National Report of Poland to EUREF 2017

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1. Introduction

Since 2015 the main geodetic activities at the national level in Poland concentrated on maintenance of gravity control and geomagnetic control, continuing operational work of permanent IGS/EPN GNSS stations, GNSS data processing on the regular basis at the WUT and MUT Local Analysis Centres, activities of MUT and WUT EPN Combination Centre, validation of GNSS orbits using SLR, activity within the EUREF-IP Project, works on GNSS for meteorology, monitoring ionosphere and ionospheric storms, advanced methods for satellite positioning, maintaining the ASG-EUPOS network in Poland, modelling precise geoid, the use of data from satellite gravity missions, monitoring gravity changes, geodynamics, activity in satellite laser ranging and their use.

2. Current status of reference frames in Poland

2.1. Horizontal and vertical

In 2016 the field inspection of geodetic control network was continued and tasks on West-North Poland were completed. In total 3850 points of horizontal and 2820 points of vertical points were visited. Due to road investments, external insulation of buildings and intensive soil cultivation many benchmarks were destroyed or damaged for the last fifteen years: 445 horizontal control (11.6%) and 657 vertical control (23.3%). Permanent damage of benchmarks of vertical control network is a serious problem for maintaining proper densification of 1st and 2nd order benchmarks in the whole country.

2.2. Vertical

Analysis of three campaigns of Baltic Sea Level Project conducted by the team of the University of Warmia and Mazury reveal that the GPS and spirit levelling data possibly contain errors which affect the determination of Sea Surface Topography and local mean geopotential value W_0^L (Kuczynska-Siehien et al.,2016). Data from three campaigns of the Baltic Sea Level Project and from the new GNSS campaign conducted in 2015 at three tide gauge stations Swinoujscie, Ustka and Wladyslawowo together with tide gauge data as well as EGM2008 global geopotential model were used to determine W_0^L. The best estimate of W_0^L for three tide stations investigated, equal to 62636857.45 $m^2\ s^{-2}$ ±0.01 m^2s^{-2}, was achieved using data from 2015 campaign.

2.3. Gravity

Research activities concerning gravity field modelling and gravimetric works performed in Poland in 2016 focused on geoid modelling, evaluation of global geopotential models, determination of temporal variations of the gravity field with the use of data from satellite gravity space missions, absolute gravity surveys for the maintenance and modernization of the gravity control, installation of the superconducting gravimeter at Borowa Gora Geodetic-Geophysical Observatory, metrological aspects in gravimetry, and investigations of the non-tidal gravity changes.

Maintenance of gravity control and gravity survey for geodynamic research

Absolute gravity measurements were carried out on regular basis with the use of FG5-230 gravimeter in the Jozefoslaw Astrogeodetic Observatory of the Warsaw University of Technology (WUT) since 2005 (Fig. 1). Ground water level was recorded by hydrostatic piezometer and soil moisture at 0.1 m and 1.0 m depth was measured (Brzezinski et al., 2016).

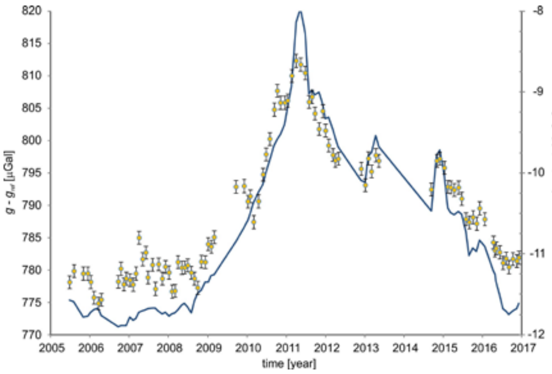


Fig. 1. Absolute gravity surveyed with the FG5-230 at Jozefoslaw (100 cm height) (g_{ref} = 981213000 µGal)

Gravimetric investigations at the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography (IGiK) were continued. A series of absolute gravity measurements on the test stations in the Observatory conducted on monthly basis with the A10-020 gravimeter since September 2008 (Fig. 2) shows high quality of A10 data.

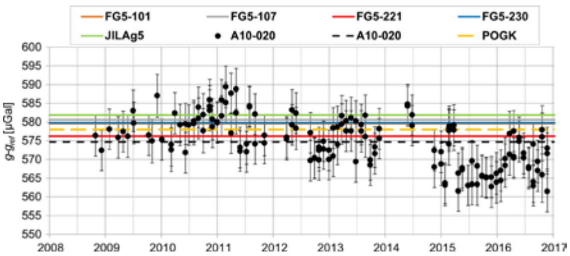


Fig. 2. Absolute gravity surveyed with the A10-020 at A-BG station in Borowa Gora (pillar level) (g_{ref} = 981125000 μGal)

Starting from late 2014, regular measurements with the A10-020 gravimeter at three sites in Borowa Gora Geodetic-Geophysical Observatory are supplemented with the monitoring of local hydrological conditions via automated stations measuring precipitation, soil humidity (at two depths 0.1 m and 0.5 m) and water table level variation. Local hydrological model was developed. Sensitivity of the A10 absolute gravimeter to the variation of local hydrological conditions allowing to detect small local hydrological changes was demonstrated (Fig. 3). It has also been proven that GLDAS/Noah hydrological model is efficient for hydrological variations analysis.

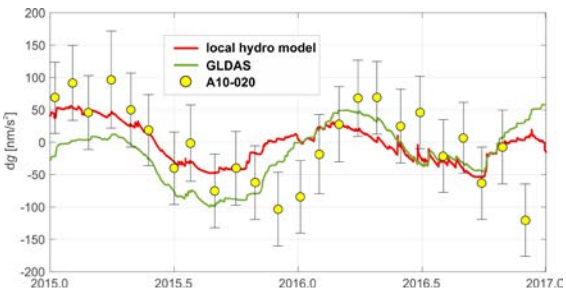


Fig. 3. Absolute gravity variations from the survey with the A10-020 at the field station 156 at Borowa Gora and from local as well as GLDAS hydrological models

The installation of the iGrav-027 – the first superconducting gravimeter in Poland, and the only one SG in this part of Europe (Fig. 4) – has been completed successfully on April 2017 (Dykowski et al., 2016a).

Since May 2016 the iGrav-027 operates at the Borowa Gora Geodetic-Geophysical Observatory (Fig. 5). Within the first month of operation the iGrav-027 reached required noise level specifications and is expected to fulfil the low and linear drift expectations in the near future. The signal collected within the first month of operation of the iGrav-027 showed its precision below the level of 1 nm/s^2 which allows the collection of the highest quality tidal signal in the area of Poland (Dykowski et al., 2016b).

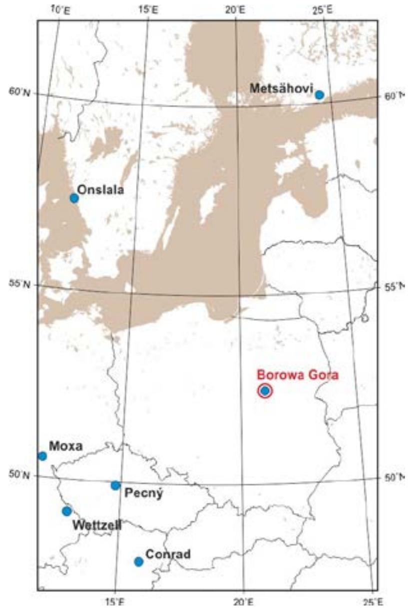


Fig. 4. Borowa Gora Observatory and the location of other SGs

Fig. 5. The iGrav-027 in the Borowa Gora Observatory

The initial calibration of the iGrav-027 sensor was carried out from 4 to 7 May 2016 with the use of three LCR G gravimeters as well as the A10-020, within the period of the timewise nearest highest amplitude of tidal curve (Fig. 6).

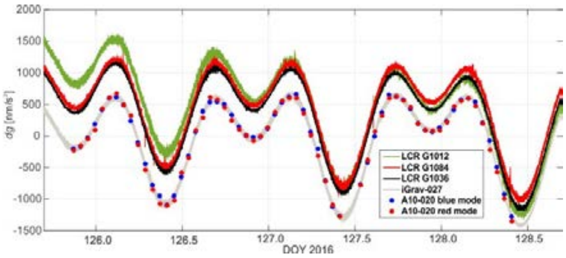


Fig. 6. Raw data from all relative gravimeters and the A10-020 absolute gravimeter used for calibration of the iGrav-027

The new instrument can be a valuable tool for controlling the national gravity standard. With the iGrav-027 superconducting gravimeter and the A10-020 absolute gravimeter the Borowa Gora Observatory with three suitable pillars can successfully serve as a site for regional comparisons of absolute gravimeters. As the A10-020 is a regular participant of the international comparison campaigns of absolute gravimeters and the iGrav-027 instrument is operational, Borowa Gora becomes eligible to be an important component of the global absolute gravity reference system as a station with a continuous reference function (Sekowski et al., 2016).

The results of the European Comparison of Absolute Gravimeters campaign ECAG2015, in which the A10-020 and FG5-230 gravimeters took part, have been processed and published (Palinkas et al., 2017). Local comparison campaign of two absolute gravimeters: A10-020 and FG5-230, supported with the iGrav-027 record, was conducted in the Borowa Gora Geodetic-Geophysical Observatory.

The Borowa Gora Observatory with LCR-G1036 and iGrav-027 gravimeters has successfully joined the International Geodynamics and Earth Tide Service (IGETS) of the International Association of Geodesy.

2.4. Magnetic

Magnetic control in Poland consists of 19 magnetic repeat stations maintained by IGiK supported by two magnetic observatories run by the Institute of Geophysics of the Polish Academy of Sciences (IGF PAS): Central Geophysical Observatory in Belsk and Magnetic Observatory in Hel. In addition, there are two permanent magnetic stations: Borowa Gora – run by IGiK, and Suwalki – run by IGF PAS (Welker and Reda, 2016) (Fig. 7).

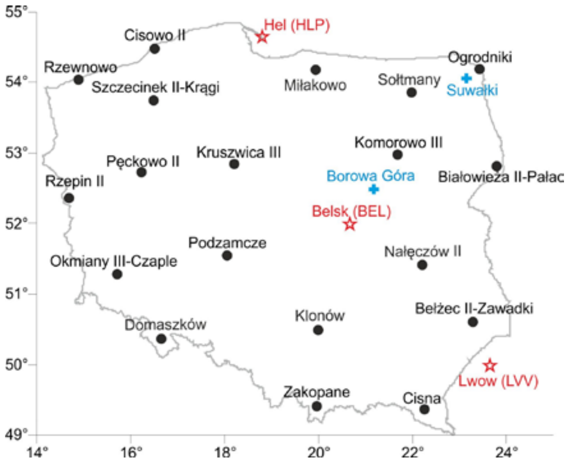


Fig. 7. Repeat stations (black dots), permanent stations (blue crosses) and magnetic observatories (red stars)

Measurements of three independent components of the magnetic intensity vector at the repeat stations are regularly performed every 2–4 years. There is also a need to repeat the magnetic measurements on the Baltic Sea (Krynski and Rogowski, 2016). In 2016 measurements of magnetic declination *D*, magnetic inclination *I* and the module *F* of the magnetic intensity vector were conducted at 5 repeat stations: Nałęczów, Bełżec, Pęckowo, Rzepin and Okmiany (Fig. 7).

3. Participation in IGS/EPN permanent GNSS networks

3.1. Operational work of permanent IGS/EPN stations

Permanent IGS and EPN GNSS stations operate in Poland since 1993. Recently 18 permanent GNSS stations (Table 1), i.e. Biala Podlaska (BPDL), Borowa Gora (BOGO, BOGI), Borowiec (BOR1), Bydgoszcz (BYDG), Gorzow Wielkopolski (GWWL), Jozefoslaw (JOZE, JOZ2), Krakow (KRAW, KRA1), Lamkowko (LAMA), Lodz (LODZ), Katowice (KATO), Redzikowo REDZ (Suwalki (SWKI), Ustrzyki Dolne (USDL), Wroclaw (WROC) and Zywiec (ZYWI) (Fig. 8) operate in Poland within the EUREF program. The stations BOGI, BOR1, JOZE, JOZ2, LAMA and WROC operate also within the IGS network (http://www.epncb.oma.be/_networkdata/stationlist.php). A brief characteristics of those stations is given in Table 1. Data from those stations are transferred via internet to the Local Data Bank for Central Europe at Graz, Austria and to the Regional Data Bank at Frankfurt/Main, Germany and together with data from other corresponding stations in Europe, were the basis of the products that are applied for both research and practical use in geodesy, surveying, precise navigation, environmental projects, etc.

Fig. 8. EPN/IGS permanent GNSS stations in Poland (2016)

Four of those stations, i.e. BOGI, BOR1, JOZ2 and WROC participated also in IGS Real-time GNSS Data project. Two stations WROC and BOR1 are also included into the IGS Multi-GNSS Experiment (MGEX) pilot project (http://igs.org/mgex).

The EPN stations at Borowa Gora (BOGI), Borowiec (BOR1), Jozefoslaw (JOZ2, JOZ3), Cracow (KRAW, KRA1), Lamkowko (LAM5), and Wroclaw (WROC) take part in the EUREF-IP project (http://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_euref-ip.htm) (Fig. 9).

Since March 2005 Ntrip Broadcaster is installed at the AGH University of Science and Technology (http://home.agh.edu.pl/~kraw/ntrip.php). Ntrip Caster broadcasts RTCM and raw GNSS data from KRAW0 and KRA10 sources take part in the EUREF-IP project and provide data to regional EUREF brodcasters at BKG, ASI and ROB.

Fig. 9. Polish EPN stations participating in the EUREF-IP project (2015)

Table 1. Permanent GNSS stations in Poland

Name (abbreviation)	Latitude	Longitude	Status
Biala Podlaska (BPDL)	52º02'07"	23º07'38"	EUREF
Borowa Gora (BOGI)	52º28'30"	21º02'07"	IGS, EUREF
Borowa Gora (BOGO)	52º28'33"	21º02'07"	EUREF
Borowiec (BOR1)	52º16'37"	17º04'24"	IGS, EUREF
Bydgoszcz (BYDG)	53º08'04"	17º59'37"	EUREF
Gorzow Wielkopolski (GWWL)	52º44'17"	15º12'19"	EUREF
Jozefoslaw (JOZE)	52º05'50"	21º01'54"	IGS, EUREF
Jozefoslaw (JOZ2)	52º05'52"	21º01'56"	IGS, EUREF
Katowice (KATO)	50º15'11"	19º02'08"	EUREF
Krakow (KRAW)	50º03'58"	19º55'14"	EUREF
Krakow (KRA1)	50º03'58"	19º55'14"	EUREF
Lamkowko (LAMA)	53º53'33"	20º40'12"	IGS, EUREF
Lodz (LODZ)	51º46'43"	19º27'34"	EUREF
Redzikowo (REDZ)	54º28'21"	17º07'03"	EUREF
Suwalki (SWKI)	54º05'55"	22º55'42"	EUREF
Ustrzyki Dolne (USDL)	49º25'58"	22º35'09"	EUREF
Wroclaw (WROC)	51º06'47"	17º03'43"	IGS, EUREF
Zywiec (ZYWI)	49º41'12"	19º12'21"	EUREF

3.2. Data processing at WUT LAC

The Warsaw University of Technology operates the WUT EPN Local Analysis Centre (LAC) since 1996. WUT AC contributes to EUREF with final (weekly and daily) and rapid daily solutions of the EPN subnetwork (Liwosz, 2015). At the end of 2016, the WUT LAC subnetwork (Fig. 10) consisted of 106 GNSS stations (5 new stations were added in 2016) from which 91% observed both GPS and GLONASS satellites.

GNSS data are processed in WUT LAC using the Bernese GNSS Software v.5.2. WUT LAC products, i.e. coordinates in SINEX format and zenith tropospheric delays, can be accessed from the following EPN data centres: BKG (ftp://igs.bkg.bund.de/EUREF/products) and EPN (ftp.epncb.oma.be/epncb/product/clusters).

Fig. 10. EPN stations providing data processed at WUT EUREF LAC (14 March 2017) (http://www.epncb.oma.be/)

3.3. Data processing at MUT LAC

The Military University of Technology in Warsaw (MUT) LAC Analysis Centre operates since December 2009 (Krynski and Rogowski, 2016). It contributes to EUREF with final (daily and weekly) solutions. At the end of 2016 MUT AC processed data from 141 EPN stations (Fig. 11) using Bernese GNSS Software v.5.2.

Fig. 11. EPN stations providing data processed at MUT EUREF LAC (14 March 2017) (http://www.epncb.oma.be/)

In 2016 MUT AC has completed the research on the impact of using different sources of the GPS antenna phase centre correction to the GPS analysis products (position and tropospheric delay). In the framework of second campaign of “EPN reprocessing” two sets of station position time series were developed. The re-analysis was done using two different approaches with the GPS analysis software GAMIT v.10.50. Data from all EPN stations starting from January 1996 until the end of 2014 were analysed (Araszkiewicz and Völksen, 2016). It has been confirmed that the use of individual calibration at reference stations does not affect significantly the current EPN frame. Therefore, there is no need to exclude such stations from those used to align the EPN to the current ITRS realisation. More noticeable impact is observed on the coordinate time series. The mean change in the coordinates is below 2 mm in horizontal component and below 4 mm in vertical component. Much less impact is visible in the zenith total/tropospheric delay (ZTD) and can be neglected (Pacione et at., 2016). Analysis of the size of shifts related to antenna changing show that if the individual calibrations are used then horizontal components are slightly improved, while the heights are degraded.

3.4. Activities of MUT and WUT EPN Combination Centre

In 2016, the EPN Analysis Combination Centre (ACC) continued to combine GNSS coordinate solutions provided in SINEX format by 16 EPN Analysis Centres into official EPN solutions. In the beginning of 2016, the ACC elaborated new reports on final weekly and daily combinations and created new scripts for checking the correctness of receiver/antenna information given in AC SINEX files (stations for which inconsistencies may have been found are automatically excluded from the combination). Since January 2016, the reports concerning weekly combinations are available and visualized on the EPN ACC website (www.epnacc.wat.edu.pl). The website contains, e.g. the total consistency of station positions between contributing weekly solutions and the reports of individual EPN Analysis Centres (see EPN LAC mail #2014).

At the end of 2016, a methodology for creating weekly combined EPN solutions was changed. Up to and including week 1924, the weekly combined solutions were created directly from the AC weekly solutions. Since week 1925 (27 November–4 December 2016), the daily AC solutions are used for that purpose; at first the daily AC solutions are combined for each day of the week, and then the seven daily combined solutions are stacked into a weekly solution. It has been verified that the new approach allows more consistently handle position outliers at a daily level (for both AC and combined solutions), and that it helps to mitigate possible inconsistencies between AC solutions which could be observed when combining at a weekly level. The weekly and daily analysis reports and the ACC webpage were further updated at the end of 2016 to reflect the changes in the combination strategy for creating weekly solutions.

In 2016, the ACC was also involved in the activities of the Working Group “EPN Reprocessing”. In the beginning of 2016 the EPN-

Repro2 reprocessing was completed. The ACC combined daily and weekly solutions computed by 5 EPN ACs for the period 1996-2013.

3.5. Validation of GNSS orbits using SLR

All satellites of new GNSS systems, i.e., GLONASS, Galileo, BeiDou, QZSS, and IRNSS, are equipped with the SLR-dedicated retro-reflectors which allow: (1) validation of GNSS microwave orbits, (2) identifying misbehaving satellites, (3) precise orbit determination using SLR-only data, (4) combinations of GNSS and SLR solutions using co-locations in space, i.e. onboard GNSS spacecraft, (5) determination of Earth rotation parameters and SLR station coordinates using SLR observations to GNSS satellites. At the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences (WUELS), the SLR observations are used for the validation of final IGS orbits, as well as for the validation of real-time streamed orbits, which are typically used for the Precise Point Positioning (PPP). Centre National d'Études Spatiales (CNES) is the only GNSS analysis centre which provides the real-time orbit and clock corrections for GPS, GLONASS, Galileo, BeiDou and QZSS systems. Using SLR allows for the assessment of the real-time products, whose quality is of crucial importance for the multi-GNSS users, because the quality of broadcasted orbits and clocks influences directly the quality of estimated positions in PPP. Figure 12 shows the results of the SLR validation of GLONASS (red), Galileo (blue) and BeiDou (yellow) real-time orbits with a distinction between different orbital planes (Kaźmierski et al., 2017).

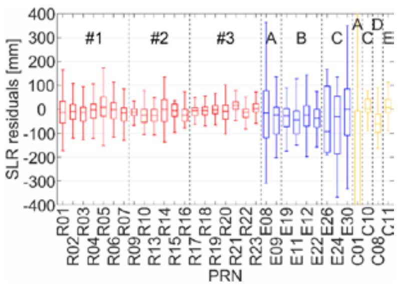


Fig. 12. Validation of real-time CNES orbits using SLR observations with a distinction between different orbital planes for GLONASS (red), Galileo (blue) and BeiDou (yellow)

GLONASS orbital planes #2 and #3 are characterized by the highest quality, due to the fact that the Sun elevation angle above the orbital planes #2 and #3 was highest in the considered period, and thus, modelling the impact of direct solar radiation pressure was not complicated. GLONASS plane #1 and Galileo plane C contain eclipsing satellites, thus, their orbit quality is inferior. The BeiDou geostationary satellite(A) is characterized by the lowest quality due to a deep 1:1 orbital resonance with the Earth rotation. BeiDou geosynchronous inclined (C and D) and BeiDou MEO satellites (E) are characterized by a comparable quality of the orbits (Fig. 12).

Furthermore, the SLR observations are used for the validation of the solar radiation pressure models. Figure 13 illustrates a comparison between the Galileo orbits provided by the Center for Orbit Determination in Europe (CODE), which are generated using two different orbit models: (1) the classical Empirical CODE Orbit Model (ECOM1), which was originally designed for GPS satellites, and the extended ECOM2 model, which was designed for new GNSS, such as GLONASS and Galileo.

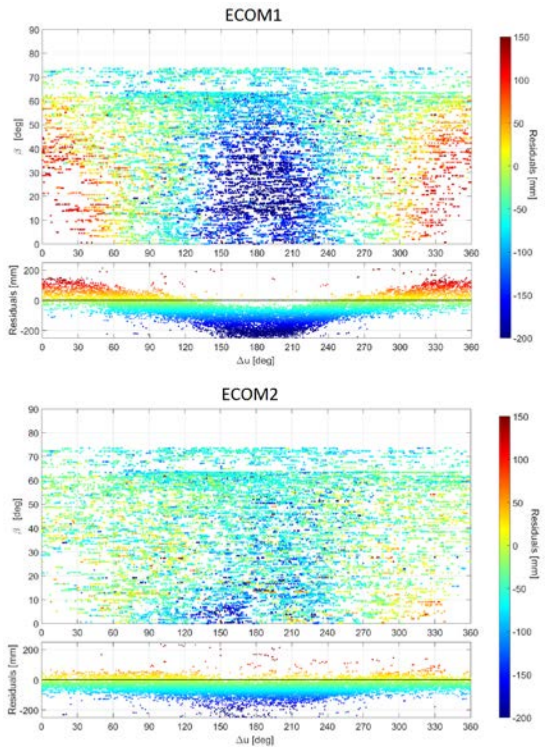


Fig. 13. Results from the validation of final CODE Galileo orbits using the classical ECOM1 model (top) and the extended ECOM2 model (bottom) using SLR data from 2014 (Sośnica et al., 2016)

Figure 13 clearly shows that using the incorrect orbit models leads to many systematic effects associated with the wrongly estimated satellite positions with the errors reaching up to 200 mm. These systematics cannot be directly recognized using the microwave GNSS observations, whereas using SLR data allows for easy assessment of the quality of GNSS and for identification all systematic orbit errors. Most of the systematic effects are substantially reduced, as soon as the extended ECOM2 model is employed (Fig. 2, bottom).

The current activities at WUELS are concentrated around launching the on-line web service for the validation of GNSS orbits using SLR data. The web service will allow a wide spectrum of analyses, such as the assessment of SLR data quality provided by different SLR stations equipped with kHz and Hz laser systems and different detector types, as well as the assessment of the orbit quality for different GNSS systems and satellites of different types and generations distributed over different orbital planes. The web service will constitute a part of the existing website: http://www.igig.up.wroc.pl/igg/.

Additional WUELS activities include the analysis of the minimum number of SLR observations, SLR stations and the geometry of SLR observations that is needed for the precise orbit determination of new GNSS satellites using the SLR-only data and the comparison between the SLR-based and microwave-based GNSS orbits (Bury, 2017).

3.6. Other EPN and IGS activities

GNSS for meteorology

Research on integrated precipitable water (IPW), i.e. columnar water vapour as climatologic and aerologic parameter, was continued in 2016 in the Warsaw University of Technology. The seasonal model of IPW change has been adjusted to the multi-year series by the least squares method. In case of Astrogeodetic Observatory in Józefosław 15 year series yields IPW trend of +0.25 mm/year (Fig. 14). It is probably a signal of global climate change (Brzeziński et al., 2016a).

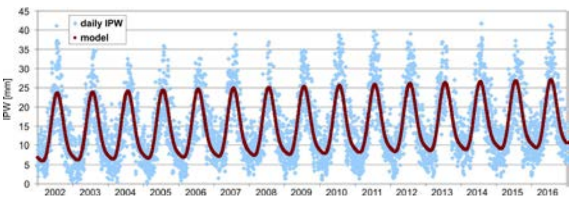


Fig. 14. IPW for JOZE (Jozefoslaw, Poland) and a model with 2 oscillations (annual and semi-annual) for 2003-2015 period, IGS tropospheric solution

Differences between tropospheric delay estimates for two permanent GNSS stations JOZE – located on the ground pillar – and JOZ2 – located on the roof of the building of the Astrogeodetic Observatory in Jozefoslaw were calculated. As JOZE is located 10 m lower, tropospheric delay estimates for those stations differ on average by about 6.5 mm (2.2 mm RMS). Those differences monitored for many years show some seasonal changes. For some periods in winter the difference even doubles, e.g. in the second half of January 2014 (Fig. 15). This is probably caused by snow covering the flat antenna of JOZE point, whereas JOZ2 has choke ring antenna with dome.

The results of two reprocessing campaigns Repro1 and Repro2 were compared (Fig. 16) in MUT to investigate the impact of the processing strategy on the long-term changes of the ZTD (Baldysz et al., 2016).

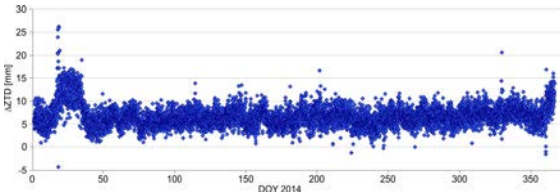


Fig. 15. Difference between tropospheric delay estimates for JOZE (pillar) and JOZ2 (on the roof) for 2014, WUT AC standard tropospheric solution

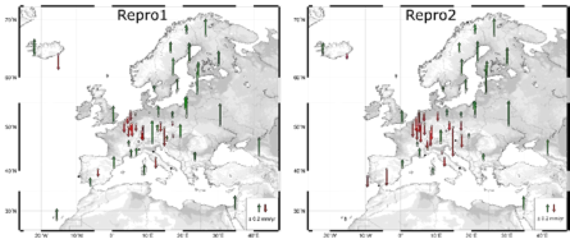


Fig. 16. ZTD trend for 16-year time series (01.1998-12.2013) obtained from the Repro1 (left) and the Repro2 (right) campaigns

Linear trends estimated from both campaigns are similar in terms of their character and spatial distribution. Differences observed (Fig. 17) are due to the use of different mapping functions (NMF and VMF1), softwares (Bernese v.5.0 and GAMIT v.10.50), elevation masks (3° and 5°), antenna calibration (absolute with individual and only absolute), ionosphere modelling (only 1st order effects and 1st, 2nd, and 3rd order effects) or applied additionally tidal and non-tidal atmospheric loadings (sourced from ECMWF and NCEP in Repro2).

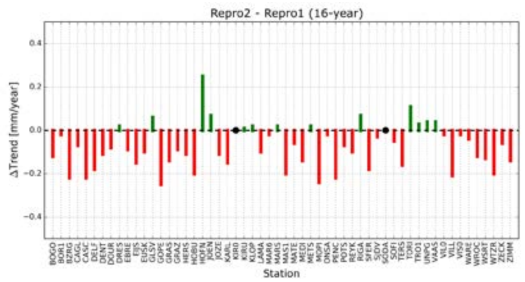


Fig. 17. Differences between the values of the linear trends in 16-year time series obtained from the Repro2 and Repro1 campaigns

Studies on the improvement of the processing strategy to reprocess GNSS data for meteorology and climatology, in particular for analysis of trends and variability of Zenith Total Delay (ZTD) and Integrated Water Vapour (IWV), were carried out at University of Warmia and Mazury in Olsztyn (Stepniak and Bock, 2016). Though GNSS data processing has been significantly improved over years regarding troposphere modelling including mapping functions and horizontal gradients models, ionosphere mitigation, satellite and receiver antenna offsets and variations, GNSS orbit determination, etc., it is still commonly observed that tropospheric parameters (ZTD and horizontal gradients) contain many outliers. Detection and removal of these outliers in GNSS time series is an important step before their use in meteorology and climatology.

The results of studies carried out for Polish permanent network – ASG-EUPOS show that outliers in double difference processing are often caused by defects in the baseline strategy (Stepniak et al., 2016a). It is shown that many outliers are due to data gaps at reference stations which cause disconnections of clusters of stations from the reference network. These outliers are common-mode biases due to the strong correlation between stations in short baselines. They can reach a few centimetres in ZTD and can be detected by a jump in formal errors. The magnitude and sign of the bias is impossible to predict, because it depends on different errors in the observations and on the geometry of the baselines.

A new baselines design strategy optimized for ZTD estimations from national networks, which reduces the number of outliers, was therefore developed (Stepniak et al., 2016b). The new strategy ensures that no station is disconnected from the main network and all clusters include long baselines which are necessary to estimate absolute tropospheric parameters. The reprocessed ZTD time series are much more continuous and homogeneous in comparison to the standard strategies (Fig. 18).

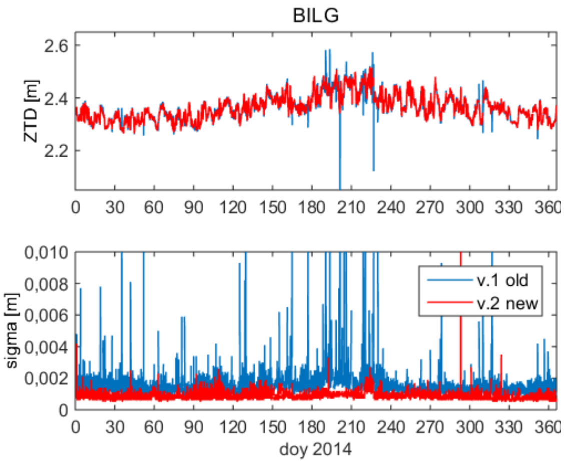


Fig. 18. Time series of ZTD and formal error of ZTD for station BILG, standard/old (blue line) and new (red line) strategies. Most spikes present in the standard solution are avoided with the new strategy

However, even when an optimum processing procedure is used, some outliers in the ZTD series still remain (e.g. due to short data gaps). Therefore, a post-processing screening procedure consisting of the removal of the first and the last ZTD estimates around observations gaps, range and outlier check of ZTD and formal errors was adjusted and applied to remove these bad values. The new-developed strategy together with screening procedure help to improve significantly the quality of GNSS tropospheric parameters estimated in national and regional networks for meteorology and climatology.

Monitoring ionosphere and ionospheric storms

A new method for accurate regional ionospheric TEC modelling based on processing of GPS carrier phase data and TEC interpolation with least squares collocation (LSC) was developed at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn (IG/UWM). The new approach uses solely carrier phase multi-GNSS observables and selection of different TEC interpolation methods, e.g., thin plate splines (TPS) and least squares collocation (LSC) or accurate TEC representation. TPS is a closed solution of a variational problem minimizing both the sum of squared second derivatives of a smoothing function and the deviation between data points and this function. This approach allows for generation TEC maps for Europe with high temporal and spatial resolution.

First, a single parameter of carrier phase bias lumping together the ambiguities and hardware delays is estimated for each continuous observation arc. The ionosphere is parametrized every 10–20 minutes using broad selection of different ionosphere parametrizing functions like spherical harmonics expansion, B-splines, general 2D polynomials, local 2D polynomials (Krypiak-Gregorczyk et al., 2014). Then, precise ionospheric delays are calculated at every observational epoch (e.g. 30 s) for each continuous observation arc. These delays are later converted to VTEC at the ionospheric pierce points (IPP) using the thin shell ionosphere approach. The estimated vertical TEC (VTEC) values at IPPs are then processed by parametrized TPS or LSC to obtain regular VTEC maps (grids). The model allows for providing ionospheric TEC maps with high spatial and temporal resolutions 0.2°×0.2° and 1 minute, respectively (Krypiak-Gregorczyk et al., 2016a; Wielgosz et al., 2016; Krypiak-Gregorczyk et al., 2017).

The performance of the approach developed (denoted UWM-rt1) was tested during one the most intense ionospheric storms of 24th Solar cycle that took place on 17 March 2015. The solution obtained was compared to IGS and UPC global and CODE regional maps, and also to Galileo's adaptation of the NeQuick model (Fig. 19). The results showed that the accuracy of UWM-rt1 maps was the highest among the tested models (Table 2) (Krypiak-Gregorczyk et al., 2016).

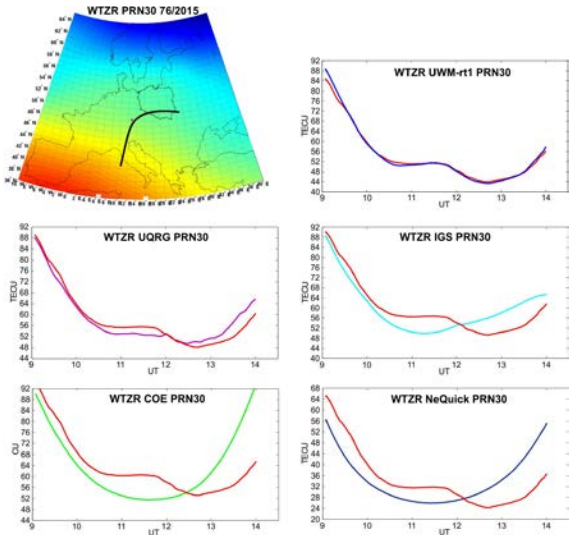


Fig. 19. Comparisons of VTEC for PRN30: red line represents fitted geometry-free (L4) observations, other colours represent different analysed models

Table 2. RMS of post fit residuals for the analysed TEC maps

DOY	UWM – rt1	UQRG	IGS	CODE	NeQuick
73	*0.84*	1.28	1.15	2.65	2.92
74	*0.87*	1.27	1.14	2.98	2.49
75	*0.97*	1.38	1.22	2.23	2.04
76	*1.09*	1.93	2.37	3.88	7.18
77	*0.39*	0.84	1.11	2.12	3.23
78	*0.38*	0.92	1.18	2.91	3.42
79	*0.33*	0.84	1.16	1.88	2.27

The team of the Faculty of Civil Engineering and Geodesy of MUT in Warsaw in collaboration with the team of the Department of Radiophysics of Geospace of the Institute of Radio Astronomy NAS of Ukraine in Kharkiv developed a new technique of the orthogonal projection of variations of electronic content of the ionosphere (OPVECI) for the mapping of TEC (Fig. 20) that allows visualization of the ionospheric irregularities (Zanimonskiy et al., 2016a).

As an example, in quiet geomagnetic activity (Kp = 0), Figure 20, left, shows a map of TID on 13 March 2013 at 08h50m. Profiles of TEC variations along the 52° parallel from 08h30m to 09h00m on 13 March 2013, as "waterfall" are presented in Figure 20, right. The modulation period was estimated as 170 km. Quasi-periodic perturbation moves to the east-northeast at a speed of 90 m/s.

The method was applied to generate TEC variations maps for the measurements of parameters of travelling ionospheric disturbances (TID's) using GPS observations data from several dense national-wide networks in Central Europe. Data from the following networks were used: ASG-EUPOS and SMARTNET (Poland), SAPOS (Germany), SKPOS (Slovakia), CZEPOS (Czech Republic), GNSSnet-HU (Hungary) and APOS (Austria) EPN stations (Nykiel et al., 2016).

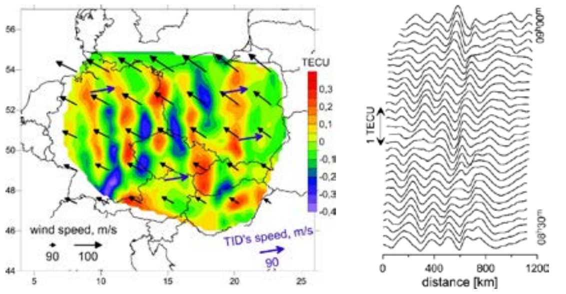


Fig. 20. Map of TEC variations over Central Europe on 13 March 2013 08h 50m (left) and profiles of TEC variations along the 50° parallel from 08h30m to 09h00m on 13 March 2013 (right)

TIDs were detected regularly, up to several times a day and are observed within time periods from a few tens of minutes to hours. The direction of the movement in most cases is opposite to the direction of the horizontal wind, calculated from HWM 07 model at the height of maximum of F2 ionospheric layer.

Maps obtained during strong (Kp = 8) geomagnetic storm at St. Patrick day, i.e. 17 March 2015 were analysed. Figure 21 shows some examples of such maps. Disturbances in the main phase of the storm, from 16h to 18h, were characterized by significant variations of TEC, two orders of magnitude larger than at quiet days.

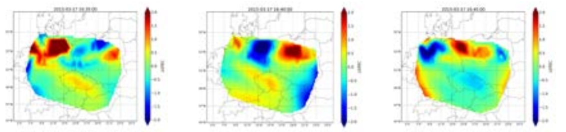


Fig. 21. Maps of TEC variations from 16h35m to 16h45m on 17 March 2015

Spatial structures apparently move with the speed, significantly greater then speed of sound at ionospheric altitudes. Thus, the effect of moving is most likely linked to the spatial and temporal changes in the flow of the ionizing agent, created surplus, compared with quite conditions concentration of electrons. Structures remained relatively stable for a maximum of units of minutes. Intensive disturbances are localized in latitudes range near 52°N-54°N as an eventual result of electrons precipitation from the Van Allen inner radiation belt partially destroyed during geomagnetic storm.

In the implemented approach, processing and analysis of GNSS data make it possible not only to map spatial heterogeneity of the ionosphere, but also to quantify their parameters over the dense regional networks on the regular basis. This technique can thus be used as cheap and convenient tool for TIDs monitoring. Close connection of TIDs parameters with characteristics of neutral winds in the case of its establishment and checking allows using monitoring data for evaluation and modelling of thermospheric winds. The presented results may be a starting point of new approach for diagnostic of the dynamic processes in the ionosphere and upper atmosphere (Zanimonskiy et al., 2016b).

4. Advanced methods for satellite positioning

The research group at the University of Warmia and Mazury in Olsztyn has carried out extensive studies in the field of algorithm and software development for precise GNSS positioning. Close attention was paid on several detailed scientific issues concerning integration of multi constellation signals in the precise point and relative positioning as well as mitigation of adverse influence of the ionospheric refraction.

Although there are recognized several strategies for integration of multi GNSS signals, still an open problem is the selection of the optimal method. The studies undertaken at the UWM were focused on the development, characterization and performance assessment of the integration strategies. The results presented in (Paziewski et al., 2016; Wielgosz and Paziewski, 2016; Paziewski and Wielgosz, 2017) indicated on high performance of both the loose and tight integration with calibrated receiver ISBs strategies (Fig. 22). These approaches have undeniable advantage over single system positioning in terms of reliability of the integer ambiguity resolution as well as rover coordinate repeatability.

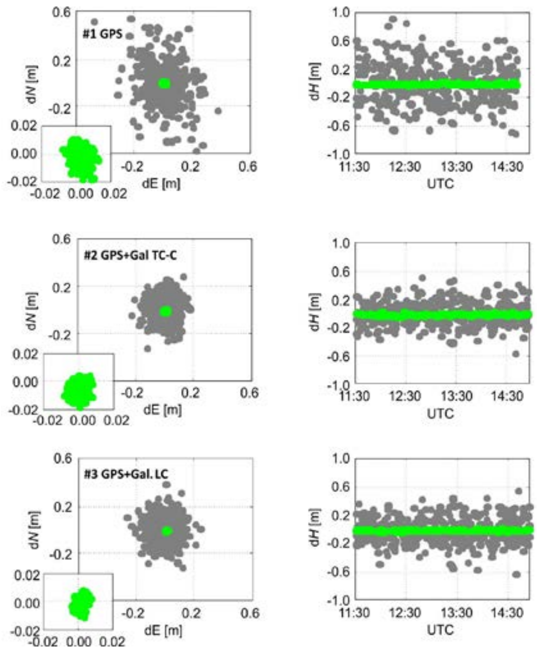


Fig. 22. Rover coordinate residuals for float (grey) and fixed (green) solutions (single GPS system – #1, GPS+Galileo tightly combined with calibrated ISB – #2, GPS+Galileo loose combined – #3)

The studies in the second area were related to the development of the original algorithm for mitigation of the influence of strong Total Electron Content (TEC) fluctuations in precise positioning (Sieradzki and Paziewski, 2016). The authors developed an algorithm mitigating the impact of dynamic temporal changes of electron content using the rate of TEC corrections. It consists of modifying the observations using the measured rate of TEC variations, and hence allows reducing the number of parameters to one ionospheric delay of a reference epoch per satellite and per session.

The Network RTK positioning mode and characterization of the properties of the ionospheric corrections during different state of the ionosphere were also investigated. The application of the ionosphere-weighted model with network-derived corrections was the subject of research. The impact of the accuracy of the network ionospheric corrections on time-to-fix in RTK-OTF positioning was investigated (Fig. 23) (Paziewski 2016). A clear coincidence of the ionospheric correction accuracy and time-to-fix in RTK-OTF was observed. During quiet and medium ionosphere periods, the mean TTFs were at a similar level for all scenarios and did not exceed 1.5 epochs. On the other hand, during disturbed periods an important lengthen of time required to obtain correct ambiguity fixing was observed.

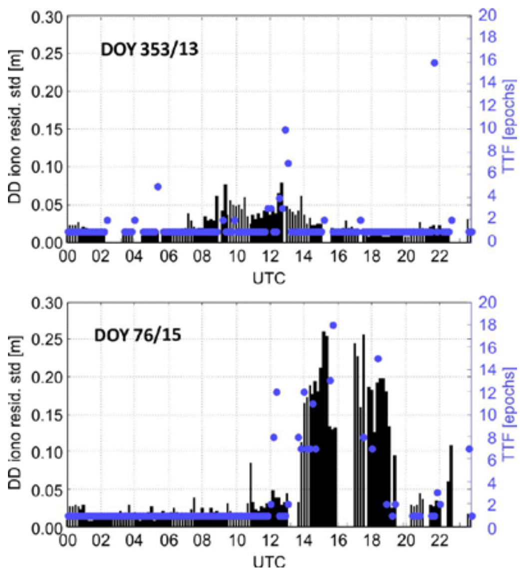


Fig. 23 Standard deviation of double differenced ionospheric correction residuals and time-to-fix at corresponding sessions in Network RTK positioning during days with different ionospheric activity (left panel medium, right panel high ionospheric activity)

An attempt has also been made to estimate the desirable accuracy of the ionospheric corrections, allowing for reliable instantaneous ambiguity resolution. The results indicated that in the multi-baseline medium-range RTK positioning, the network ionospheric correction residuals should not exceed ~1/3 of L1 wavelength for obtaining the successful single-epoch ambiguity resolution with high confidence level.

The existing network solution quality indicators, that reflect mostly the accuracy of the determination of network corrections, do not provide possibility of practical interpretation of their indications, understood as the usefulness of quality indexes to indicate epochs or the time periods, for which the expected reliability of precise positioning solution is low.

A new approach of the estimation of reliability of GNSS Network Real-Time Kinematic (RTK) positioning using two indices as quality indicators: solution accuracy and solution availability (Prochniewicz et al., 2017) was developed at the Warsaw University of Technology (WUT). These indexes utilize the existing parameters describing the reliability of the ambiguity resolution for the carrier-phase observations and the fixed solution error estimation and they are based on the Network-Based Stochastic Model (NBSM) (Prochniewicz et al., 2016) which takes into account the residual ionospheric and geometric errors. They depend solely on the variance-covariance observation matrix and the design matrices and they do not require current observations from the user's receiver which predestines them for use as external parameters describing the possible reliability of the Network RTK solution and greatly facilitates their application. The indexes were determined for the test field composed of a part of the regional ASG-EUPOS reference stations network and compared with the results of the instantaneous Network RTK positioning model solution as well as with the indices (I95, RIM, RIU) commonly applied to estimate the reliability of network positioning.

The proposed indices are much more effective (Fig. 24) and their interpretation enables a much easier identification of the periods for which the reliability of performance may be reduced. Their additional advantage is that they do not only depend on the residual errors, as the existing indices, but also on the number of satellites, applied method of ambiguity estimation and the observation measurement noise. Thus they take into account all the parameters affecting the quality of the positioning solution.

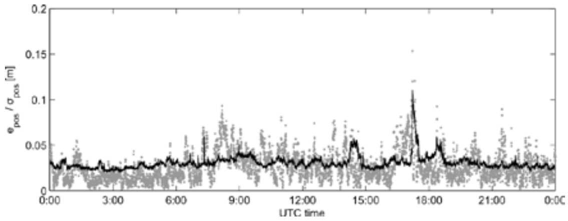


Fig. 24. Positioning accuracy of the fixed solution for the test baseline – instantaneous values of the accuracy index: black—estimated errors (1σ), gray—actual errors

5. ASG-EUPOS network

5.1. Status of the ASG-EUPOS network

At the end of 2016 the network of the ASG-EUPOS system consisted of 125 operating permanent reference stations (all of them track GPS and GLONASS; most of them track also Galileo satellites) (Fig. 25) (www.asgeupos.pl).

Fig. 25. Reference stations of the ASG-EUPOS system (31 December 2016)

A number of changes in the ASG-EUPOS system took place in 2016. 13 stations in northern and southern regions of Poland have been modernized (receiver and antenna have been replaced). 4 new RTN data streams were created to provide GPS+GLONASS Network RTK data for whole area of Poland. 2 new monitoring station in Dziwie and Holowno were established and launched (http://system.asgeupos.pl/MemberPages /PositionScatterPlot.aspx). An Internet application for automatic payments for ASG-EUPOS services has been launched in April 2017 available through https://pzgik.geoportal.gov.pl/imap/.

Since 12 July 2014 when all services in ASG-EUPOS system became fully payable the total number of users with activated subscriptions reached 5705. At the end of 2016 the number of active users for RTN, RTK and DGNSS services reached 3478 where the average number of users accessing the system every working day exceeds 1900.

In 2017 the modernization of ASG-EUPOS is to be continued and further replacement of the equipment on another 12 stations is planned. In the following years a software in the system management centres will be updated as well as new stations are to be established for tracking GPS, GLONASS and Galileo satellites and to provide RTN correction data from these systems for whole area of Poland.

6. Modelling precise geoid

Activities of the team of the Institute of Geodesy and Cartography (IGiK) on the improvement of precise quasigeoid model for Poland were continued. A new gravimetric quasigeoid model GDQM-PL16 was developed with the use of the new global geopotenitial model GECO which is the combination of GOCE data with the EGM2008. It has been evaluated using height anomalies at the stations of GNSS/levelling control traverse and the ASG-EUPOS network. The statistics of differences of height anomalies are given in Table 3.

Table 3. Statistics of differences between height anomalies obtained from GDQM-PL16 model and the respective ones at the stations of GNSS/levelling control traverse and the ASG-EUPOS network [m]

	Traverse 1st order	Traverse 2nd order	ASG-EUPOS
No of points	44	140	98
Min	0.064	0.038	0.044
Max	0.122	0.124	0.134
Mean	0.097	0.084	0.074
Std	**0.013**	**0.016**	**0.019**
Max-Min	0.058	0.086	0.090

7. The use of data from satellite gravity missions

Quality of the newest 15 global geopotential models developed in 2014-2016 with the use of data from satellite gravity missions was investigated in IGiK. They were evaluated in terms of height anomalies using GNSS/levelling data at ASG-EUPOS stations, and absolute gravity data at 168 stations of national gravity control. Standard deviations of differences of height anomalies $\sigma(\zeta)$ and gravity anomalies $\sigma(\Delta g)$ are given in Table 4.

Table 4. Statistics of the evaluation of GGMs investigated

GGM	$\sigma_{(\zeta)}$ [cm]	$\sigma_{(\Delta g)}$ [mGal]
Combined (d/o 2190)	2.2	1.7
GRACE (d/o 130)	3.8	1.8
GOCE, GRACE/GOCE no compensation (d/o 270)	16.0	9.8
GOCE, GRACE/GOCE with compensation (d/o 200)	3.4	1.8

The possibility of using monthly based time series of absolute gravity data for calibration/validation of temporal mass variations derived from satellite observations was discussed. Temporal gravity variations obtained from RL05 GRACE-based GGMs and from GOCE/GRACE-based GGMs were compared with the corresponding ones obtained from the time-series of absolute gravity measurements conducted with the A10-020 gravimeter at the Borowa Gora Geodetic-Geophysical Observatory (Fig. 25) (Godah et al., 2016a).

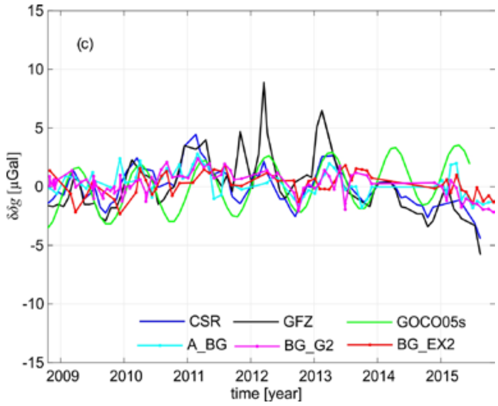


Fig. 25. Time series of gravity variations at the Borowa Gora Geodetic-Geophysical Observatory obtained from the CSR and GFZ RL05 GRACE-based GGMs, the GOCO05s and the smoothed/reduced gravity data obtained from the measurements with the A10-020 reduced and smoothed using the local hydrology and the moving average

The results of the comparison were analysed. They indicate that time series of gravity data from the measurements with the A10-020 gravimeter can be regarded as a valuable tool for the calibration/validation of the long term temporal gravity variations at Borowa Gora Geodetic-Geophysical Observatory.

The comparison between these GGMs and the Global Land Data Assimilation (GLDAS) hydrological models in terms of equivalent water thickness (Fig. 26) confirms the suitability of GRACE data to study the short term temporal mass variations over Poland (Godah et al., 2016b).

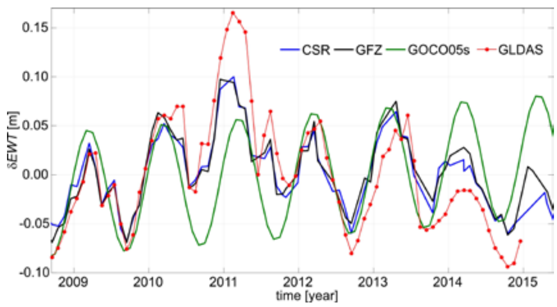


Fig. 26. Time series of δEWT at the Borowa Gora Geodetic-Geophysical Observatory obtained from the CSR and GFZ RL05 GRACE-based GGMs, the GOCO05s and GLDAS hydrological models

Temporal geoid height variations obtained from GGMs developed by GFZ on the basis of GRACE data were calculated for four 3° × 5° subareas in Poland (Fig. 27).

In the subareas investigated variations of geoid height from one epoch to the other can reach 10 mm while differences of geoid height variation between subareas reach 2 mm for the same epoch and 11 mm for different epochs (Fig. 28).

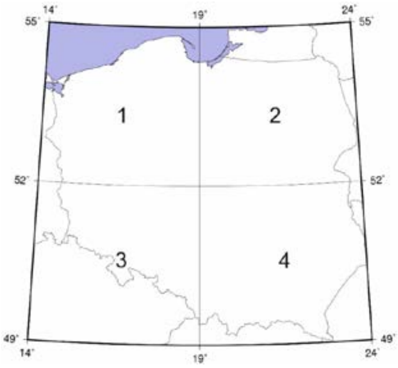


Fig. 27. Subareas in Poland for which geoid height variations were investigated

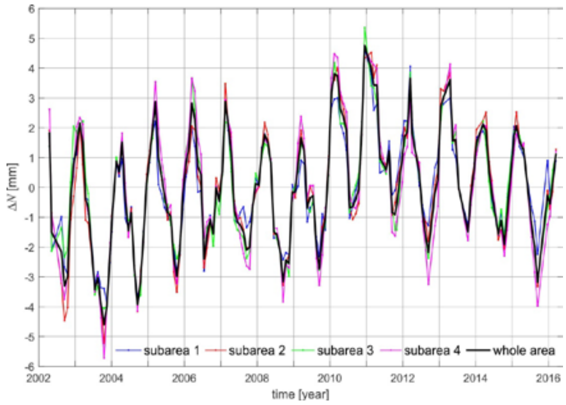


Fig. 28. Time series of geoid height variations in subareas investigated

The research on ground water level changes and water budget evaluation on the basis of GRACE data and a high resolution hydrological GLDAS data was conducted by the team of the University of Warmia and Mazury (Birylo et al., 2016; Rzepecka et al., 2017). Accuracy of water budget prediction using was investigated (Birylo et al., 2017).

The influence of land hydrosphere on polar motion excitation functions at seasonal time scales was investigated by the team of the Space Research Centre of the Polish Academy of Sciences. The Terrestrial Water Storage (TWS) changes determined from GLDAS hydrological model and CMIP5 Miroc5 and CMIP5 MPI climate models were compared with TWS changes derived from GRACE data (geopotential models from CSR, GFZ and JPL centres) (Nastula et al., 2016). Then χ_1 and χ_2 components of hydrological-gravimetric excitation functions of polar motion were calculated from those models and compared with geodetic residuals in the parts of seasonal oscillations, non-seasonal oscillations as short term period, and long term period oscillations (Fig. 29).

None of the hydrological - gravimetric functions is fully compatible with the geodetic residuals. However, there is a good agreement between GRACE-based excitation functions and the geodetic residuals at the seasonal time scales.

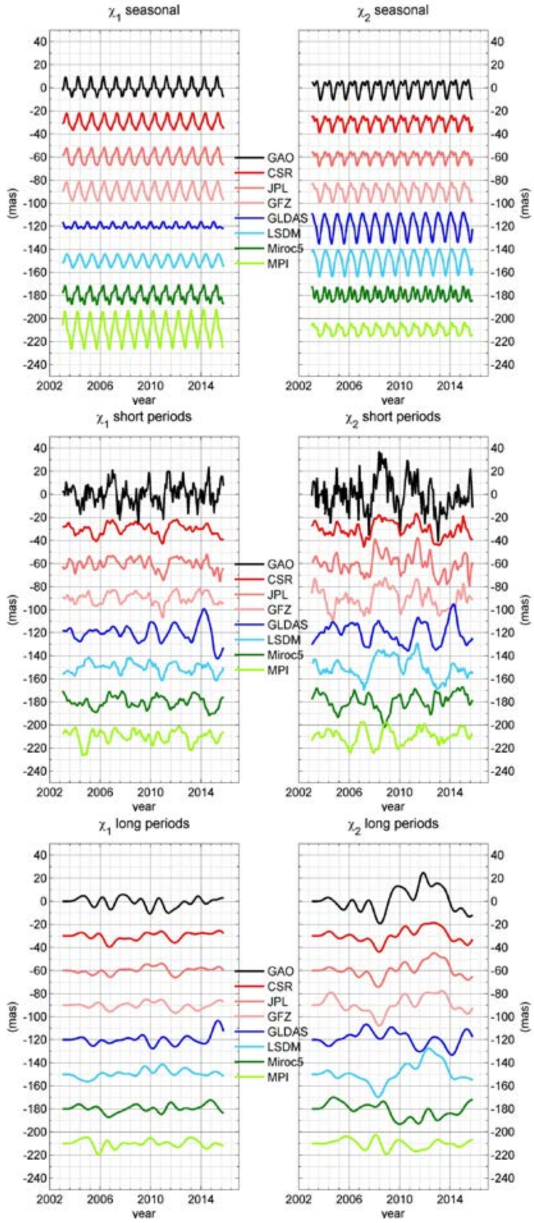


Fig. 29. Seasonal (a), short period (b), and long period (c) variations of χ_1 and χ_2 components of geodetic residuals (GAO) with gravimetric (CSR, JPL, GFZ) and hydrological (GLDAS, LSDM, MIROC, MPI) excitation functions

Differences among hydrological excitation functions computed from hydrological models are still considerable (Winska et al., 2016).

8. Monitoring gravity changes

Earth tides were continued to be monitored in 2016 at the Borowa Gora Observatory of IGiK with the LCR G1036 gravimeter equipped with the LRFB-300 feedback system (Fig. 28).

Gravity record from 2012-2016 acquired with the LCR G1036 gravimeter was processed using Fourier transform to determine its spectral characteristics (Fig. 29).

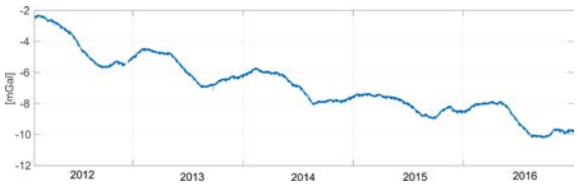


Fig. 28. Gravity record with LCR-G1036 gravimeter in Borowa Gora Observatory averaged in 1 hour window

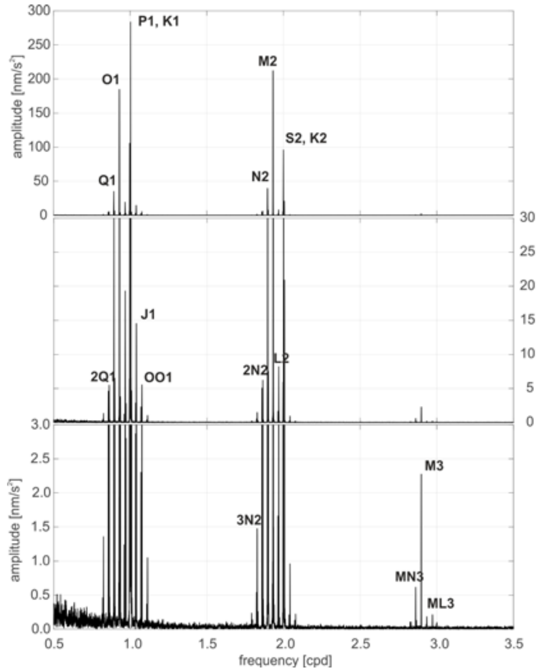


Fig. 29. Spectrum of the tidal signal

Further analysis of tidal data was conducted using the ETERNA 3.40 software. Parameters of the new local tidal model for Borowa Gora were determined. The residua of tidal adjustment obtained from the using the ANALYZE software, their power density spectrum and their histogram are given in Figure 30.

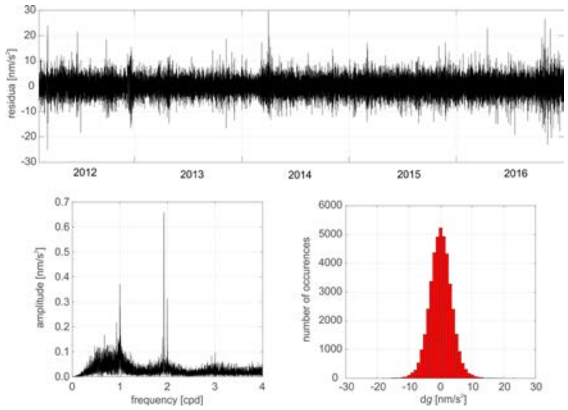


Fig. 30. Residua of tidal adjustment obtained from the using the ANALYZE software, their power density spectrum and their histogram

Since May 2016 a continuous gravity signal is collected by the iGrav-027 superconducting gravimeter at the Borowa Gora Geodetic-Geophysical Observatory with 1 second sampling rate. Recorded tidal variations of gravity are shown in Figure 31.

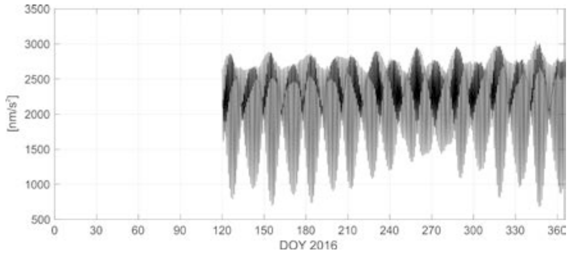


Fig. 31. Tidal record with the iGrav-027 gravimeter in 2016

9. Activity in Satellite Laser Ranging and their use

On 26 April 2016 the Satellite Laser Ranging station BORL at Borowiec of the Space Research Center of the Polish Academy of Sciences successfully completed quarantine procedure provided by International Laser Ranging Service Analysis Centers. All results of the station were released to the public after 1 February 2016 (Lejba et al., 2016). The quarantine bias report obtained from Joint Center for Earth System Technology/Goddard Space Flight Center (JCET/GSFC) NASA confirmed high quality of the observations of LAGEOS-1 and LAGEOS-2 provided by BORL station (Fig. 32). The mean Range Bias was 11.0 mm for L1 and 12.0 mm for L2, respectively.

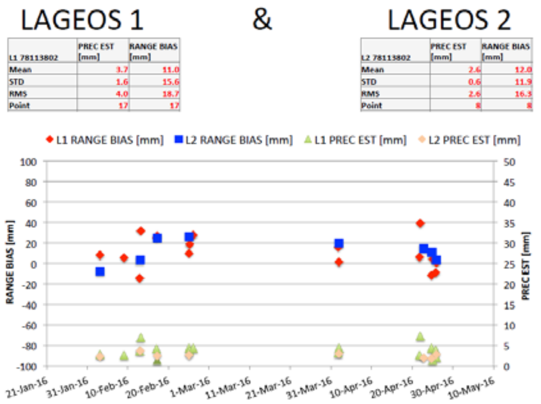
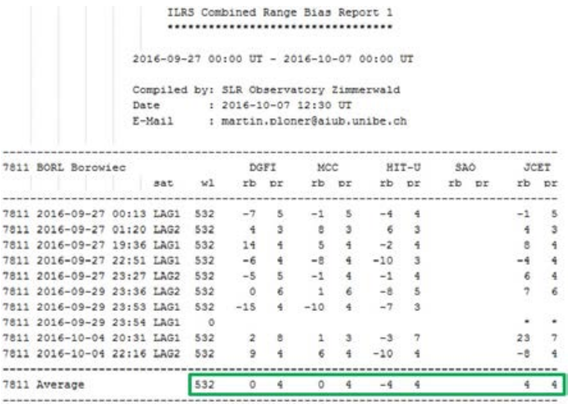


Fig. 32. JCET/GSFC quarantine BORL bias report obtained on 26 April 2016

In 2016 SRC Borowiec station tracked 32 satellites, 21 LEO and 11 MEO. An average RMS ranges from 1.19 to 5.54 cm (700 passes, 664 599 single good shots and 10 293 normal points). From all tracked satellites 8 were typical passive geodetic-geodynamic satellites (Ajisai, Etalon-2, Lageos-1, Lageos-2, Larets, Lares, Starlette and

Stella) which gave in total 385 passes, 442 135 single good shots and 4195 normal points. All results were sent to Crustal Dynamics Data Information System (CDDIS) and Eurolas Data Center (EDC). All results obtained by BORL station in 2016 are available at http://www.cbk.poznan.pl/ stacja_laserowa/ lista_obserwacji_2016.php.

In 2016 BORL has regularly received combined range bias reports (based on Lageos-1 and Lageos-2 observations) produced by several independent ILRS ACs from Germany, Russia, Japan and USA. A sample report showing and confirming high quality of the observations of LAGEOS-1 and LAGEOS-2 performed by BORL station is presented in Figure 33. The average observational range bias for both satellites is at the level of single millimetres.


ILRS Combined Range Bias Report 1

2016-09-27 00:00 UT - 2016-10-07 00:00 UT

Compiled by: SLR Observatory Zimmerwald
Date : 2016-10-07 12:30 UT
E-Mail : martin.ploner@aiub.unibe.ch

7811 BORL Borowiec				DGFI		MCC		HIT-U		SAO		JCET	
		sat	wl	rb	pr	rb	pr	rb	pr	rb	pr	rb	pr
7811	2016-09-27 00:13	LAG1	532	-7	5	-1	5	-4	4			-1	5
7811	2016-09-27 01:20	LAG2	532	4	3	8	3	6	3			4	3
7811	2016-09-27 19:36	LAG1	532	14	4	5	4	-2	4			8	4
7811	2016-09-27 22:51	LAG1	532	-6	4	-8	4	-10	3			-4	4
7811	2016-09-27 23:27	LAG2	532	-5	5	-1	4	-1	4			6	4
7811	2016-09-29 23:36	LAG2	532	0	6	1	6	-8	5			7	6
7811	2016-09-29 23:53	LAG1	532	-15	4	-10	4	-7	3				
7811	2016-09-29 23:54	LAG1	0									*	*
7811	2016-10-04 20:31	LAG1	532	2	8	1	3	-3	7			23	7
7811	2016-10-04 22:16	LAG2	532	9	4	6	4	-10	4			-8	4
7811 Average			532	0	4	0	4	-4	4			4	4

Fig. 33. Range bias report for SRC Borowiec laser station, 7 October 2016

In 2016, SRC BORL station launched regular tracking of space debris objects (inactive satellites and rocket bodies) in the frame of Space Debris Study Group (SDSG) of ILRS. A total of 151 space debris passes were observed with the average RMS ranging from 1.49 to 75.33 cm (151 passes, 137 836 single good shots and 2528 normal points). All results were sent to SDSG data bank. The laser measurements from SRC BORL station (Kucharski et al., 2017) supports global research in satellite and space debris rotation determination of TOPEX/Poseidon, which is essential for an improvement of the theory of motion of artificial satellites.

Second independent laser system, fully dedicated for Space Surveillance and Tracking programme, developed by European Space Agency and European Commission is under construction at SRC Borowiec. The new system will based on azimuth-elevation mount with 65 cm Cassegrain transmitting/receiving telescope and 20 cm Maksutov guiding telescope equipped with new servo drives providing tracking accuracy below 1 arcsec. The whole system will be controlled by multiplatform steering/tracking software (under development) supporting space debris prediction, real-time laser observations, system calibration, ADSB monitoring, data post-processing and other functions. The system will operate 24 hours a day, 7 days a week.

10. Geodynamics

IGiK, WAT and WUELS, integrated into the GGOS-PL network, together with the Institute of Geophysics of the Polish Academy of Sciences and with some other institutions made further progress towards establishing a common geodynamics research in the framework of the European Plate Observing System Programme (EPOS). EPOS–PL project – the Polish Earth science infrastructure integrated with the EPOS programme started at the end of 2016 (Bosy et al., 2016).

Research on the developing the integrated system of surface deformation monitoring caused by man-made factors, based on Persistent Scatterer Interferometry, measurements from permanent GNSS stations and precise levelling has been continued in IGiK in cooperation with two other institutions (Ziolkowski et al., 2016). Height changes of GNSS stations from the solutions of short vectors and PSI measurements were investigated. Relative deformations in height component between GNSS stations obtained from GNSS (weekly solutions) and PSI (average) data were compared (e.g. Fig. 34)

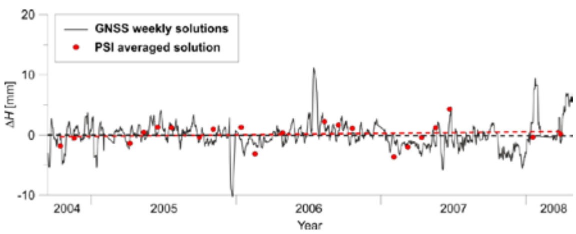


Fig. 34. Comparison of relative deformations in height component between Borowa Gora and Jozefoslaw obtained from GNSS (weekly solutions) and PSI (average) data

It has been shown that the use of mutually complementing observation techniques for monitoring deformations in the investigated area, such as GNSS and PSI, can substantially increase reliability of the interpretation of the results obtained. Common use of both techniques allows in the variations considered as noise observation to extract the signal of height changes that is below the limit of measurement error. Simultaneously, the analysis of results of two completely independent observation techniques leads to the increase of reliability of results obtained using each of these methods (Zak et al., 2016).

The analysis of time series of permanent GNSS stations coordinates to achieve the most reliable possible velocities for geodynamical studies was continued by the team of the Military University of

Technology (Bogusz et al., 2016b). This activity includes a research on the periodicity and common structures in the stochastic part of the time series.

Gruszczynska et al. (2016) used time series of Precise Point Positioning (PPP) daily solutions for 18 Central European stations determined by the Jet Propulsion Laboratory (JPL) with the GIPSY-OASIS software. Two approaches: Least-Squares Estimation and Singular Spectrum Analysis were tested to estimate the seasonal signal. Contribution of annual and semi-annual signal was estimated for 18 stations investigated (Fig. 35).

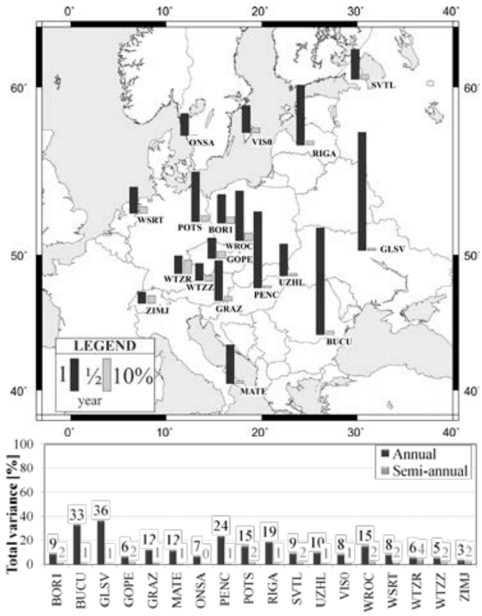


Fig. 35. Contribution of annual (black bars) "1" and semi-annual signals (grey bars) "½" in the height time series in terms of a percentage of total variance; "10%" refers to height of the reference rectangle meaning a percentage of a total variance

Klos et al. (2016) employed data from 42 European IGS stations processed at the EPN Local Analysis Centre MUT to analyse spectral indices and power-law noise amplitudes. The stochastic part determined is the coloured noise between white and flicker noise. The amplitudes range from 3 to 6 mm/year-κ/4 for horizontal components and from 6 to 15 mm/year-κ/4 for vertical component (Fig. 36)

Bogusz et al. (2016a) investigated the stochastic part of GPS-derived topocentric coordinates changes. It usually exhibits a relatively high autocorrelation with focusing on a self-similarity. The residuals of daily topocentric coordinate changes of more than 130 ASG-EUPOS (Active Geodetic Network EUPOS) stations from Poland over 5 years were analysed by means of the Rescaled Range method with the Hurst parameter and the Detrended Fluctuation Analysis with the scaling exponent α. The analysis was followed by noise investigation with a Maximum Likelihood Estimation. It has been found that by omitting the noise amplitude data, the long-range dependence methods led to an underestimation of H values and their misinterpretation what can cause wrong conclusions (Fig. 37).

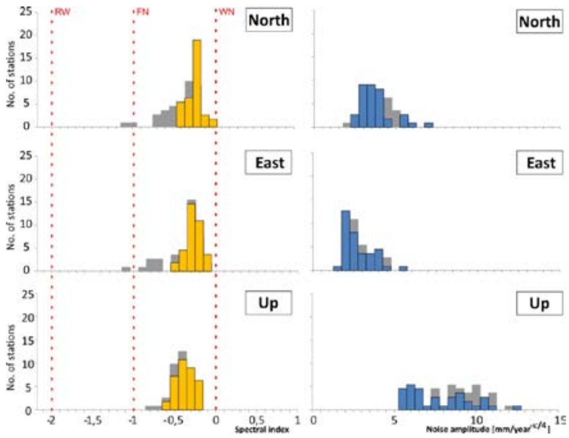


Fig. 36. The histograms for spectral indices (left) and power-law noise amplitudes (right) for topocentric components North, East and Up (from the top) [mm/year-κ/4]; the integer spectral indices: -2, -1 and 0, marked in red, represent random-walk (RW), flicker noise (FN) and white noise (WN); the spectral indices and noise amplitudes marked yellow and blue represent the stochastic part after spatio-temporal filtering, while grey represents the noise parameters before stacking

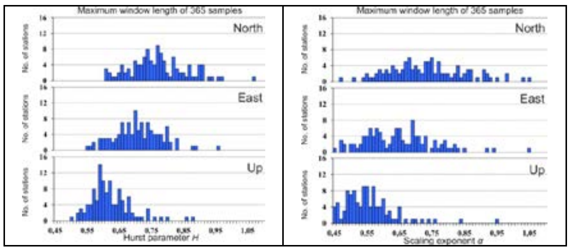


Fig. 37. The Hurst parameter *H* (left) and the scaling exponent *α* (right) estimated for the North, East and Up components for all ASG-EUPOS stations

Gruszczynski et al. (2016) investigated the necessity of spatio-temporal filtering of time series for the determination of highly reliable velocities of permanent stations for plate motion or earthquakes studies or for the maintenance of kinematic reference frames. The PPP solutions processed at JPL by GIPSY-OASIS software were examined using the Principal Component Analysis (PCA) assuming the existence of a non-uniform spatial response in the network to the CME (Common Mode Error). One of the most important consequences related to spatio-temporal filtering of GNSS time series is the improvement of the accuracy about 70% at average, comparing to the after-filtration accuracy of determined velocity (Fig. 38).

The team of the Warsaw University of Technology was continuing geodynamic investigations Pieniny Klippen Belt, in Southern

Poland. Horizontal displacements in the area investigated were determined on the basis of GNSS data as well as gravity changes obtained from absolute gravity measurements in 2004-2015 (Walo et al., 2016).

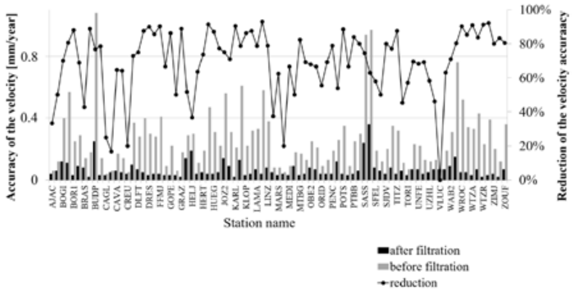


Fig. 38. Reduction of velocity accuracy resulting from the use of the PCA-based method of spatio-temporal filtering; bars refer to the left side axis and show the accuracy of the velocity computed before the subtraction of CME (gray) and after filtration (black); the line refers to the right side axis and exhibits the relative reduction of accuracy resulting from spatio-temporal filtering

Predictions of *x*, *y* pole coordinates data, UT1-UTC data and precession-nutation extrapolation model are needed to compute real time transformation between the celestial and terrestrial reference frames. Pole coordinates data predictions are computed each day in the IERS by the combination of the least-squares (LS) extrapolation and autoregressive (AR) prediction models (LS+AR). The differences between pole coordinates data and their LS+AR predictions increase with prediction length and depend mostly on starting prediction epochs. To check such differences the time series of them for 2, 4 and 8 weeks in the future were analysed using time-frequency amplitude spectra. Such spectra of these differences computed by the Fourier transform band pass filter are very similar and show some power in the frequency band corresponding to the prograde Chandler and annual oscillations (Brzezinski et al. 2016b). It shows that the increase of prediction errors is partly caused by mismodelling of these oscillations by the LS extrapolation model. The highest maxima in these time frequency amplitude spectra correspond to years: 2006, beginning of 2007 and from 2011 to beginning of 2012 where the prediction errors of pole coordinates data attained the biggest values. Using the normalized Morlet wavelet transform it is possible to compute instant amplitudes as a function of periods in such differences between pole coordinates data and their LS+AR predictions (Fig. 39). These amplitudes are big for the residual Chandler and annual oscillations, however in the high frequency band there is a remaining signal corresponding to chaotic variations with periods less than about 200 days. Such short period oscillations are very irregular thus these are main causes of errors in short term polar motion predictions.

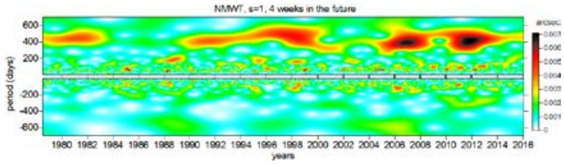


Fig. 39. The Normalized Morlet wavelet transform amplitudes as a function of periods T ($\sigma = 1$) of the differences between the *x-iy* pole coordinates data and their LS+AR predictions at 4 weeks in the future

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