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*Review paper*

# Research on GNSS positioning and applications in Poland in 2015–2018

**Paweł Wielgosz[1]*, Tomasz Hadaś[2], Anna Kłos[3], Jacek Paziewski[4]**

[1,4]University of Warmia and Mazury in Olsztyn
2 Michała Oczapowskiego, 10-719 Olsztyn, Poland
[1]e-mail: pawel.wielgosz@uwm.edu.pl, ORCID: http://orcid.org/0000-0002-5542-1481
[4]e-mail: jacek.paziewski@uwm.edu.pl, ORCID: http://orcid.org/0000-0002-6033-2547

[2]Wroclaw University of Environmental and Life Sciences
Institute of Geodesy and Geoinformatics
53 Grunwaldzka, 50-357 Wroclaw, Poland
[2]e-mail: tomasz.hadas@igig.up.wroc.pl, ORCID: http://orcid.org/0000-0002-4409-5078

[3]Military University of Technology
Faculty of Civil Engineering and Geodesy
2 Witolda Urbanowicza, 00-908 Warsaw, Poland
[3]e-mail: anna.klos@wat.edu.pl, ORCID: http://orcid.org/0000-0001-6742-8077

*Corresponding author: Paweł Wielgosz

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**Abstract:** This review paper presents research results on geodetic positioning and applications carried out in Poland, and related to the activities of the International Association of Geodesy (IAG) Commission 4 "Positioning and Applications" and its working groups. It also constitutes the chapter 4 of the national report of Poland for the International Union of Geodesy and Geodynamics (IUGG) covering the period of 2015-2018. The paper presents selected research, reviewed and summarized here, that were carried out at leading Polish research institutions, and is concerned with the precise multi-GNSS (Global Navigation Satellite Systems) satellite positioning and also GNSS-based ionosphere and troposphere modelling and studies. The research, primarily carried out within working groups of the IAG Commission 4, resulted in important advancements that were published in leading scientific journals. During the review period, Polish research groups carried out studies on multi-GNSS functional positioning models for both relative and absolute solutions, stochastic positioning models, new carrier phase integer ambiguity resolution methods, inter system bias calibration, high-rate GNSS applications, monitoring terrestrial reference frames with GNSS, assessment of the real-time precise satellite orbits and clocks, advances in troposphere and ionosphere GNSS remote sensing methods and models, and also their applications to weather, space weather and climate studies.

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

## 1. Introduction

Research on positioning and applications covers important activities of the International Association of Geodesy (IAG). In order to coordinate this research, IAG has established its Commission 4 on "Positioning and Applications". Since IAG recognizes the central role of Global Navigation Satellite Systems (GNSS) in providing high accuracy positioning information today and into the future, Commission 4 focuses on research for improving models and methods that enhance and assure the positioning performance of GNSS-based positioning solutions for a range of geodetic applications (Drewes et al., 2016). The research starts from different aspects of positioning and continues into remote GNSS atmosphere sounding. These topics are primarily investigated by IAG Sub-Commissions: 4.1 "Emerging Positioning Technologies and GNSS Augmentation", 4.3 "Atmosphere Remote Sensing" and 4.4 "Multi-constellation GNSS". It is worth to notice that many Polish researchers very often take part in activities of Commission 4 working and study groups, frequently taking leading roles. Therefore studies related to GNSS positioning and atmosphere remote sensing are very popular in Poland. And this in turn results in large number of published research results. Nevertheless, in this review, the authors tried to select the most interesting ones. Additional selection criteria were: the rank of the journal and participation of the authors in IAG working and study groups.

## 2. Advances in relative positioning

The content of this section summarizes selected recent contributions devoted to precise positioning algorithm development and applications conducted at the University of Warmia and Mazury in Olsztyn, Warsaw University of Technology and Gdansk University of Technology. In this field, the papers concern selected issues, such as integration of multi-constellation signals, inter-system biases handling, mitigation of ionospheric delays and disturbances, ambiguity resolution and validation methods, stochastic modeling, studies on Network Real-Time Kinematic (Network RTK) reliability as well as monitoring the terrestrial reference frames with relative GPS (Global Positioning System) and GNSS positioning.

### *2.1. Study on multi-GNSS observables integration and inter system bias problem in relative positioning*

Initial contributions concerning multi-constellation relative positioning revealed important influence of the differences between receiver hardware delays caused by acquisition of multi GNSS signals. Thus, this phenomenon was investigated in detail. Theoretical background of the receiver differential Inter System Bias (ISB) estimation and handling was given in (Paziewski and Wielgosz, 2015). In this paper, the tightly combined multi-constellation model and method of estimation of receiver ISB were presented. Taking advantage of developed methodology, the short and long term stability of ISBs, as well as magnitude of between GPS – Galileo-IOV inter system biases was characterized on the basis of data derived from several pairs of multi-GNSS receivers. The results justified the thesis on the receiver ISB stability. In specific the stability of ISBs proved that it is feasible to calibrate phase and code ISBs for a particular pair of receivers using zero or short baseline and introduce them as corrections to GPS+Galileo tightly combined positioning (Paziewski and Wielgosz 2015). Hence, in practice we can use one receiver as reference one and determine the relative values of receiver ISBs using subsequent receivers. Such approach combined with the application of previously calibrated ISBs strengthens the observational model, which is beneficial for reliability of ambiguity resolution, and in consequence, performance of positioning.

Detailed studies on the receiver ISBs have also revealed the existence of the quasi-periodic effect in the time series of phase ISB estimates (Paziewski and Wielgosz, 2015). Thus, the frequency, amplitude, as well as the potential source of the phenomenon was investigated in the following publication (Paziewski et al., 2015). The detailed studies exposed that the oscillations were caused by PRN E11 and E12 Galileo-IOV satellite observations. The time-frequency analysis indicated that these small scale oscillations with similar amplitude and frequency present in phase ISB time series are caused by raw phase observations of E11 and E12 satellites. Borio et al. (2016) indicated the problems with initial algorithm applied for the integration of the frequency references provided by the couple of clocks simultaneously operated in Galileo PRN11 and PRN12 satellites as a potential source of the phenomena.

The continuation of studies in the field of multi-GNSS precise positioning was the development of the strategies for multi-GNSS signals integration in medium range relative positioning with ionosphere and troposphere weighted parameters. The analyses were supported by practical performance assessment based on GPS, Galileo and BeiDou Satellite System (BDS) signals (Paziewski and Wielgosz, 2017; Paziewski and Sieradzki, 2017). It was clearly demonstrated that both GPS+Galileo tightly combined with previously calibrated ISBs and loosely combined strategies are superior to single system solution. This was especially clear in the ambiguity resolution domain. Benefits from multi-GNSS signal processing were also noticeable in the coordinate domain, specifically considering the precision of float solution. Both loosely and tightly combining strategies provided comparable results in the ambiguity resolution and coordinate domains, assuming that the latter approach is supported by the previously calibrated receiver ISBs. The developed functional models were applied to instantaneous multi-baseline positioning with real BDS signals. The study of Paziewski and Sieradzki (2017) is concerned with the analysis of BDS and GPS signal noise, the definition of the functional and stochastic models of multi-GNSS medium range RTK positioning and empirical positioning performance assessment. The stations used in this experiment were located at the territory of China, which ensured as much as high number of available BDS satellites. It was justified that combined GPS+BDS positioning is superior to the solution based on single GNSS system with regard to ambiguity fixing. This holds especially true in an obstructed observing environment. However, in the case of high number of tracked satellites, there were no important differences in the performance of GPS and integrated GPS+BDS positioning in terms of the ambiguity resolution domain. They have, however, experienced deterioration of the ambiguity resolution success rate and coordinate accuracy for BDS-only positioning with respect to GPS-only based. This was caused by relatively small number of available BDS satellites signals in comparison to GPS.

Another study related to the field of multi-GNSS data processing is concerned with potential contribution of the couple of Galileo FOC satellites injected to highly eccentric and thus incorrect orbits to high precision surveying and geodetic applications (Paziewski et al., 2018). The analyses were carried out in the field of stochastic properties of GNSS observations including the carrier-to-noise density ratio and signals noise. The study exposed that the signal power of PRN E14 and E18 satellites was higher with respect to other Galileo satellites, what was caused by the satellites' lower altitude over the test area. However, the differences in the noise of the signal of all Galileo satellites were negligible. The subsequent analyses were devoted to selected indicators of instantaneous high precision medium range positioning performance: ambiguity resolution success rate and coordinate accuracy as well as a level of post-fit observation residuals. Experiment revealed that E14 and E18 satellites did not influence in a high extent on the performance of integer ambiguity resolution and coordinate accuracy. Hence one can conclude that the Galileo satellites with highly eccentric orbits are fully applicable to high precision geodetic applications and many others. This claim holds true providing precise ephemeris of satellites in a post processed mode.

### *2.2. Advances in functional models taking advantage of observation and parameter constraining*

Another way of improving the performance and reliability of precise GNSS positioning apart from application of multi constellation signals is the development of the mathematical models which take into account the relations between observables and parameters of the model as additional constraints. An original approach presented in (Paziewski, 2015) takes the advantage of the closely located antenna relations to improve the real-valued ambiguity solution, and consequently, the integer ambiguity resolution performance. In the novel approach, not only the ambiguity relationships, but also similar ionospheric and tropospheric conditions at multiple receiver configuration stations are used to improve the atmospheric delay modelling. The solution strengthens the observational model, and thus enhances the reliability and effectivity of the ambiguity resolution process. In (Paziewski, 2015) it was clearly demonstrated that an enhancement in the ambiguity resolution domain can be achieved taking the advantage of multi-rover receiver processing with novel algorithms. A clear improvement up to ~5% was observed in the ambiguity success rate against the standard single baseline positioning in all verified cases using baselines up to 70 km.

### *2.3. Study on ionosphere delay handling in relative positioning*

The ionospheric refraction is still considered as one of the dominating source of errors in the GNSS positioning. On the other hand, the ionosphere is the dispersive medium for frequencies employed in GNSS systems; hence this property can be used for monitoring its state.

Therefore, the properties of the network ionospheric corrections supporting RTK positioning as well as their impact on time to fix in RTK positioning were examined in (Paziewski, 2016). In this specific issue, an attempt was also made to derive the threshold accuracy of the ionospheric corrections, which allow reliable integer ambiguity resolution with the use of observations of single-epoch and baselines up to ~100 km. This characteristics of the ionospheric corrections accuracy may be beneficial for the definition of the stochastic model of the ionospheric corrections in the ionosphere-weighted positioning model. The empirical studies were based on analysis of the double differenced ionospheric delay corrections taking the advantage of networks established in the frame of the Polish active reference network ASG-EUPOS (Active Geodetic Network – European Position Determination System) and different ionospheric activity. From the results one can learn that to obtain reliable and precise RTK solution based on single-epoch observations we should provide ionospheric corrections with the error less than 1/3 of carrier-phase length (Paziewski, 2016).

The elimination, or reduction, of ionospheric disturbances' impact is still one of unsolved issues in precise GNSS positioning (Sieradzki and Paziewski, 2018). This is particularly crucial in a rapid mode performed with raw dual-frequency phase and code measurements and thus, the improvement in this field was also the goal of investigations conducted at the University of Warmia and Mazury in Olsztyn. In order to eliminate the influence of disturbances, manifesting in GNSS data as dynamic variations of Total Electron Content (TEC), an original algorithm was proposed. It utilizes rate of TEC (ROT) corrections derived from geometry-free combination to modify raw phase and code observables. These corrections are applied at the data preprocessing step. As the result, the ionospheric delay for each observational arc becomes constant and may be parametrized as a single unknown parameter. Thus, the evaluation of the algorithm involving the relative GPS positioning performed with an ionosphere-weighted model, can be also applied to multi-GNSS positioning including also functional models. The conducted tests reported its efficiency during disturbed periods for different ionospheric regions. The extreme case study for high latitudes (Sieradzki and Paziewski, 2016; Paziewski and Sieradzki, 2018) revealed almost 10 times increase of the ambiguity resolution success rate (ASR), and ASR increased up to 59%. The investigations for mid-latitudes, which are affected by the occurrence of medium traveling disturbances (MSTID), demonstrated the growth of ASR up to 90% (Sieradzki and Paziewski, 2015). According to these works the application of the algorithm does not distort the results for quiet ionospheric conditions. Furthermore, it implicated the continuous increase of ASR depending on session length. Another issue investigated at UWM (as a part of working group 4.3.4 "Ionosphere and Troposphere Impact on GNSS Positioning" of the International Association of Geodesy) and related to the ionosphere was the impact of high-order ionospheric terms. In the work of Banville et al. (2017) the authors proposed a modified approach of precise point positioning (PPP) including the estimation of the first- and second-order ionospheric terms in the positioning filter. Its implementation confirmed that proper modelling of higher-order ionospheric terms leads to the improvement of results. On the other hand, as shown in theoretical background and the results presented in the above-mentioned paper, neglecting of different code biases (DCB) causes the biases at the level of a few millimeters.

### *2.4. Advances in integer ambiguity resolution methods*

In the last decade, the new approach of precise positioning has been developed. This approach has been named Modified Ambiguity Function Approach (MAFA). First time the Ambiguity Function Method (AFM) was proposed in 1981 by Counselman and Gourevitch. However, this approach in its classical form was considered as less efficient and with poorer theoretical foundations than the prevalent recent approach based on three stages: float solution, ambiguity resolution and fixed solution (e.g. the Lambda method). However, the MAFA method provides meaningful improvements on the classical form of AFM. There were also observed some advantages of this approach over the methods based on searching for solution in the ambiguity domain. Unlike the Lambda method where the search procedure is conducted in ambiguity domain, the MAFA method is conducted in the coordinate domain. The main advantage of searching for a fixed solution in coordinate domain is the constant dimension of a search space. Thus, unlike the Lambda method, the computational complexity is independent from the number of satellites. The crucial problem in search procedure conducted in the coordinate domain is setting correct search region and grid of candidates inside it. It was proposed in (Cellmer et al., 2018) to assume the error ellipsoid of the approximate position as the search region. In the same article, the length of the search step (density of the grid of candidates) was set empirically based on simulated data for different configurations of satellites. In Cellmer et al. (2017), the analytical derivation of the length of the search step is considered for the extreme unfavourable shape and arrangement of the Voronoi cells of points respecting the integer ambiguities in relation to the orientation of the grid of candidates inside the search region.

The detailed discussion on the MAFA method as a non-conventional mixed integer-real least squares (MIRLS) estimation was presented in (Nowel et al., 2018), whereas some other issues related to the MAFA method were presented on the international conferences held in 2016 and 2017 (Kwaśniak et al., 2016; Kwaśniak et al., 2017ab; Nowel et al., 2017).

### *2.5. Stochastic modeling of GNSS observations*

Research on stochastic modelling of GNSS observations was carried out at the Warsaw University of Technology (WUT). These studies dealt with the improvement of the stochastic model for instantaneous Network Real-Time Kinematic (RTK) positioning, called the Network-Based Stochastic Model (NBSM) (Prochniewicz et al., 2016). The NBSM is a kind of weighted model which used network-based variance estimations to capture the characteristics of ionospheric and geometric residual errors. What is essential for this model compared to other solutions of this type is the possibility of describing residual errors on the basis of single-epoch observations. This model also does not require observations from an additional monitoring station. These features predispose NBSM instantaneous positioning applications which utilized single epoch measurements. Figure 1 presents the Network RTK positioning scheme with three groups of algorithms: network solution, network correction and positioning model. The extension of these algorithms with additional data flow included by the NBSM has been marked in red.

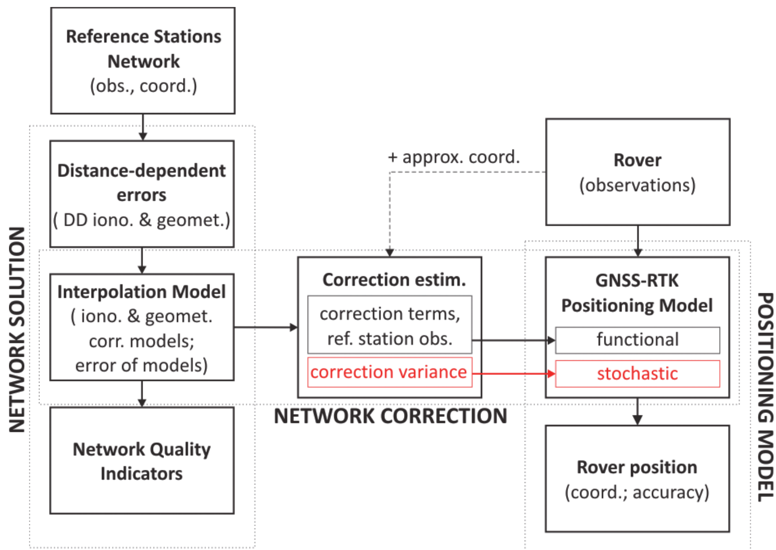


Fig. 1. Network RTK positioning model based on NBSM

Comparative tests of the proposed weighted NBSM model with the ionosphere-fixed troposphere-fixed model were carried out for singe-epoch performance. The results lead to the conclusion that the ambiguity integer estimation and its validation can be achieved with a significantly higher success rate compared to the use of the standard fixed model. Application of the NBSM can also reduce positioning errors by 15-30% (Prochniewicz et al., 2016).

### *2.6. Reliability of GNSS Network RTK positioning*

These studies were focused on developing of a new method for describing the positioning reliability for Network RTK technique. The method based on the so-called network solution quality indicators (QI) which depict the impact of dispersive and non-dispersive errors on rover positioning accuracy and reliability. The impact of these errors in Network RTK positioning is significantly mitigated by the use of ionospheric and geometric network corrections, thus QI mostly reflects the correction estimation accuracy. However, from the practical point of view, the existing QIs do not give the indications when the reliability of rover's position can be challenging to achieve. This is due to the undefined accurate critical values for these parameters.

In the paper (Prochniewicz et al., 2017), the new methods of deriving the QI, the so-called solution accuracy and solution availability, were proposed. The solution accuracy describes the accuracy of rover's position, and it is calculated as an estimated fixed baseline solution error for each epoch (for confidence level of $1\sigma$) with the assumption of correct ambiguity resolution. The solution availability describes the reliability of carrier-phase ambiguity resolution, and it is derived as an hourly ASR indicator with the confidence level of 95%. Both of them depend only on the variance-covariance observation matrix and the design matrices which do not require any actual measurements. However, the proper handling of the residual ionospheric and geometric errors in the stochastic model is crucial to their precise estimation. And this can be achieved by applying the NBSM methods (Prochniewicz et al., 2016).

A part of the regional ASG-EUPOS reference station network was used to test the proposed new QI for single-epoch Network RTK performance. The analysis of the variability of solution availability clearly indicated the periods when the correct ambiguity resolution was difficult to achieve, e.g. when only 5 satellites were observed (ASR was below 50%). The tests showed that for GPS-based instantaneous Network RTK positioning the alarm value of ASR set at 90% allows identifying the period with low reliability of ambiguity resolution. Also the solution accuracy index effectively identified the periods for which the position accuracy was reduced.

Compared to the existing indicators, e.g. I95, RIM, RIU, the proposed availability and accuracy, QIs are much more effective, and their indications are much easier to interpret. They are based not only on residual errors, like other indexes, but take into account the satellite geometry, applied method of the ambiguity resolution and the measurement noise of observations. Therefore, these features make them a useful tool for the reliability monitoring of Network RTK solution.

### *2.7. Monitoring the terrestrial reference frames with relative GNSS positioning*

Since 2017, at the Faculty of Civil and Environmental Engineering of Gdansk University of Technology (GUT) a new scientific group focusing on satellite geodesy, was formed. A brief review of the currently proceed studies is presented below.

One of the major tasks is monitoring the terrestrial reference frame using GNSS. This in particular concerns the International Terrestrial Reference Frame (ITRF) and the International GNSS Service (IGS) frame. In Figurski and Nykiel (2017), results related to the influence of ITRF2014/IGS14 frame on positioning of reference stations were presented. They found high consistency between ITRF2014/IGb14 and ITRF2008 solutions. Despite the great consistency of the ITRF solution itself, the introduction of the

IGS14 antenna phase center calibrations, both for ground and satellite antennas, cause insignificant differences of stations' coordinates. The updated calibrations cause change in the network scale, which was estimated about 0.7 ppb. In turn, using new IGS14 antenna models leads to changes of the vertical coordinates of the stations, which reach up to several millimetres. This is caused mainly by the introduction of new and updated absolute calibrations. These coordinate changes have impact on the realization of the European Terrestrial Reference Frame (ETRF). In order to show how much the ITRF2014/IGS14 and improved antenna calibrations affect the stability of the EUREF Permanent GNSS Network (EPN) stations, they present coordinate time series for POTS00DEU (Potsdam, Germany), where type mean calibration (in IGS08.atx) was changed to the individual (in IGS14.atx). For this station the authors estimated two solutions: (i) in IGb08 frame with IGS08.atx from the GPS weeks 1928 through 1937 (Figure 2, black line), and (ii) in IGS14 frame with IGS14.atx from the GPS weeks 1928 through 1933 (Figure 2, green line). They obtained significant shifts for North and Up components which amounted about 5 mm. They concluded that only new reprocessing of archived observations can remove the discontinuities caused by the new calibrations.

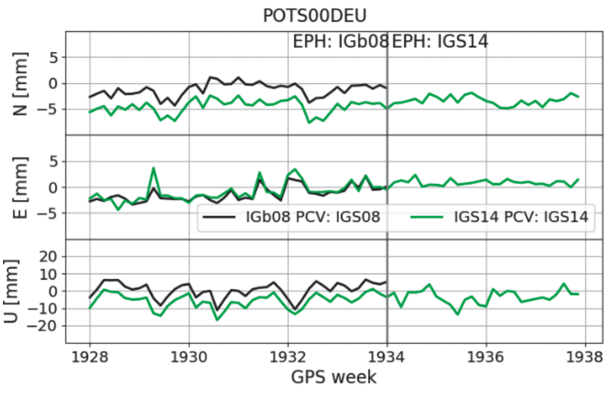


Fig. 2. Topocentric coordinates (top: North, middle: East, bottom: Up) of station POTS00DEU (Potsdam, Germany) estimated w.r.t. IGb08 cumulative solution from EPN. Results obtained in IGb08 frame with IGS08.atx are marked by black line, while the green line denotes results in IGS14 frame with IGS14.atx

During the research carried out at GUT, the researchers also focus on the impact of the Galileo observations on the multi-GNSS positioning. In the paper of Nykiel and Figurski (2017), positioning results with different combinations of the GNSS systems were presented. The authors tested the following solutions: GPS-only, Galileo-only, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. They stated that Galileo-only positioning were characterized by the highest standard deviation compared to the other solutions. This was caused by the low number of the Galileo satellites during the analyzed period of the time. However, despite the incomplete constellation of Galileo system, the Galileo-only positioning was performed with the precision below 1 cm for both horizontal and vertical components (Figure 3). In Figure 3 it can be seen that

Galileo observations have noticeable impact on the multi-GNSS results. The highest horizontal precision was obtained for GPS/Galileo solution and amounted to 1.95 mm for North and 1.96 mm for East coordinates. The obtained results were even better than GPS/GLONASS. However, for this solution the better precision was characterized for the Up component (5.35 mm). This was due to the fact that in the analyzed period there were more GLONASS satellites than Galileo, resulting in better geometry of the GLONAS system. Despite this, GPS/Galileo observations allowed to achieve lowest bias for all topocentric coordinates.

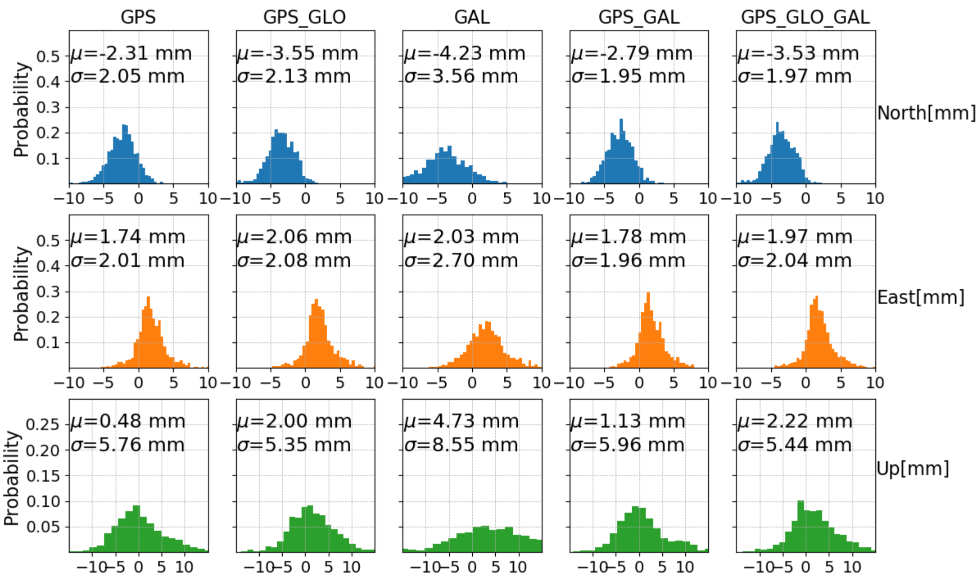


Fig. 3. Residuals for analyzed solutions (from left to right: GPS-only, GPS/GLONASS, Galileo-only, GPS/Galileo, GPS/GLONASS/Galileo) after the GPS week 1920. From the top: North, East and Up components

In Nykiel and Figurski (2017), the authors also analyzed the ambiguities resolution for wide-lane (WL) and narrow-lane (NL) linear combinations (Figure 4). After the EOC (1920 GPS week) and the few weeks earlier, the average percentages of Galileo ambiguities resolution were $80.85 \pm 4.31\%$ for WL and $70.97 \pm 5.68\%$ for NL linear combinations. For the multi-GNSS solutions, the higher ambiguity resolutions were obtained when GPS and Galileo observations were processed jointly (GPS WL: $79.15 \pm 3.45\%$, GAL WL: $93.14 \pm 2.45\%$). Based on the presented results, the authors concluded that GPS/Galileo solution allows for obtaining the best results in the case of ambiguity resolution and the position determination as well. The results are better even when all GNSS systems were used (GPS/GLONASS/Galileo).

In the paper Nykiel and Figurski (2017), the differences of antenna phase center corrections (PCC) between individual calibrations for Galileo E5 and for GPS L2 frequencies were also presented. The authors achieved differences between $-6$ mm and 8 mm, which show that copying calibration from L2 to E5 causes significant errors. They also

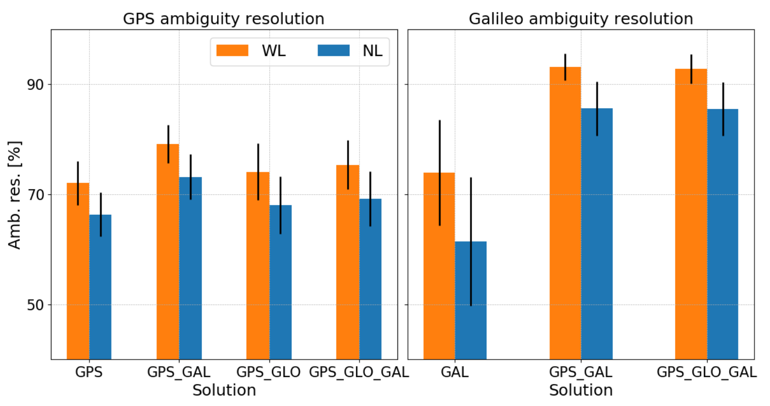


Fig. 4. Average percentage of the ambiguity resolutions (GPS (left) and Galileo (right)) for the analyzed solutions. WL and NL linear combination are marked by orange and blue, respectively

presented Galileo-only positioning results with antenna calibration for E5 frequency. Its usage caused Up shifts for all tested stations during comparison to the solutions where calibrations were copied from GPS L2. The authors conclude that this was caused by the propagation of the network errors, because for some stations (for which there was no calibration for Galileo E5 signal) the GPS L2 calibration was used. It seems that, in differential positioning, usage of antenna calibrations for Galileo signals makes sense only if all stations in the processed network support it.

## 3. Advances in Precise Point Positioning

This section presents summary of studies contributing to the subject of Precise Point Positioning which were conducted at the Wroclaw University of Life and Environmental Science, the University of Warmia and Mazury in Olsztyn and the Koszalin University of Technology. Moreover, algorithm development related to indoor and integrated positioning and navigation is presented.

### *3.1. Assessment of the real time precise orbits and clocks and optimal weighting scheme development supporting PPP*

PPP technique relies on external products, namely satellite orbits and clock corrections, the quality of which directly affects its quality. Since April 2013, IGS is running the real-time service (RTS) that allows for realtime PPP. A very first complex assessment of the IGS RTS products was presented in (Hadas and Bosy, 2015). Moreover, the algorithm of RTS product application was described in detail, focusing on issues important for final users, i.e. compatibility with broadcast ephemeris, reference frame and reference point. Analyses of availability, latency and accuracy of realtime orbits and clocks were performed over a week period for two streams, namely IGS01 and IGS03, which are GPS-only and GPS+GLONASS streams respectively, by comparison with ESA/ESOC final products. It was found that the availability of realtime corrections is over 92% for both GNSS streams, however, for GLONASS satellites during the eclipse the availability is reduced to 40%. The latency of the products, which reflects the time required for data processing and combining at the Analysis Centers and for data transfer to the end user, was found to be 28 s and 31 s for IGS01 and IGS03 streams, respectively. From the comparison of RTS products with ESA/ESOC final products (Table 1), it was confirmed that the RTS orbits are of high accuracy – in general, it is 48 mm for GPS and 132 mm for GLONASS. The accuracy of real-time clocks is 84 mm (0.28 ns) and 245 mm (0.82 ns) for GPS and GLONASS, respectively. Therefore the estimation of real-time GLONASS clocks requires further development to reach the target level of 0.3 ns.

Table 1. Root-mean-square errors (RMSE) for GPS and GLONASS products with respect to final ESA/ESOC products [m]

| | GPS (IGS01 stream) | GLONASS (IGS03 stream) |
|---|---|---|
| Radial | 0.015 | 0.031 |
| Along | 0.039 | 0.106 |
| Cross | 0.025 | 0.079 |
| 3D Orbit | 0.048 | 0.134 |
| Clock | 0.084 | 0.245 |

The research was further continued in (Kaźmierski et al., 2018b), which presents a complex analysis of the quality of GPS, GLONASS, Galileo and BDS, real-time orbits and clocks, that are provided by the CNES (Centre National d'Études Spatiales) – one of the IGS analysis centres. Multi-GNSS products were investigated by means of their availability over time, the accuracy of orbits and clocks, consistency of orbital arcs, residuals with respect to satellite laser ranging (SLR) observations and clock stability analysis with modified Allan deviation. Analyses confirmed the high availability of real-time products (over 90% for all systems). Compared to final CODE MGEX (Multi-GNSS experiment) products (Fig. 5), the accuracy of real-time orbit and clocks is 0.03 m for GPS and 0.08 m for GLONASS. For Galileo, the accuracy of orbits is 0.12 m and accuracy of clocks is 0.09 m. For BDS it is 0.20 m and 0.10 m, respectively, however, for geostationary BeiDou satellites, the accuracy of products is not assessed, due to the missing information in final products. However, analyses of the SLR residuals indicated the poor quality of geostationary satellite orbits. Finally, the real-time positioning results with PPP were presented in several variants of GNSS combination, which revealed limited improvements of multi-GNSS PPP with respect to GPS-only solution, neither in static nor kinematic case.

Unsatisfactory results of real-time multi-GNSS PPP stimulated research towards the improvement of the inter-system weighting (Kaźmierski et al., 2018a). Using information on pseudorange and carrier-phase noises (Cai and Gao, 2013) and multi-GNSS

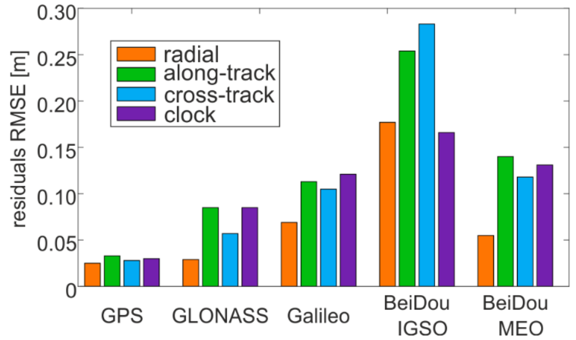


Fig. 5. Root-mean-square errors (RMSE) of real-time orbits and clocks compared to the CODE MGEX solutions

real-time products quality assessment results to calculate Signal in Space Range Error (SISRE, Montenbruck et al., 2015), five weighting schemes for real-time multi-GNSS PPP processing were proposed. The PPP results were compared against GPS-only solution by means of a posteriori error of estimated coordinates, coordinate repeatability and time required for static solution to converge below 1 cm precision level (Table 2). It was found that equal weighting in multi-GNSS solution leads to degradation of coordinate repeatability by up to 50%, even when their formal error is reduced. Among the proposed weighting schemes, the one based on SISRE coefficients occurs to be superior. In this scheme, smaller weights are imposed on both pseudoranges and carrier phases for GLONASS, Galileo and BeiDou compared to GPS. As a result, a coordinate repeata-

Table 2. Coordinate formal errors, coordinate repeatability and 1 cm level convergence time for selected inter-system weighting variants

| | GPS-only | Equal weights for all GNSS | Superior inter-system weighting scheme |
|---|---|---|---|
| Mean formal errors of coordinates [mm] | | | |
| North | 0.9 | 0.7 | 0.6 |
| East | 2.0 | 1.5 | 1.2 |
| Up | 3.8 | 3.0 | 2.3 |
| Mean coordinate repeatability [mm] | | | |
| North | 4.2 | 6.5 | 3.9 |
| East | 8.4 | 14.0 | 8.0 |
| Up | 11.0 | 16.1 | 10.1 |
| Mean convergence time to reach 0.01 m accuracy level [hours] | | | |
| North/East | 3:34 | 2:31 | 2:11 |
| Up | 5:43 | 3:34 | 3:01 |

bility from daily solutions was improved by 6% on the average, the formal error was reduced by 39% on the average, and the convergence time was reduced on the average by 39% and 47% for horizontal and vertical components, respectively.

### *3.2. Troposphere delay modelling for Precise Point Positioning*

An alternative approach to improve the real-time PPP performance has been proposed in (Wilgan et al., 2017a), where a numerical weather prediction model was used as an additional source of information on the troposphere state. For zenith total delay (ZTD) modelling, GNSS observations and short-term weather forecasts are combined (Wilgan et al., 2017b). Then, the ray-tracing technique was used to deliver coefficients of mapping functions that allows calculating tropospheric delays in a satellite direction. It was found that using the external troposphere models in static positioning could reduce the systematic error of receiver height by 20 mm on the average, at a cost of a worse coordinate repeatability by 1.5 mm (Fig. 6). No significant differences were observed for horizontal coordinates. In the kinematic positioning, both systematic error and coordinate repeatability of the vertical component were improved, but the quality of horizontal coordinates was slightly degraded. Systematic error of 3D coordinates was reduced by 10 mm, and coordinate repeatability for all processing variants differed within the 4 mm range. Moreover, a significant reduction of the initialization time was observed: 13% for the horizontal components and 20% for the vertical component. The choice of mapping function was insignificant because differences were noticeable only for very low elevation angles.

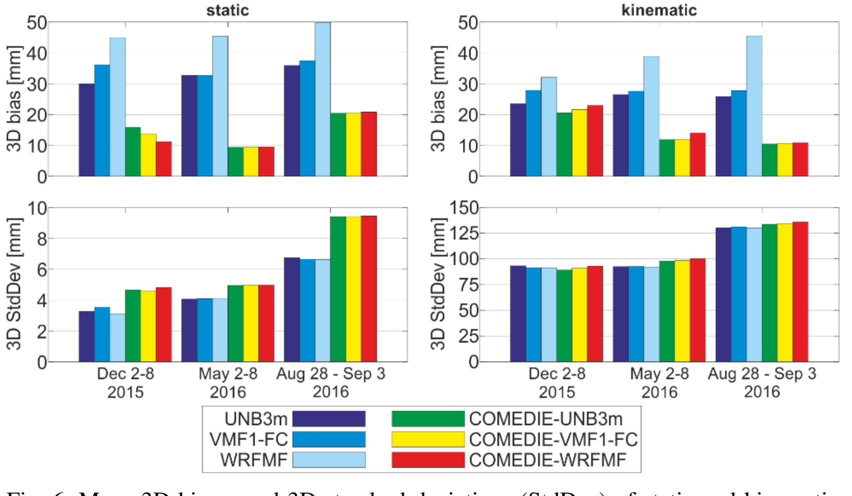


Fig. 6. Mean 3D biases and 3D standard deviations (StdDev) of static and kinematic coordinate residuals (estimated – EPN official) averaged from 14 Polish EPN stations

The research focused on analyzing impact of initial tropospheric delay estimates on the quality of PPP (Kalita and Rzepecka, 2017). During first minutes of PPP processing the initial biases of the a priori estimates can be significantly amplified while passing through the filter. In the analysis, PPP solution for several tropospheric models, i.e. MOPS (Minimum Operational Performance Requirement), GPT2w (Global pressure and temperature 2 wet) and VMF1 (Vienna Mapping Function 1), was referenced to the solution that uses IGS Final tropospheric product with several variants of initial filter variances appropriate for each tropospheric model. During the first 10 minutes of processing, the differences between the analyzed models can generate respective differences in the PPP solution that reach up to 30 cm and extend the initial bias several times. Using VMF1 model in PPP increases the height components' accuracy by about 35% when comparing to the GPT2w and MOPS. The improvement in horizontal components is up to 30%. The results show that the difference between applying blind and numerical weather prediction (NWP)-based tropospheric models plays an important role during convergence of PPP.

### *3.3. Developments in high-rate PPP*

The advances in algorithm development optimized for high-rate multi-GNSS data processing were presented in the study of Paziewski et al. (2018) performed at the University of Warmia and Mazury in Olsztyn. The paper provided not only the methodology, but also assessed the performance of millimetre level dynamic displacements determination. The novelty of the paper was the application of several modified or newly developed methods such as Precise Point Positioning, relative kinematic positioning, as well as novel direct phase observations processing method to high-rate multi constellation observations (up to 50 Hz). Since current regular kinematic PPP as well as medium to long baseline RTK do not offer position solution at millimetre level accuracy, the processing techniques were extended and these were applied to dynamic displacements determination. In the experiment the authors have processed 50 Hz observational data collected with the use of in-house developed shake-table ensuring periodic horizontal motion of GNSS antenna with amplitude of ~3 cm and frequency of ~4.5 Hz. The developed algorithms of high-rate PPP, RTK of medium range and direct phase observation processing method demonstrated to be capable of providing consistent and reliable results at the millimetre level precision of the dynamic displacement estimates.

### *3.4. Using PPP to analyze periodic signals in GNSS position time series*

Recently, GNSS measurements can provide position components estimation with millimetre accuracy. Processing of GNSS observations repeated periodically shows that methods and algorithms are constantly improving. This applies particularly to modelling and removing errors which are a source of inaccuracy of GNSS measurements. The above-mentioned increase of accuracy of GNSS observations processing reveals some jumps undetected so far and periodic signals. Discovered phenomenon can be a result of errors, still present in applied models (e.g. tidal models, solar radiation pressure models). Inaccuracies in GNSS antenna phase center variation models can be also one of the sources of these periodicities (jumps).

In Dawidowicz and Krzan (2016, 2017), it was investigated how differences present in GNSS antenna phase center correction models (individual and type mean) affect position estimates. Sub-daily solutions were analyzed using PPP technique. Obtained results proved that visible in PCC model differences affect GPS-only (as well as GLONASS-only) solutions and can be a source of periodic variations mentioned earlier. In the case of GPS-only solutions a periodicity equal to half of a sidereal day was found. The amplitude of the discovered periodicity was up to 10 mm. For GLONASS-only solutions the periodicity was close to 3 cpd which can be associated with the number of GLONASS orbital planes. Additionally, position component offsets caused by using individual PCC instead of type-mean PCC were estimated. For example, estimated up position component offset reach up to 5 mm for different stations with the same type of antenna. This proves that the same type antennas have different phase characteristics and cannot be represented with high accuracy by type-mean PCC. In Dawidowicz (2018) similar analysis was performed using daily GPS observation windows.

### *3.5. Determining normal heights with the use of Precise Point Positioning*

Normal heights determination using PPP method was analyzed in Krzan et al. (2017). For the purposes of the analysis, GNSS observations covering one week were processed using NAPEOS software. Processing of the observations was based on the standard PPP method as well as using Multi-Station PPP approach (with ambiguity fixing). Seven days of observations were divided into 1 hour, 30 minutes and 15 minutes sessions. This allows to examine the correlation between session duration and position determination precision. Geoid undulations were determined based on PL-geoid-2011 model. Obtained results proved that PPP method derived normal heights can have similar accuracy as Relative GNSS Positioning derived normal heights.

### *3.6. The application of ZigBee phase shift measurements to indoor positioning*

In modern society, industry and business, more and more attention is paid to indoor navigation. The main purpose of indoor navigation is to provide a function similar to the GNSS function, but in places where satellite signals are not available. There are many algorithms and concepts for indoor positioning systems: inertial systems, pseudolite systems or computer vision systems. In addition, there are other technologies that allow positioning and navigation inside buildings. Radio Frequency (RF) technology has become the concept of indoor positioning in the last few years. There are two basic methods for obtaining distances in RF networks – flight time (and its variants) and algorithms based on Radio Signal Strength Indicator (RSSI). Compared to other systems, the communication networks used to accomplish this task have many advantages. One can use existing infrastructure and devices. These devices are usually inexpensive and widely available, and besides navigation they can also be used for other purposes. However, a significant disadvantage is the low accuracy of the results obtained by these systems. The most commonly used systems based on RSSI can be accurate up to several meters, and these are not expected and satisfactory values (ideally 1–2 metres). In addition, it strongly depends on the environment, thus the functionality of these systems is very limited in a changing environment. The new method of obtaining distances between nodes in an RF network is a new approach based on the measurement of phase shift.

The new approach based on the ZigBee protocol and phase shift measurement shows promising results in this area (Rapiński, 2015; Rapiński and Śmieja, 2015; Janicka and Rapiński, 2016). Assessing the results, it was noted that a large number of distances is disturbed and significantly differs from the reference values. To obtain the correct distance, filtering the measurement results was applied. Therefore, RANSAC (Random sample consensus) and FIR (Finite impulse response) algorithms have been tested and the results have been analyzed (Rapiński and Janicka, 2015). Besides the accuracy of the measurement itself, the selection of the appropriate algorithm affects the final positioning result. Therefore, it was proposed to use Nelder–Mead symplex method for optimization of the objective function, which allows to obtain better results than methods based on the linearization of observation equations (Rapiński and Cellmer, 2015). Furthermore, it was also proposed to solve the problem of phase ambiguity, which also occurs during the positioning inside buildings (Rapiński and Janicka, 2017).

### *3.7. Integrated multi-sensor navigation*

Augmentation of satellite navigation is one of the current research trends studied by research centers around the world. There are several augmentation methods that are used in recent times. They can be divided into two types. The first type is based on the processing of other signals sent from external sources (Wi-Fi, Zigbee). The second type is based on the use of integrated inertial navigation systems (INS) and GNSS systems, which enable the augmentation of satellite systems with the results from inertial measurement unit (IMU).

The research done for the needs of improving integrated systems was the analysis of the observational data of the IMU inertial module. The most important part of conducted research was to develop and determine the accuracy of the attitude heading reference system (AHRS) algorithm. This algorithm is used to determine INS attitude alignment (Tomaszewski et al., 2015). In this process the initial position of the inertial module relative to the north direction and the direction of gravity is determined. Inertial navigation sensors alignment if defined by specifying Euler angles (pitch, roll, yaw) which are an unambiguous orientation of the sensor coordinate system relative to external coordinate system. The Kalman filter developed as part of the AHRS algorithm allows to determine these quantities (Tomaszewski et al., 2017). As part of the latest research, the integrated navigation algorithm was implemented. Next, practical tests of the use of an algorithm integrated in car navigation were performed (Tomaszewski, 2017). Studies have shown that the applied solutions increase the accuracy, reliability and integrity of the navigation system.

## 4. Troposphere studies

### *4.1. Improvements in the estimation strategy of GNSS troposphere products*

Stepniak et al. (2018) investigated main factors leading to outliers in ZTD time series obtained from the processing of GPS regional networks. It was found that the continuity and quality of ZTD time series strongly depends on the baseline design strategy in a double-difference processing. An alternative baseline strategy was proposed. This minimizes network disconnections, preventing gaps and outliers in ZTD time series. The reprocessed ZTD time series obtained with the developed strategy implemented in the Bernese GNSS Software v.5.2 occurred to be more continuous and homogeneous compared to the common strategies (Table 3).

Table 3. Statistics of ZTD estimates and formal errors (STD) after outlier rejection based on the range check on ZTD [0.5 m; 3.0 m] and on sigma [0 m; 0.1 m]; results from one year of processing data from 104 ASG-EUPOS stations

| Strategy | Rejected data | Used data | Mean STD (ZTD) | Mean STD (sigma) |
|---|---|---|---|---|
| standard | 148 | 468332 | 14.2 mm | 1.19 mm |
| obs-max | 109 | 471666 | 13.3 mm | 0.67 mm |
| new | 84 | 469534 | 12.9 mm | 0.79 mm |

Other studies focused on the accuracy, stability, and homogeneity of the estimated tropospheric parameters obtained with 1) double-difference (DD) processing of a network of stations and 2) zero-difference PPP processing of a single stations (Gołaszewski et al., 2017a). For short baselines in DD mode, the estimated ZTD are correlated and may be biased in their absolute values. Although the errors are not propagated between stations in PPP, the quality of the obtained ZTD depends strongly on the quality of orbits and clocks. ZTD estimates from DD and PPP solutions were compared. The authors noted outliers in DD solution caused by very few observations common to other stations in the baseline, which were not seen in PPP ZTD time series.

### *4.2. Near real-time and real-time troposphere delay estimation*

Wroclaw University of Environmental and Life Sciences (WUELS) established an Analysis Centre that estimates ZTD and troposphere horizontal gradients in near real-time (NRT) regime for GNSS stations located in Poland (Fig. 7), Lithuania and Victoria state in Australia. Results are submitted hourly to the database of E-GVAP (The EUMETNET EIG GNSS water vapor programme, http://egvap.dmi.dk/). Within the framework of the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC, 2013–2017, http://gnss4swec.knmi.nl/), WUELS contributed to the developments towards ultra-fast service (15-minute of delay) and multi-GNSS solution, by participating in the dedicated benchmark. The benchmark has aimed to support the development and validation of advanced GNSS tropospheric products, in particular high-resolution and ultra-fast ZTD, slant troposphere delays (STD) and tropospheric gradients derived from a dense permanent network. Data and metadata were prepared for GNSS stations located in the Polish part of the benchmark. A complex data set was collected for the 8-week period when several extreme heavy precipitation episodes occurred in Central Europe which caused severe river floods in this area (Douša et al., 2017).

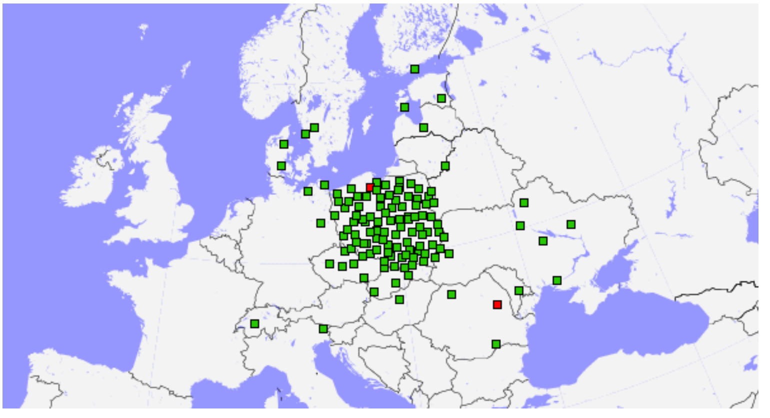

Fig. 7. GNSS stations in NRT ZTD solution for Poland, status on 7 November 2018

Dymarska et al. (2017) provided accuracy analyses of NRT GNSS ZTD validated against final IGS products, Weather Research and Forecasting (WRF) NWP model and radiosonde profiles. A biases of 3 mm to 11 mm with related standard deviations from 10 mm to 14 mm were found. Therefore, considering the data quality, the authors assessed that NRT ZTD products can be assimilated into NWP models.

An extensive validation of line-of-sight tropospheric standard deviations (STD) from GNSS, ray tracing in NWP model fields and microwave water vapour radiometer (WVR) was presented by Kačmařík et al. (2017). Seven institutions delivered GNSS STDs obtained with 5 different software and 11 strategies for 10 GNSS stations using data from almost 2 months in 2013 (including severe weather events). Evaluations demonstrated a good mutual agreement of various GNSS STD solutions ignoring post-fit residuals (mean bias and standard deviation scaled to zenith direction was $-0.6$ mm $\pm$ 3.7 mm), especially when compared to numerical weather model (NWM) and WVR STDs (10 mm $\pm$ 2 mm and 12 mm $\pm$ 2 mm, respectively). Although the post-fit residuals cleaned of visible systematic errors (multipath) generally showed a slightly worse performance, they contained significant tropospheric signal on top of the simplified model. They are thus recommended for the reconstruction of STDs, particularly during high variability in the troposphere.

The NRT ZTD obtained with GPS data from ASG-EUPOS network in January 2011 was used for verification of the implemented WRF-Chem model v3.5 over Poland, in which the main purpose was to quantify the direct and indirect feedback effects of aerosols on simulated meteorology and aerosol concentrations (Werner et al., 2016). ZTDs were recalculated to Integrated Water Vapour (IWV) above the GNSS stations with the meteorological data for three WRF simulations and used to verify the water vapour content.

Hadaś et al. (2017b) showed that the troposphere constraints in GNSS processing, modelled as a random-walk process, should have been time and location specific. Therefore, they proposed to take benefit from numerical weather prediction models to define optimum random walk process noise (RWPN) for the ZTD estimation in real-time. Using archived VMF-G grids, they obtained RWPN global grids for hydrostatic and wet parameter (Fig. 8), which can easily be implemented in a software as a look up table to define the optimum RWPN value for any station located worldwide. Alternatively, a short-term weather forecast can be used to perform ray-tracing in order to forecast ZTD and then to calculate RWPN dynamically in real-time. The advantage of this approach is that the wet RWPN is regularly adjusted to the expected tropospheric conditions. The approach utilizing the global grid can successfully replace the initial empirical testing for effective constraining, while the dynamic approach is even superior by up to 18% compared to the standard static approach.

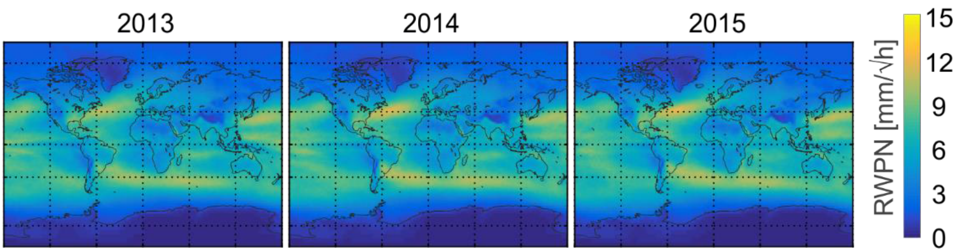


Fig. 8. Global maps of the optimum wet RWPN for years 2013, 2014 and 2015

### *4.3. Development of troposphere models supporting positioning and VLBI*

In Kaźmierski et al. (2017), UNB3m model was adjusted to the actual meteorological parameters from Europe. Although the same mathematical formulas were used as in UNB3m model, latitude-specific meteorological parameters were replaced by in situ meteorological measurements. In such a way a new UNBe.eu model was developed that covers the EGNOS (European Geostationary Navigation Overlay Service) augmentation system area. For over 70% of test stations an improvement was found in the consistency between UNBe.eu and radio sounding, however, for some locations near oceans and seas the new model was less accurate than original UNB3m model, which was probably related with the lack of relative humidity amplitude estimation from meteorological stations.

Wilgan et al. (2015) presented inter-comparison of tropospheric and meteorological parameters from different data sources: NWP model COAMPS (Coupled

Ocean/Atmosphere Mesoscale Prediction System), ZTD GNSS calculated from the ASG-EUPOS network, ground-based meteorological observations from EPN stations and radiosondes. The values of meteorological parameters from COAMPS were compared w.r.t. EPN and radiosondes. From the comparison of GNSS ZTD with NWP model it was concluded, that the troposphere model based on NWP may have insufficient accuracy for precise positioning (approx. 20 mm), but a high spatial resolution. Thus, the best solution for positioning is the integration of NWP models with GNSS products of high quality.

The troposphere delay model dedicated to real-time application was developed by Wilgan (2015), who presented the short-term predictions of NRT ZTD using autoregressive (AR) and autoregressive moving average (ARMA) statistical models. The forecasts were included in local (each station has a separate prediction model) and global (one statistical model provided for all stations simultaneously) mode. The statistical forecasts showed much better agreement with the reference GNSS data than ZTDs from GPT2 model or NWP model COAMPS. For the 5 h local forecasts, the statistical models exhibited the average bias close to 0 with standard deviations of 5–10 mm, the COAMPS model bias ranged from −20 to 20 mm with a standard deviations of 8–10 mm, and for the GPT2 the bias ranged from −40 to 40 mm with a standard deviation of approx. 10 mm. It was also concluded that there is no need to use the local mode, only the global one, which allows for the automation of the prediction process for all stations simultaneously, without the loss of accuracy.

Integrated models of troposphere based on the least-squares collocation technique were presented in Wilgan et al. (2017a). It was found that for mountainous areas (Switzerland) the highest agreement with reference radiosonde data was obtained when the total refractivity was calculated from meteorological measurements and ZTD from GNSS stations, but adding the horizontal gradients of ZTD did not improve the model. In the lowlands area (Poland) the height distribution of ground-based meteorological stations was too flat to reconstruct the refractivity profiles with the collocation technique. Thus, the best agreement was obtained when the troposphere model was built based on high-resolution NWP WRF model data integrated with GNSS data. The developed ZTD model was compared with NRT ZTD for 9 days in May 2014, during which a severe weather event occurred. A bias of 3.7 mm with standard deviation of 16.7 mm was observed. In the following study the integrated troposphere model for Poland based on WRF and GNSS data was applied into real-time PPP (Wilgan et al., 2017b). The proposed model is a high-resolution alternative for the state-of-art models such as UNB3m or Forecast Gridded VMF1-FC model. It allowed for the reduction of coordinate bias and shortening of the convergence time. Please, see section 3 (Advances in Precise Point Positioning) for more details.

The tropospheric delay prediction method proposed by Rzepecka et al. (2015) can be placed between empiric and NWP-based models. It uses the fact that after removing annual and semi-annual signals from VMF1 time series the autocorrelation of the result residuals is significant for lags far exceeding one day. For the analyzed case, the zenith wet delays range from 0 to about 30 cm and the residuals range from −10 cm to +10 cm. After modeling the residuals as the ARMA processes, the result value is a sum of the linear regression functions and the models of residual processes. One-step forecasts based on the above models were estimated to be within ±2.5 cm to ±4 cm for 80% of confidence level.

Kroszczyński (2015) analyzed GPS waves propagation in the atmosphere, focusing on the low ($< 20°$) elevation angles. He noticed, that slant tropospheric delay is a function of azimuth, which reflects spatial heterogeneousness of the atmospheric state including the distribution of humidity, and may cause anisotropy of slant delays reaching 1 m. Atmospheric refraction model can be obtained by using the non-hydrostatic mesoscale model forecast data, which determines various atmospheric conditions.

Nykiel et al. (2018) conducted research related to the usage of water vapour derived from GNSS processing for very-long-baseline interferomatry (VLBI) applications. A correlation between the GNSS IWV obtained with several strategies and the atmospheric opacity ($\tau_0$) from the sky-dip method was greater than 0.94, with only small differences in linear regression coefficients and in standard error (Fig. 9). It is concluded that GNSS IWV can be successfully used for calibration of VLBI observations or validation of $\tau_0$. On the other hand, $\tau_0$ can be a valuable verification of estimated IWV.

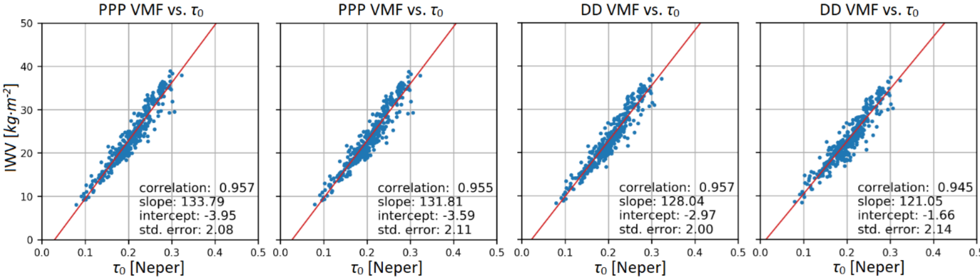


Fig. 9. Correlations between IWV derived from GNSS processing and $\tau_0$ from sky-dip method

### *4.4. Climate studies and meteorology*

Baldysz et al. (2015) investigated whether the long-term and seasonal changes of the ZTD parameter may reflect the real long term weather changes, or not. They found a correlation between the character of the ZTD time series and prevailing weather conditions occurring over a given region. Distribution of the ZTD linear trends characters (positive and negative) was found to result from the real tropospheric changes. Long-term changes of the ZTD parameter seemed to reflect some decadal variations which took place in the troposphere over the analyzed 16-year and 18-year time span. Therefore, Baldysz et al. (2016) presented a comparative analysis of the ZTD long-term changes obtained on the basis of two independently processed GNSS data, namely Repro 1 and Repro 2. Both reprocessing campaigns were different from each other in terms of tropospheric mapping functions, ionospheric delay modelling, applied tidal and non-tidal loadings. In vast majority, differences in the ZTD linear trends between solutions indicated smaller linear trends values for Repro2. It is concluded that adopted processing strategy affect estimated linear trends and in consequences, may disturb a proper and reliable usage of the GNSS products in a climate changes monitoring. These works were continued in (Baldysz et al., 2018) in order to identify factors affecting the estimated IWV time series the most. IWV was obtained using meteorological data from ECMWF (European Centre for Medium-Range Weather Forecasts) ReAnalysis (ERA-Interim) NWP model and ZTD obtained with 10 different processing schemes, and compared with radiosonde data. It was found out that the solutions obtained using PPP approach were characterized by higher consistency to the radiosonde observations than DD solutions, regardless of the used mapping function and the zenith hydrostatic delay (ZHD) *a priori* values.

Gołaszewski et al. (2017b) analysed the characteristics of water vapour surrounding an extreme weather event using high-resolution GNSS tropospheric estimates. GNSS results obtained with Bernese GNSS Software v.5.2 and G-Nut software were compared against IWV from ERA-Interim reanalysis and microwave radiometer collocated to GNSS station. Validation confirmed that both GNSS software provide high-quality tropospheric products that are with a very high agreement with the IWV from ERA-Interim and radiometer.

### *4.5. Application of Radio Occultation measurements in troposphere studies*

The GPS radio occultation (RO) technique utilizes a receiver on a low-Earth orbiting (LEO) satellite to derive profiles of geophysical parameters from a limb viewing geometry. Radio signals propagating from a GPS satellite experience a phase delay and gets refracted as a result of atmospheric density. The inversion process that attributes the measured excess phase to profiles of the bending angle, refractivity and further to dry pressure and temperature in the neutral atmosphere has been implemented in a retrieval software (Hordyniec et al., 2018). The occultation signals collected on-board FORMOSAT-3/COSMIC satellites are inverted by means of geometrical optics in the upper atmosphere and the tropospheric multipath is resolved with radio-holographic Full Spectrum Inversion (FSI) method. The statistical optimization compensates the higher order ionospheric noise using an adaptive weighting of bending angle profile based on measured signal to noise ratio (SNR). An excellent agreement with radiosonde data is observed within the upper troposphere and lower stratosphere (UTLS) region where the dry-air assumption in the retrieved pressure and temperature is no longer an issue.

Amongst a number of factors that contribute to the atmospheric refraction, the gaseous terms associated with pressure, temperature and water vapour dominate over liquid and solid particles. Contributions of frequently observed cloud water fractions as well as significant examples were studied in terms of induced retrieval errors in radio occultation profiles (Hordyniec, 2018). Clouds typically produce single-spike structures in the refractivity profiles with a fractional difference up to 1%, which corresponds to an error of 4% in the bending angle. The distribution of cloud water along the propagation plane allows for the application of Abel transform due to its spherically symmetrical characteristic. However, horizontal inhomogeneities should be considered in the case of a significant cloud content to avoid overestimation of propagation effects. The uppermost contribution of liquid clouds can exceed fractional differences of 10% in the bending angle and 2% in the refractivity, whereas the ice water is generally within 1% and 0.5%, respectively.

Lasota et al. (2018) used RO technique to examine the influence of dense clouds present in tropical cyclones on the GNSS signal. The RO technique is widely assumed to be insensitive to clouds, however, it was confirmed that positive mean biases of refractivity and bending angle anomalies are present and reach up to 0.5% and 1.6%, respectively. Furthermore, analysis of RO bending angle sensitivity on cloud ice and liquid water contents derived from collocated CloudSat profiles with respect to the RO bending error was performed. It was found out that clouds' influence exceeds bending angle uncertainty in 21 out of 50 examined cases. In general, for single observations, most of the clouds are detectable between 8 and 14 km while mean cloud impact is significant between 9.0 and 10.5 km with a mean contribution to the total bending angle of 0.1%. Slightly less than 15% of the cases with detectable clouds' influence surpass a height of 16 km, which is assumed to be a minimum height of the tropopause in tropics.

The GPS RO technique utilizes a receiver on a LEO satellite to derive profiles of geophysical parameters from a limb viewing geometry. Radio signals propagating from a GPS satellite experience a phase delay and gets refracted as a result of atmospheric density. The inversion process that attributes the measured excess phase to profiles of the bending angle, refractivity and further to dry pressure and temperature in the neutral atmosphere has been implemented in a retrieval software (Hordyniec et al., 2018). The occultation signals collected on-board FORMOSAT-3/COSMIC satellites are inverted by means of geometrical optics in the upper atmosphere and the tropospheric multipath is resolved with radio-holographic FSI method. The statistical optimization compensates the higher order ionospheric noise using an adaptive weighting of bending angle profile based on measured SNR. An excellent agreement with radiosonde data is observed within the UTLS region where the dry-air assumption in the retrieved pressure and temperature is no longer an issue.

## 5. Ionosphere studies

Banville et al. (2017) investigated the effect of accounting for both first- and second-order ionospheric effects on the slant ionospheric delay parameter estimates when GPS observations are estimated within a static and kinematic PPP solution. They examined the approach of Zehentner and Mayer-Gürr (2016) introducing additional constraints on slant TEC and providing more numerical tests and examples. They employed four European permanent stations situated in mid-latitudes and auroral oval with observations covering high solar activity. Four cases were tested: (1) without higher-order ionospheric corrections applied, (2) higher-order ionospheric corrections added within PPP, (3) first and second-order corrections applied within the PPP filter and (4) the same as (3) but with additional constraints on the slant TEC added. The authors found that the PPP solution is affected by higher-order ionospheric effects. Especially, changes in the positions reaching up to few millimetres were observed. They recommended that the receiver differential code biases need to be properly handled to provide unbiased estimates of the receiver position. As the conclusion, they stated that the explicit estimation of higher-order ionospheric effects should not be performed within the PPP filter.

Araszkiewicz et al. (2015) examined the coordinates and baselines between 30 European EPN stations when different higher order ionospheric corrections (I2 and I3) added at the stage of the GPS processing. They observed, that for the northern part of Europe adding higher order ionospheric corrections causes the root-mean-square value of the North component to increase. For the remaining areas, the horizontal coordinates changed between 0.1 and 0.2 mm.

Hadaś et al. (2017a) employed GPS and GLONASS observations from a global and two regional networks in Poland and Brazil to examine the impact of the higher order ionospheric (I2+) terms on the GNSS products, i.e. satellite orbits, satellite clock corrections, Earth rotation parameters, troposphere delays, horizontal gradients and receiver positions. They employed a global GNSS solution, RTK and PPP algorithms. They developed a Web service (http://www.smartnetleica.pl/o-nas/horion/#horion-pl) which helps to remove the I2+ effects directly from the RINEX (Receiver Independent Exchange System) file. They examined two different areas, i.e. the low-latitude network in Brazil and the mid-latitude network in Poland, with three test periods to evaluate various ionosphere conditions with high solar maxima, minima and a geomagnetic storm. They found that the I2+ corrections are tightly related to the signal frequency (L1/L2) and dependent on the TEC level; the greatest corrections ranged, for the L1 signal, between −15 mm and 2 mm during the geomagnetic storm and, for the L2 signal, between −24 mm and +23 mm for the high TEC level period. The satellite orbits and satellite clock corrections reached up to 20 mm when I2+ corrections were applied. The impact of higher order ionospheric terms was found to be insignificant for ZTD and horizontal tropospheric gradients estimated within the GNSS data processing. However, the I2+ corrections influence the positions' estimates leading to their shift up to −11 mm for the most active ionosphere conditions.

Krypiak-Gregorczyk and Wielgosz (2018) presented a completely new approach, suitable for ionospheric modelling on global and regional scales, to estimate the carrier phase bias of the scaled L1 and L2 differences. Their algorithm was based on the ambiguities, the ionospheric delay and hardware delays. Using varying ionospheric conditions, the authors proved that they are able to estimate the carrier phase bias of geometry-free linear combination with a very high accuracy. The uncertainty lower than 1 TECU was obtained for the TEC values.

Nykiel et al. (2017) employed a dense GNSS network to analyze the TEC variations over Central Europe and demonstrated that this kind of network allows to analyze a structure and temporal evolution of mesoscale ionospheric irregularities. They focused on a special type of plasma inhomogeneities, which is called MSTID. A usage of dense GNSS network allowed to obtain MSTID characteristics as spatial dimensions, velocities, and directions of their movement. They analyzed two days of magnetic storm, i.e. $17^{th}$ March 2013 and 2015, and proved that the TEC values form a dynamic structures during the magnetic storms which do significantly differ from the dynamics of ionospheric processes on quiet days. The authors found a clear, easily observable boundary of TEC variations increase during the storm, situated at 52° N. Hernández-Pajares et al. (2017b) presented disturbances in precise GPS processing. They employed a network of GNSS receivers in Poland operating during two days: one in winter and one in summer, and demonstrated that the direct GNSS Ionospheric Interferometry (dGII) technique helps to obtain a reliable RTK position faster of 13 to 30 s comparing to uncorrected observations. They concluded that their MSTID mitigation methodology is suitable for spare GNSS networks and helps to reduce the error up to 90%. The dGII algorithm can also be applied in real-time conditions under MSTID activity and depends only on reference ionospheric data from a single permanent receiver.

Krypiak-Gregorczyk et al. (2017a) proposed to employ the un-differenced multi-GNSS carrier phase data to estimate the TEC values and dense the existing ionospheric maps, especially on a regional scale. They also derived the slant-TEC-based methodology to analyze the self-consistency of the ionospheric products. These ionospheric maps were compared to global solutions for different ionospheric conditions, including also the geomagnetic storm. The authors showed that the accuracy of their regional solution is better than 1 TEC unit and at least 2 times better than the global products. Global ionospheric maps were also computed by Sun et al. (2017) who employed the a set of ground-based GNSS receivers and FORMOSAT-3/COSMIC GPS occultation experiment to construct the TEC map named Taiwan Ionosphere Group for Education and Research (TIGER) Global Ionospheric Map (GIM). This map was built applying the Kalman filter and spherical harmonic formula. As a result, a map of 5 min temporal resolution and $2.5° \times 5.0°$ spatial resolution was obtained. They proved that this map correlates well with global GIM published by international institutes. GIMs were also discussed in details by Hernández-Pajares et al. (2017a) who characterized the observations and methods employed for their construction and assessment. They analyzed the consistency of GIM-derived TEC using the vertical TEC delivered from altimetry measurements and the difference of slant TEC based on the 26 GPS observables. Both measurements were collocated to each other. This kind of comparison between altimetry- and GPS-derived TEC values was also performed by Roma-Dollase et al. (2018) to prove a consistency of various GIMs during one solar cycle. The authors compared all IGS-delivered GIMs and concluded that despite different various GIM techniques and algorithms are applied, all maps are very consistent to each other.

A usage of the least-square collocation method with a noise variance was presented by Krypiak-Gregorczyk et al. (2017b) to model the TEC values on a regional scale. In this way, they obtained the high accuracy ionospheric maps with a high spatial and temporal resolution of TEC variations. To examine the new TEC regional solutions, the authors derived the double-difference ionospheric corrections directly from these maps and analyzed their accuracy, comparing to IGS and UPC global and CODE regional maps. Moreover, they also applied the ionospheric corrections to GNSS positioning and analyzed the ambiguity resolution. Tests were performed for ionospheric storms. Results prove that the accuracy of the relative ionospheric corrections is better than 10 cm in most cases. Based on that, the authors concluded that their newly delivered regional TEC maps can support the ambiguity resolution in kinematic GNSS positioning.

A completely new IGS ionospheric product named as Rate of TEC Index (ROTI) Maps was introduced to geodetic community by Cherniak et al. (2018). This product presents the irregularities and intensities of ionosphere for high and middle latitudes of the Northern Hemisphere and allows to monitor it continuously. It is based on the ground-GPS 30-s sampled measurements collected at the number of 700 permanent stations. The assessment of ROTI Maps performance was provided for the geomagnetically quiet period and for the geomagnetic storms.

A new field of study is the use of the LOw-Frequency ARray (LOFAR) to perform solar and space weather studies was proved by Dąbrowski et al. (2016). They described a set of 50 European LOFAR stations, 3 of which are situated in Poland, and discussed their role to observe a radio source. A great attention was paid to the ionosphere layer, which causes a delay and therefore, also, the phase errors. This topic was further investigated also by Kotulak et al. (2017) who stated that LOFAR is not able to estimate the ionospheric corrections in a proper way due to too long baselines. Therefore, is should be combined with other dataset, which provide accurate ionosphere observables. Nowadays, the geodetic community is supported with the GNSS technology which permanently sounds the ionosphere. On this basis, using a wide range of GNSS stations, vertical TEC measurements can be interpolated into a continuous fields and successfully used to accompany LOFAR observations.

The state of the high-latitude ionosphere was also the subject of intensive studies presented in (Sieradzki, 2015; Sieradzki and Paziewski, 2018). In the first paper it was confirmed that the current distribution of the GNSS stations allows permanent monitoring of the ionosphere with subdaily temporal resolution. Moreover it was revealed that ROTI values strongly depend on the orientation of the GNSS signal in space. In the second paper the researchers proposed an innovative method suitable for detection of the large scale ionospheric disturbances. The method was applied to the characterization of the interhemispheric patches during St. Patrick geomagnetic storm. The paper justified high applicability of the method and consistency of the results with other techniques such as SWARM mission.

## 6. Summary and conclusions

This report provides selected examples of research activities on GNSS positioning and atmosphere remote sensing carried out at Polish research institutions during years 2015–2018. In particular, improvements in the mathematical and stochastic models and carrier phase ambiguity resolution, together with advances in troposphere and ionosphere modelling were demonstrated. It shall be noted that these research were often carried out in the frame of IAG Commission 4 working and study groups, and their results were published in high-quality scientific journals. The most active research groups in these fields of studies are affiliated with the Gdansk University of Technology, the Military University of Technology (Warsaw), the University of Warmia and Mazury in Olsztyn, the Warsaw University of Technology and the Wroclaw University of Environmental and Life Sciences.

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