphere-Fixed Troposphere-Fixed Model with the NBSM is shown in Figure 2.

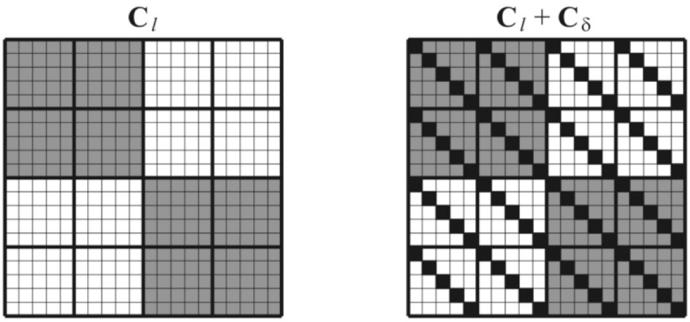

Fig. 2. Comparison of the non-zero elements of the variance-covariance matrix for the Ionosphere-Fixed Troposphere-Fixed Model with the NBSM

The presented examples correspond to dual-frequency phase and code observations for six satellites for which the cross-correlation between observations of the given type for two frequencies are taken into account. Gray and black colours mark the non-zero elements of the relevant matrices $\mathbf{C}_\delta$ and $\mathbf{C}_\delta$. Based on this comparison it can be noted that the NBSM takes into account additional correlations of the observation that were not included in the Fixed Model.

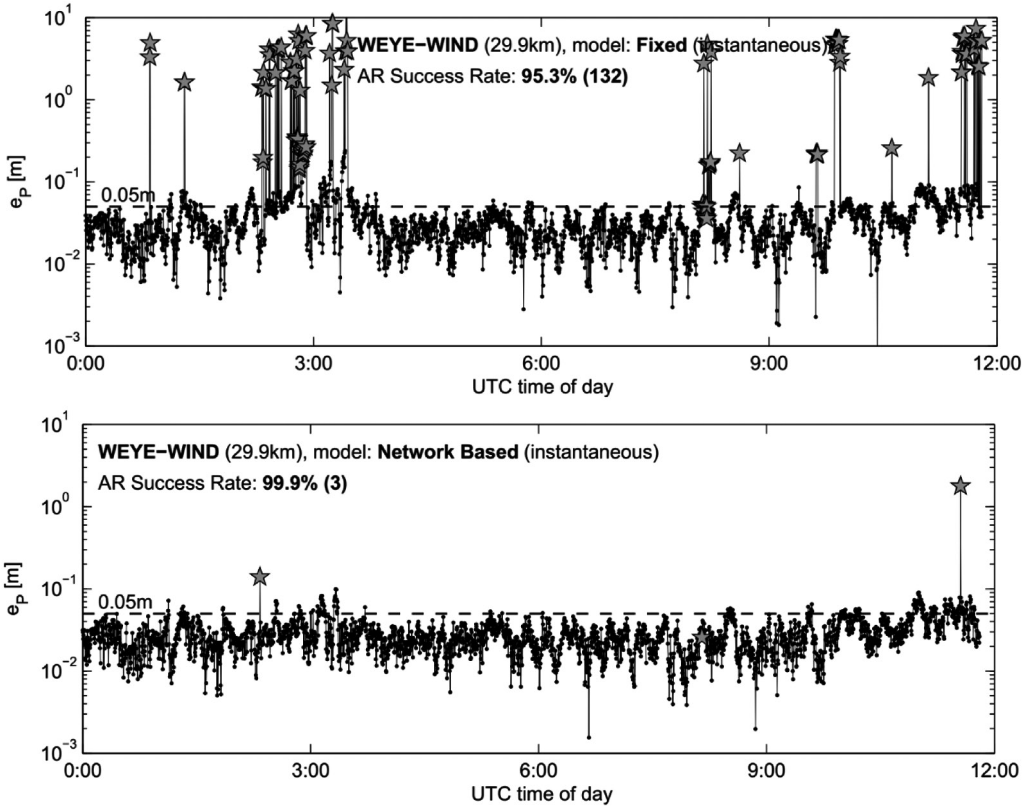

Fig. 3. Resulting position comparison for the ionosphere/troposphere fixed model (upper plot) and NBSM (bottom)

In order to analyse the influence of the correction accuracy characteristic on the reliability of instantaneous Network RTK solution results, the Fixed Model and proposed NBSM approach were compared. The network used in the test was a fragment of Austrian regional network EPOSA characterized by significant differences in station elevation. Also, the test GPS data were collected during severe ionospheric disturbances. Two reference stations (WIND and LIEZ, baselines length of 30 km and 46 km) located within the area covered by the reference station network were excluded from the network solution and used as test stations (user stations). The tests performed include ambiguity estimation, ambiguity validation and position estimation for compared models.

The resultant errors of the user position calculated on the basis of the comparison of the estimated position and known (reference) positions are shown in Figures 3 and 4. Star symbol marks solutions for which ambiguity was estimated incorrectly. It can be observed that utilizing the estimated correction accuracy in the NBSM model increases the number of correct ambiguity estimation solutions by approximately 5–8% to a level of 98.9–99.9%. In addition, the results of validation of the ambiguity estimation for the test data for three discrimination tests (R-ratio, F-ratio and D-test) show that using NBSM allows to increase the Ambiguity Resolution Success Rate by 3–15%. It was shown that use of the NBSM model makes possible a significant improvement in the precision of the estimated positions by approximately 30% for horizontal components, and approximately 20% for vertical component. The test results support the conclusion that including the real correction accuracy in the stochastic model for instantaneous positioning, as proposed in the NBSM approach, is an effective method that increases the reliability of Network RTK positioning.

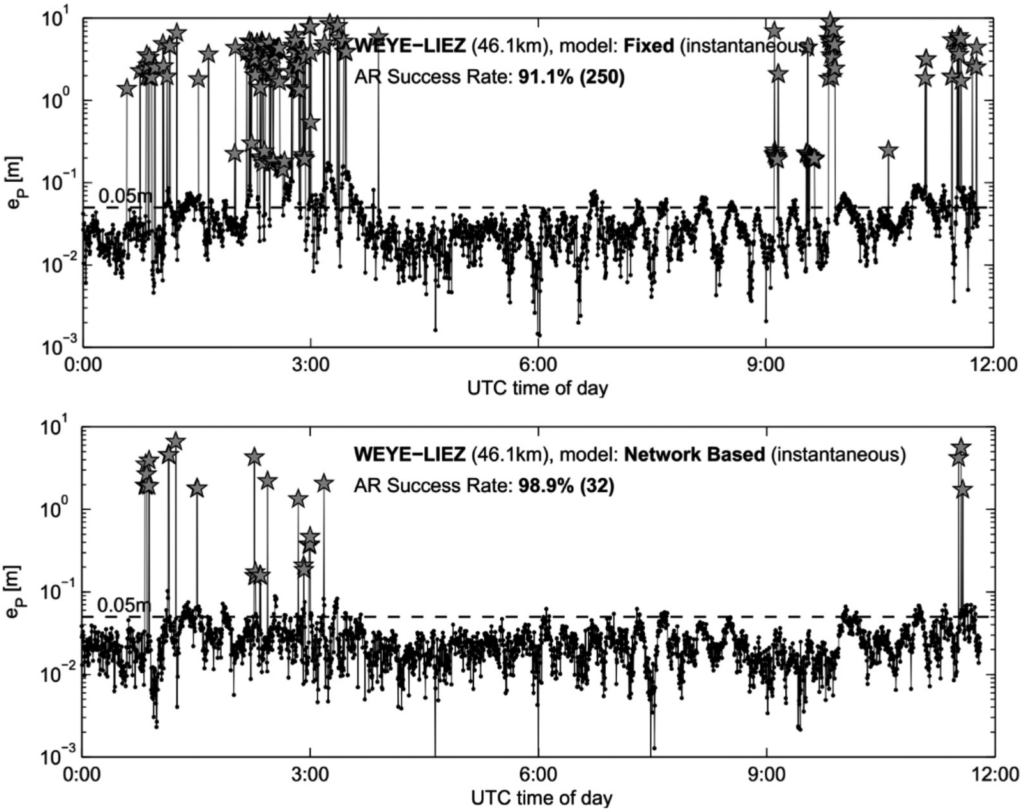

Fig. 4. Resulting position comparison for the ionosphere/troposphere fixed model (upper plot) and NBSM (bottom)

### *2.4. Studies on calculation of the satellite positions*

In the years 2011–2014, some practical aspects of implementing the generalized problem of two fixed centres, for computing positions and velocities of GNSS satellites were studied at AGH University of Science and Technology (AGH). The problem of two fixed centres is a special case of the restricted three – body problem. The equations of motion of the satellites in the generalized problem of two fixed centres are integrable in quadratures. The intermediate orbit of the satellite, based on solving the generalized problem of two fixed centres, fully takes into account the influence of the second $J_2$ and third $J_3$, as well as a major part of the fourth zonal harmonic of the expansion of the Earth's gravity potential. The analytical algorithms of computation of orbital elements and positions of GLONASS satellites, based on the asymmetric variant of the generalized problem of two fixed centres, have been described (Goral and Skorupa, 2012). Other main disturbing accelerations, i.e. due to the Moon and the Sun attraction, were also computed analytically. Proposed analytical method of computation position and velocity of GLONASS satellites is an interesting alternative for presently used numerical methods. The obtained results open up new prospects for practical applications of the generalized problem of two fixed centres (Goral and Skorupa, 2012). They can be used for analytical studies of the motion of not only GLONASS satellite but also GPS and Galileo satellites.

### *2.5. Studies on calculation of the satellite positions*

The Polish Head Office for Geodesy and Cartography supports and maintenances an active GNSS reference network – ASG-EUPOS (Bosy et al., 2007). ASG-EUPOS provides a variety of positioning services, including on-line automatic post-processing service – POZGEO. In order to improve ASG-EUPOS services, POZGEO in particular, ASG+ project was carried out (Figurski et al., 2011). A new automatic GNSS data post-processing module POZGEO-2 was developed as one of the tasks within the project (Paziewski et al., 2014). The module internal methodology is based on the approach used in the scientific GNSS post-processing software – GINPOS, which was developed at UWM (Paziewski, 2012). POZGEO-2 requires minimum of 5 minutes of dual-frequency carrier phase and pseudorange GNSS data (with interval of 10 seconds). RINEX data files are sent by the users through a dedicated web page. The data processing is performed using relative geometry-based model. A position is obtained in a network (multi-station) solution using GNSS data from three surrounding ASG-EUPOS permanent stations. The model parameter estimation is based on sequential LSA (Least Squares Adjustment) with constraint equations. In the adjustment, all mathematical correlations between the observations are taken into account. The LAMBDA method is applied for the ambiguity resolution. POZGEO-2 uses information about atmospheric delays from other modules, dedicated for atmosphere modelling, which were also developed within the ASG+ project. The new module is capable of processing GPS and Galileo data (L1/E1, L2 and

L5/E5a frequencies). It is expected that POZGEO-2 will offer horizontal position with accuracy of 2 cm.

### *2.6. Investigation of uncertainty of GNSS-based distance metrology*

Nowadays surveyors and researchers in geosciences are facing the challenge of measuring distances over several hundreds of metres up to 1 kilometre with uncertainties at a single millimetre level and below. Electronic distance meters and GNSS are available for this task and long length metrology complies with GNSS-based short distance measurements. Both approaches, however, are currently not capable of achieving traceability to the SI definition of the metre with one or even sub-millimetre uncertainty over the respective distances.

Therefore, researchers from the Institute of Geodesy and Cartography (IGiK, Warsaw) in cooperation with scientists from UWM, and also from the NSC Institute of Metrology (Kharkiv, Ukraine) and Institute of Radio Astronomy of NAS (Kharkiv, Ukraine) have carried out research aimed at better understanding of the uncertainty of GNSS-based distance metrology. Long time series of vector components, derived from processing GNSS data from double EPN stations, were analysed. The time series provided extremely rich information on variability of GNSS solutions that together with the external data enabled qualitative and quantitative analysis of those variations as well as their reliable statistical estimate. The experiments performed concerned the investigation of the response of the measuring system to tropospheric perturbations as well as to site specific effects vs. measured distance. Numerical experiments conducted indicate that the potentiality of GNSS positioning is not fully exploited in high-end applications. Also, analysis of time series of GNSS solutions may result in improvement of modelling of GNSS observations and GNSS-based distance metrology (Zanimonskiy et al., 2014).

## 3. Atmosphere remote sensing and modelling

### *3.1. Troposphere*

One of main objectives of WUT LAC is a routine ZTD estimation, monitoring of the results and research on Integrated Precipitable Water (IPW) time series derived both from GNSS and NWP (Numerical Weather Prediction) models. Two operational numerical prediction models: COSMO-LM (maintained by Polish Institute of Meteorology and Water Management) with two different resolutions of 14 km and 2.8 km, and a global model GFS (operated by NCEP) were used as input data to generate IPW and ZTD required for GNSS tropospheric products quality assessment. Various factors affect the final results of the determination of IPW and ZTD from the model grid, i.e. interpolation of data in space, numerical integration in zenith direction, correction for topography, physical equations applied for humidity parameters conversions, etc. Different models with different GNSS products exhibit systematic differences. For individual stations the observed bias might substantially vary (Kruczyk and Liwosz, 2012). Annual model for multi-year series of ZTD from IGS was applied to detect climate change signal in residuals. Also more complicated model consisting of annual and semiannual terms as well as linear trend was fitted using the least squares approach. The authors showed that the application of the more advanced model reduced RMS of the residuals. They provide several examples confirming that findings, but also show that no climate changes were detected.

The ZTD is a valuable input for weather forecasting and nowcasting, however full exploitation of results requires validation in challenging weather conditions. The joint team of Wroclaw University of Environmental and Life Sciences (WUELS) – Royal Melbourne Institute of Technology University, Australia (RMIT University) discussed this problem (Rohm et al., 2014a). The baseline, network or Precise Point Positioning approach using post-processed and predicted orbits and clocks were used. The results are quite optimistic: GNSS proves to be an optimal integrated water vapour data source in all weather conditions, e.g. IWV standard deviation with respect the radiosonde data below 3 mm. In the presence of severe weather the variability of troposphere estimates is observed doubled and it should be reflected in the applied constraints. Otherwise the formal errors increase also by a factor of two.

The high standard ZTD to IPW conversion procedures and quality monitoring of integrated ASG-EUPOS – meteorological ground sensors network for water vapour retrieval was studied (Hordyniec, 2014). The author utilized alternative data sources in case direct measurements at the GNSS stations were unavailable. He has proved that the pressure from standard empirical models (GPT, GPT2, UNB3m) would induce a noise in IWV at the level of 2.5 mm. In contrary, hourly data of Numerical Weather Prediction model reduce this discrepancy roughly by 0.6 mm. Still, the numerical forecast needs to be treated with care when applied for high altitude stations as additional bias can occur. A priori wet delay modelling using Saastamoinen model provides rather crude IWV estimate as 3 mm and higher uncertainties were achieved.

In order to satisfy real-time users with more precise products, IGS launched a real-time service (IGS-RTS) on 1 April 2013. Although RTS products are under daily monitoring, an additional, detailed analysis were performed at WUELS, in order to assess the quality of RTS products (Hadas and Bosy, 2015). It was shown, that the general availability of GPS correction was over 95%, and for GLONASS over 90%. From the comparison of RTS products with ESA/ESOC final products (Fig. 5), it was confirmed that the RTS orbits are of high accuracy – in general at the level of 48 mm for GPS and 132 mm for GLONASS. Real-time clocks accuracy was 84 mm (0.28 ns) and 245 mm (0.82 ns) for GPS and GLONASS, respectively, so estimation of real-time GLONASS clocks require further development to reach the target level of 0.3 ns. Further studies were related to RTS corrections quality degradation over time and to attempts short-time prediction of correction on the basis of prior data. The relation between the product latency and accuracy, with respect to GPS block and type of onboard clock or

GLONASS year of launch, was determined. On average, 5 cm of additional error is expected when using orbit corrections with 3 minutes of latency and clock correction with 1 minute latency. Using polynomial fitting, it is possible to reliably forecast the orbit corrections up to 8 minutes for GPS and 4 minutes for GLONASS. The proposed short-term prediction methodology can be used, e.g. for the outliers detection in RTS corrections.

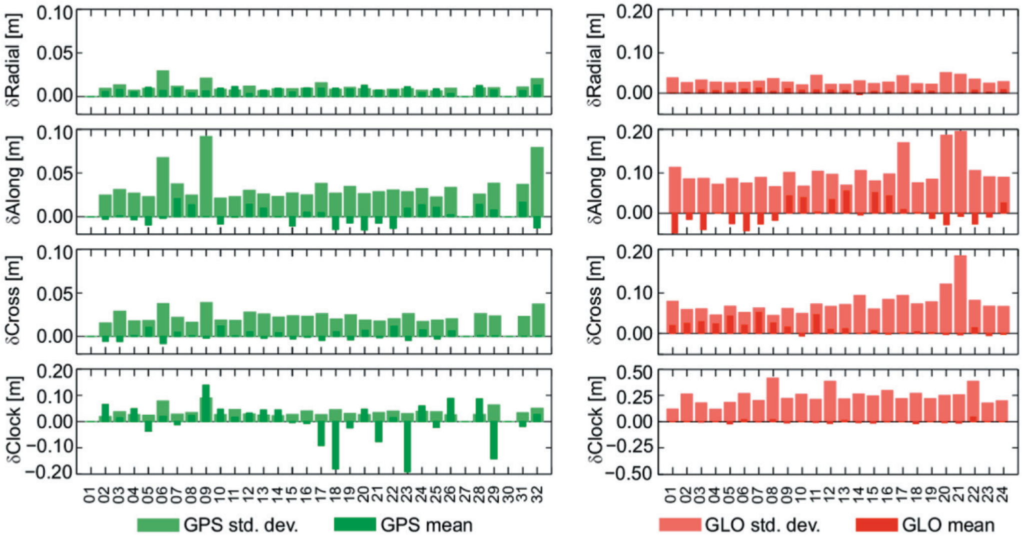

Fig. 5. RTS orbits and clocks quality with respect to ESOC final products during DOYs 208–214, 2013

These products, i.e. real-time orbits and clocks, were used to resolve one of the current challenge of GNSS meteorology that is a real-time (zero latency) ZTD/IWV retrievals. Joint WUELS – RMIT research teams developed and globally tested (Yuan et al., 2014) methodology that address this issue. The solution was based on the BNC PPP solution, however a number of modifications were implemented, i.e. antenna phase centre variation models, ocean and earth tides, advanced mapping functions and a priori information (GPT2), Kalman filter stochastic and functional model modification. These advancements tested against globally distributed IGS stations and radiosonde profiles show that the real-time retrieval of integrated water vapour is feasible with an accuracy of 3 mm.

Another research direction at WUELS was related with real-time kinematic Precise Point Positioning (PPP) and its support with regional tropospheric delay model obtained from near real-time (NRT) GBAS network analysis and/or meteorological data. A common procedure in PPP is to have the adjustment model accounting for the correction to an a priori value of the troposphere delay given at the first epoch of data processing, and the delay filter is updated epoch by epoch. This approach requires some time so that a change in constellation geometry allows to efficiently de-correlate among tropospheric delay, receiver clock error and user height.

At first, it was investigated how the regional troposphere models may support kinematic PPP in post-processing and real-time modes, by providing a priori information on zenith total delay (ZTD) (Hadas et al., 2013). It was demonstrated, that a reliable a priori troposphere information allows to reduce PPP convergence time and improves the precision and accuracy, especially for vertical component, when compared to a standard PPP procedure that uses Saastamoinen formula. In the same way, the PPP was used as a method to validate the developed troposphere models. It was noted, that the ZTD model based on meteorological data only (IGGHZ-M) requires further improvement in aspects of the interpolation in time/space procedures. The ZTD model performance was much better, however a reduction of its latency (currently over 1 hour) should provide improvements in real-time positioning.

Finally, it was demonstrated how regional, near-real time ZTD model may improve real-time kinematic PPP by constraining the ZTD estimates (Fig. 6). The difference between unconstrained solution and the constrained one is significant for the vertical component, while the horizontal coordinates remain similarly accurate. In standard approach, the height residuals may reach tens of centimetres and the error may reach up to 20 cm; at the same time the ZTD estimates were poor (large residuals with respect to reference, near-real time solution). In case the troposphere delay was constrained, the standard deviation for the vertical component was reduced by 40%, from 14 cm to 8 cm. From the very beginning of the data processing, the residuals for all three coordinates were much smaller, even though the estimated error was relatively large. The results confirmed the usefulness of near-real time troposphere delay models in real-time PPP kinematic processing and a significant improvement should be observed in unusual or severe weather conditions.

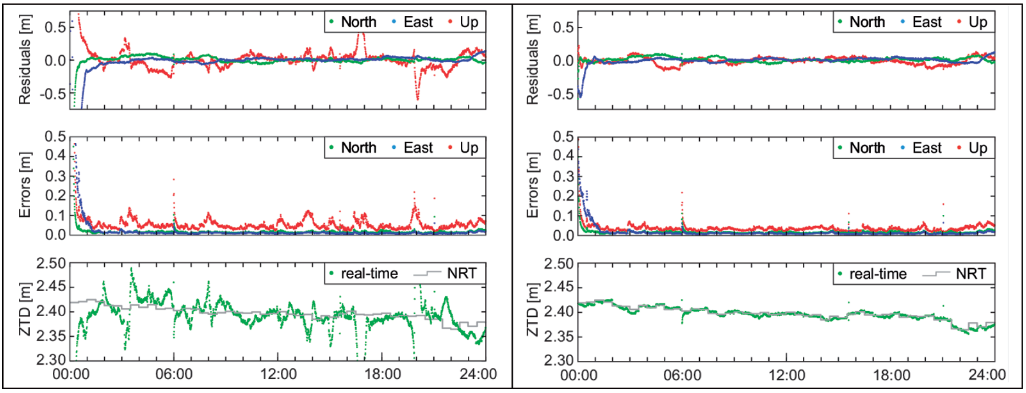

Fig. 6. Results of unconstrained (left) and NRT-ZTD constrained (right) kinematic PPP solution for station WROC, DOY 116, 2014

Continuing development of GNSS tomography methodology, GNSSandMeteo Working Group team from WUELS removed constraints and apply robust Kalman filtering to retrieve wet refractivities (Rohm et al., 2014b). The authors identify that the major problem for further advance in tomography models and their applications in atmosphere sciences are linked with the constraint equations that limit variability of the troposphere. Therefore the implicit constraints were removed from the tomography equation system and Kalman filter was applied to tie the troposphere conditions between observations epochs and to resolve the equation system iteratively with procedure removing outliers in place.

Applying tomography models to resolve vertical and horizontal structure of Mesoscale Convection System was one of the first attempts world-wide to observe internal processes of severe weather using GNSS signal (Manning et al., 2014), collaboration between RMIT University and WUELS resulted in resolving one storm event (6 March, Victoria, Australia) using tomography approach (Fig. 7). The solution was validated against the weather radar data, showing strong correlation of intensive rain with rapid drop of wet refractivity and increase of the wet flux at the front of the storm. These results were found to be in agreement with the conceptual model of Mesoscale Convection System.

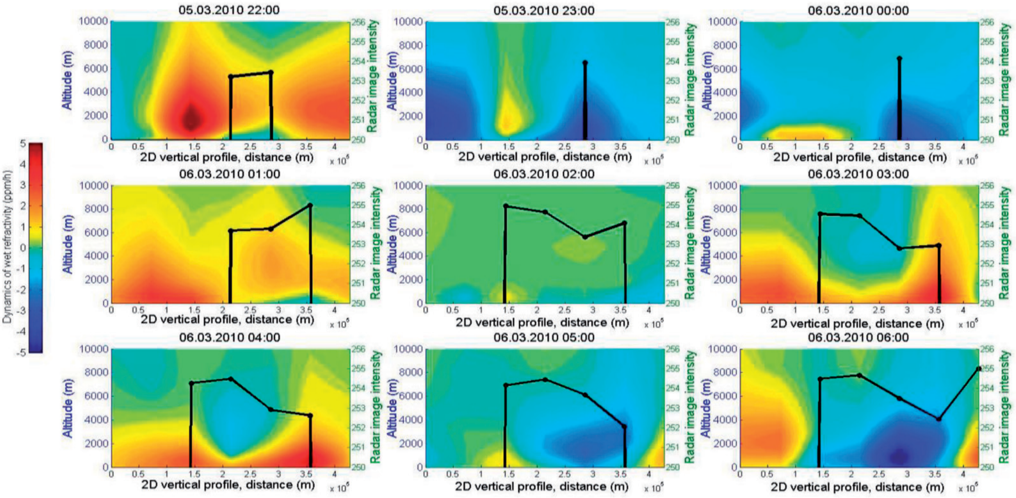

Fig. 7. Cross section of tomography model along the storm propagation line (from 0 to 10 000 m), colour-coded are wet refractivity variations in time, whereas the black line shows the radar rain intensity and location of storm

The same team together with the experts in Radio Occultation from RMIT University and Australian Bureau of Meteorology have investigated the quality of RO profiles in Australia region comparing it with the gold-standard for atmosphere profiling – radiosonde measurements (Norman et al., 2014). The mid and top troposphere retrievals were resolved exceptionally well in the RO profiles, but unexpected bias in temperature near the stratosphere was detected.

Another field of study included the application of the new troposphere models for supporting of precise GNSS positioning. Researchers from WUELS and UWM collaborate on this topic. They carried out analyses of two near real-time tropospheric delay estimation models, IGGHZG (Institute of Geodesy and Geoinformatics one Hour ZTD GNSS) and IGGHZM (Institute of Geodesy and Geoinformatics one Hour ZTD Meteo), in fast-static precise positioning (Wielgosz et al., 2013). The former model is based on the processing of GPS data collected from ground-based reference stations, the latter one uses metrological data fed into the Saastamoinen model. The applicability of these models to precise positioning was studied by their application to ultra-fast static positioning. Baselines from 65 km to 72 km, with height differences from 39 m to 379 m were processed. The authors concluded that ZTDs derived in near real-time based on GPS data from the reference network gave much better results. This was confirmed by the ultra-fast static positioning tests. In addition, the IGGHZM model based on meteo data gave significantly worse results regarding both coordinate repeatability of the height component and the ambiguity resolution, and could not be recommended for precise positioning. However, the WUELS research group is currently conducting extensive work on the development of both IGGHZG and IGGHZM models (Hadas et al 2013), and it may be expected that these models will bring improved results in the future.

### *3.2. Ionosphere studies*

The reporting period covered the last phase of the solar minimum. Researchers at UWM analysed the ionosphere behaviour during moderate geomagnetic storm which occurred on 11 October 2008. The electron density profiles retrieved from the COSMIC radio occultation measurements were examined in order to estimate the possibility of its use as additional data source to study changes in electron density distribution occurred during ionospheric storms. The short-term positive effect was clearly revealed in GPS TEC and ionosonde measurements that was also confirmed by RO profiles (Zakharenkova et al., 2012).

A new regional ionosphere monitoring service over the ASG-EUPOS network was launched at UWM (http://ginpos.uwm.edu.pl/iono/index_en.php). For the ionospheric modelling, dual-frequency GPS data from the Polish national ground based augmentation system ASG-EUPOS are used. This permanent GNSS network operating since 2008, opened new possibilities for accurate regional modelling of Earth’s upper atmosphere. The network consisting of ~110 stations with mean distance between stations of 70 km is a part of the European Position Determination System (EUPOS) project involving 18 countries of Central and Eastern Europe. At the beginning of its operation, the service used carrier phase-smoothed pseudoranges as its input observables (Krypiak-Gregorczyk et al., 2013). Since 2014, however, the regional ionospheric model is computed using only precise, absolute (undifferenced) carrier phase GNSS measurements, a few orders of magnitude more precise comparing to pseudorange measurements. Also, new total electron content (TEC) parameterization algorithms based on geometry-free linear combination of the carrier phase data and two-dimensional functions (local polynomials), was implemented. The main product of the service is precise local ionospheric model over ASG-EUPOS network. The model has spatial resolution of 0.25° × 0.25° and temporal resolution of 5 minutes. In addition, the new ionosphere monitoring service provides mean hourly TEC values over Poland. Another important products of the service are the differential code biases (DCBs). The service provides daily and monthly DCB calibrations for every GNSS receiver of the ASG-EUPOS system (Krypiak-Gregorczyk et al., 2014).

Another ionosphere monitoring system developed at UWM is also based on processing GPS observations and concerns the ionospheric irregularities at the Northern high latitudes (Cherniak et al., 2014). Monitoring of these irregularities is important for both scientific point of view and GNSS applications, as the occurrence of the ionospheric irregularities can impact a variety of communication and navigation systems. Cherniak et al. (2014) described the methodology and the service for continuous generation of high-resolution maps of the ionospheric irregularities at high latitudes. They use data collected from three ground-based GPS networks of the Northern Hemisphere. The service is based on ROT (rate of TEC change) and ROTI (index of ROT) parameters employed to study the occurrence of TEC fluctuations. ROTI maps are provided as a horizontal grid with 2° × 2° resolution in the magnetic local time and corrected magnetic latitude frame. The ROTI maps allow estimation of the overall fluctuation activity and auroral oval evolutions. In general, the ROTI values are correlated with the probability of GPS signals phase fluctuations. It was demonstrated that the occurrence and magnitude of TEC fluctuations increased dramatically during space weather events.

## 4. Summary

This report provides selected examples of research activities on GNSS data processing applications carried out at Polish research institutions during years 2011–2015. The research concerns multi-GNSS relative and absolute positioning. In particular, improvements in the stochastic models and carrier phase ambiguity resolution were demonstrated. The application of new real-time IGS products, ionosphere and troposphere modelling and orbit estimation also brought new advances in precise GNSS applications. The obtained results were published in high-quality scientific journals, and the studied problems are currently further investigated as they concern still open research issues in the field of geodesy.

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