National Report of Poland to EUREF 2016

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1. Introduction

Since 2014 the main geodetic activities at the national level in Poland concentrated on maintenance of gravity control and magnetic 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 of gravity changes, geodynamics, activity in satellite laser ranging and their use.

2. Current status of reference frames in Poland

Research activities concerning reference frames and reference networks performed in Poland in a period of 2011–2014, i.e. implementation of IUGG2011 and IAU2012 resolutions on reference systems, implementation of the ETRS89 in Poland, operational work of permanent IGS/EUREF stations in Poland, operational work of ILRS laser ranging station in Poland, active GNSS station networks in Poland, maintenance of vertical control in Poland, maintenance and modernization of gravity control, and maintenance of magnetic control in Poland were summarised (Bosy and Krynski, 2015).

2.1. Horizontal

No activities in 2015.

2.2. Vertical

Gravity potential difference ΔW between the Kronstadt86 local vertical datum in Poland and the global vertical datum was determined by the team of the University of Warmia and Mazury (Lyszkowicz et al.,2015b). It was a revised version of previous computations (Lyszkowicz et al., 2015a) by taking into account the influence of vertical movements of Earth' crust, and unification of the tide systems in satellite and levelling networks. Ellipsoidal heights from GNSS data, normal heights obtained from the levelling campaign and height anomalies computed from the EGM2008 geopotential model were used. Computed value of potential difference between the local and global vertical datum vary from 0.158 m^2s^{-2} to 0.606 m^2s^{-2} which corresponds to 2 cm and 6 cm, respectively. The results indicate that there are still unexpected differences in the estimated value of the parameter ΔW, computed from three different satellite networks: POLREF, EUVN-DA and ASG-EUPOS.

2.3. Gravity

Research activities concerning gravity field modelling and gravimetric works performed in Poland in the period of 2011–2014, i.e. geoid modelling in Poland and other countries, 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 in Poland and overseas, metrological aspects in gravimetry, maintenance of gravimetric calibration baselines, and investigations of the non-tidal gravity changes were summarised (Krynski, 2015).

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).

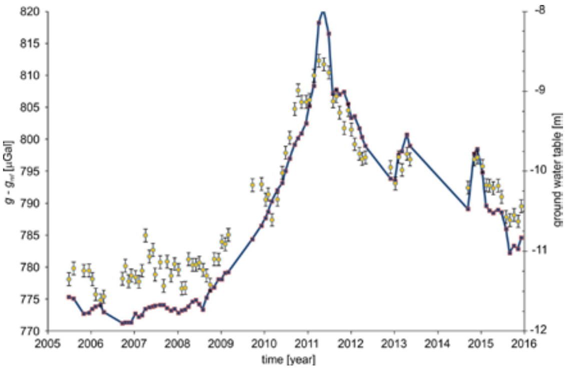

Fig. 1. Absolute gravity surveyed with the FG5-230 at Jozefoslaw (100 cm height) (g_{ref} = 981213000 μGal)

Gravimetric investigations at 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 of the Borowa Gora Geodetic-Geophysical Observatory conducted on monthly basis with the A10-020 gravimeter since September 2008 (Fig. 2) shows high quality of A10 data.

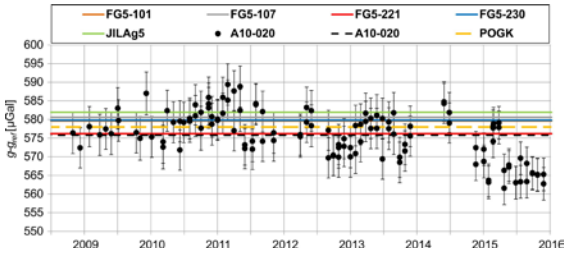

Fig. 2. Absolute gravity surveyed with the A10-020 at Borowa Gora (pillar level) (g_{ref} = 981125000 μGal)

Regular monthly measurements were performed on three stations at Borowa Gora Observatory (e.g. Fig. 2) during the course of the project concerning the establishment of gravity control, following the same methodology as applied on PBOG14 stations. They were used for quality assessment of the A10-020 absolute gravimeter during the course of the project. The standard deviation of these determinations equals 5.8 μGal. This value was further used as a component of the Total Uncertainty value for PBOG stations (Dykowski et al., 2015b).

Although free of common relative measurement errors (e.g. instrumental drift) and effects of network adjustment, absolute gravity determinations for the establishment of gravity control require advanced corrections due to time dependent factors, i.e. tidal and ocean loading corrections, atmospheric corrections and hydrological corrections. Time dependent corrections to absolute gravity determinations in the establishment of modern gravity control were investigated in IGiK. Figure 3 (blue dots) presents the hydrological correction (monthly solutions) with respect to the absolute gravity data obtained from GLDAS model.

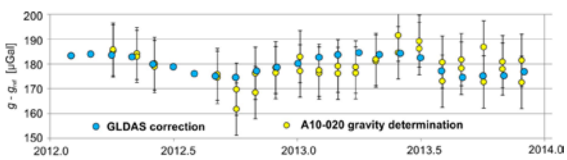

Fig. 3. Regular monthly absolute determinations of gravity on field station at Borowa Gora Observatory with respect to GLDAS hydrological model correction (g_{ref} = 981 250 000 μGal)

Estimated correlation of 0.58 is significant enough to state that the A10-020 gravimeter is sensitive to large scale hydrological variations. The results obtained showed that for detailed analysis of the results on the PBOG14 the GLDAS hydrological model correction should be taken into consideration (Dykowski et al., 2015b).

Services and software currently available provide accurate corrections for atmospheric (based on digital weather models, e.g. ECMWF) and hydrological (based on hydrological models, e.g. GLDAS/Noah) gravitational and loading effects. For the area of Poland the atmospheric correction based on weather models can differ from standard atmospheric correction by even ±2 μGal. The hydrological model shows the annual variability of ±8 μGal. The use of standard tidal parameters in comparison to local tidal model (based on tidal observations) shows further discrepancies especially when applied to the A10-020 gravimeter measurement methodology. Local tidal model determined in Borowa Gora Observatory shows differences up to ±2.5 μGal when compared to the model used for absolute gravity determinations. Overall the sum of atmospheric and hydrological effects and tidal model uncertainty easily exceeds the Total Uncertainty of the A10-020 gravimeter which makes these effects vital for current and future absolute gravity determinations for the needs of gravity control.

The variability of the atmospheric, hydrological and tidal corrections based on selected models for the area of Poland, especially for the time period of the survey of base stations of the gravity control in Poland in 2012 and 2013 was investigated. The discrepancies between simplified corrections and the advanced ones show the importance of the use of advanced corrections. The time series of 5 years of absolute gravity determinations with the A10-020 gravimeter on laboratory and field stations in Borowa Gora Observatory test network has been analyzed to assess the observed variation of gravity with the use of advanced correction models. Also gravity measured on a few PBOG14 stations have been measured in two epochs, which allowed to examine the obtained gravity difference. Analysis of the A10-020 data includes metrological calibrations as well as traceability to the ICAG and ECAG campaigns (Dykowski and Krynski, 2015).

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) and water table level variation. Sensitivity of the A10 absolute gravimeter to the variation of local hydrological conditions were investigated. First results obtained indicate that the sensitivity of the A10-020 gravimeter allows to detect small local hydrological changes. They also show that

GLDAS/Noah hydrological model is efficient for hydrological variations analysis (Dykowski et al., 2015a).

Activities towards the realization of the project on modernization of the Polish gravity control were continued. Complementary surveys at base stations of the new gravity control have been conducted by IGiK (Krynski et al., 2015). They consist of absolute gravity measurements with the A10-020 gravimeter at 6 basic points and relative gravity measurements at 1 basic point. In addition on each gravity control station a vertical gravity gradient was determined with at least 2 static gravimeters. The gravimetric data was included into the state register of geodetic, gravimetric and magnetic control networks (pol. PRPOG).

2.4. Magnetic

Magnetic control in Poland consists of 19 magnetic repeat stations (Welker, 2015a) supported by two magnetic observatories (Welker et al., 2015) run by the Institute of Geophysics of the Polish Academy of Sciences: Central Geophysical Observatory in Belsk and Magnetic Observatory in Hel. In addition, there are two permanent magnetic stations: Borowa Gora – run by the Institute of Geodesy and Cartography, and Suwalki – run by the Institute of Geophysics of the Polish Academy of Sciences (Fig. 4).

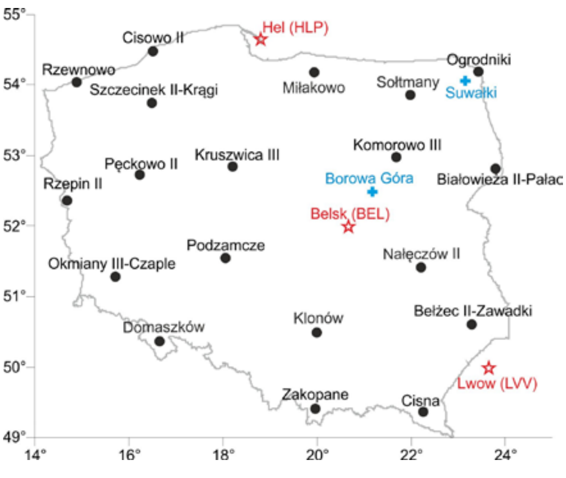

Fig. 4. Repeat stations (black dots), permanent stations (blue crosses) and magnetic observatories (red stars)

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 (Welker, 2015b). In 2015 measurements of magnetic declination *D*, magnetic inclination *I* and the module of the magnetic intensity vector *F* were conducted at 6 repeat stations: Kruszwica, Nałęczów, Ogrodniki, Rzewnowo, Sołtmany, Szczecinek.

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. 5) 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/_trackingnetwork/stations.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.

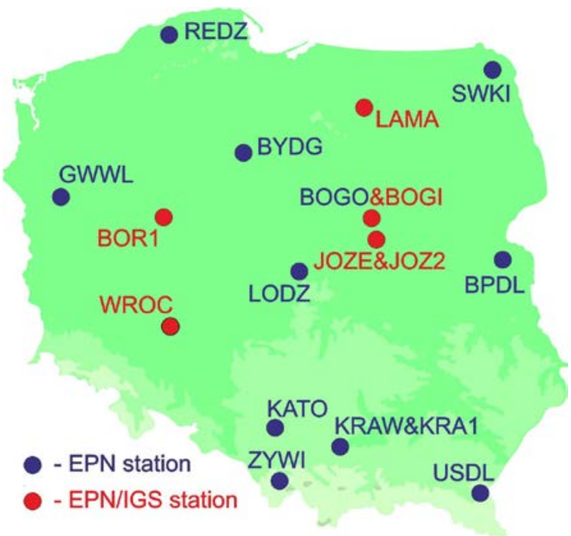

Fig. 5. EPN/IGS permanent GNSS stations in Poland (2015)

Four of those stations, i.e. BOGI, BOR1, JOZ2 and WROC participated also in IGS Real-time GNSS Data project. The station WROC since 2014 is 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. 6).

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

Fig. 6. 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 2015, the WUT LAC subnetwork (Fig. 7) consisted of 103 GNSS stations from which 80% 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).

In addition, WUT AC tested new analysis options and their effect on GNSS results of the regional network, e.g., inclusion of non-tidal loading effects, or the usage of Vienna Mapping Function versus Global Mapping Function for troposphere modelling (Liwosz 2015a; Liwosz 2015b).

In 2015, WUT AC together with the Polish Head Office for Geodesy and Cartography (GUGiK) reprocessed 3.7-year GNSS data from the Polish national GNSS network and created a new realization of ETRS89 for Poland (Liwosz and Ryczywolski, 2015; Ryczywolski and Liwosz, 2015). The new solution was accepted as Class A solution by EUREF Technical Working Group on EUREF Symposium in Leipzig (EUREF, 2015).

Fig. 7. EPN stations providing data processed at WUT EUREF LAC (April 2016) (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, 2015). No significant changes in network and processing strategy were done since GPS week 1812. Currently MUT LAC processes data from 138 EPN stations (Fig. 8) using the Bernese GNSS Software v.5.2.

Fig. 8. EPN stations providing data processed at MUT EUREF LAC (April 2016) (http://www.epncb.oma.be/)

In 2015 most of the activities were focused on the second campaign of "EPN Reprocessing" project. The reanalysis covers all EPN stations of from January 1996 (GPS week 835) up to end of 2014 (GPS week 1825). MUT was one of the five LACs providing solutions in the second campaign and one of three providing daily solutions from entire network. All computations were conducted using the GPS analysis software GAMIT v.10.50, as the continuation of the work started during the first campaign. All solutions were uploaded and are available on BKG data centre. They are based on the GPS system only and follow the IERS standards. MUT provides four solutions to investigate the effects of antenna modelling and considering the non-tidal atmospheric loading. Two of them differ in the methodology using either only type mean or type mean plus individual receiver antenna correction model (Fig. 9). Other two solutions differ in applying or not applying the non-tidal atmospheric loading (Araszkiewicz et al., 2015).

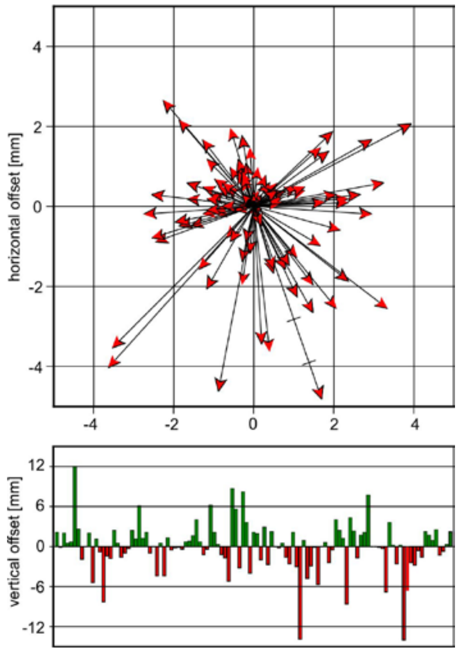

Fig. 9. Position offsets related to mixing type mean and individual antenna phase centre corrections; each arrow/column refers to one antenna+radome mounted at one station (stations in alphabetical order)

3.4. Activities of MUT and WUT EPN Combination Centre

In 2015, 16 of 18 existing ACs were submitting routine solutions, i.e. SINEX solutions for the weekly EPN combination. The GOP AC focuses on the EPN reprocessing activities. The DEO AC does not submit its solutions anymore since 2009, but is planning to restart routine analysis in 2016. Fourteen ACs process both GPS and GLONASS data with the Bernese GNSS Software v.5.2, two remaining ACs use Bernese v.5.0 and GIPSY-OASIS II software.

Routine solutions are combined in the Analysis Combination Center (ACC) run by consortium of the Military University of Technology and the Warsaw University of Technology. All combinations are performed with Bernese v.5.2. Weekly and daily final positions products are delivered on the basis of 16 individual ACs solutions, while rapid daily and ultra-rapid solutions use input from 10 and 3 ACs, respectively. ACs were encouraged to consider submission of rapid and ultra-rapid solutions to strengthen the reliability of these products.

Regarding the final product, only stations processed by at least three ACs are taken into consideration in the final daily and weekly solutions. This enables the detection of outliers and increases the reliability of the solutions. Exceptions are made for new stations; in the beginning of their lifetime they may be processed by less than three ACs. Prior to the combination process, the SINEX files provided by different ACs are automatically checked against possible metadata inconsistencies (e.g. antenna types and calibration models, receiver types) and problematic stations are excluded from the combination. Short reports from final combinations are distributed using EUREF and AC mail system while full reports are available at ftp://epncb.oma.be/pub/product/combin/WWWW. EPN ACC webpage (http://www.epnacc.wat.edu.pl) presents results of final, rapid and ultra-rapid combinations. For the final combinations the following information is available: agreement between ACs solutions for all EPN stations separately for horizontal and vertical components, Helmert transformation parameters of all solutions with respect to the combined solution and time series of all stations residuals with respect to the position resulted from the combination.

Rapid and ultra-rapid analyses are performed mainly for the purpose of network monitoring. Maps presenting current status of the EPN stations and their position time series plots for these two products are available. For rapid solutions current position of each station is compared to the mean value from last 4 weeks. Stations that exceed specified threshold (10 mm for horizontal and 15 mm for vertical component) are indicated, but not excluded from the final solution. Similarly, current ultra-rapid positions are compared with the mean values from last 72 hours with 10 mm and 20 mm thresholds for horizontal and vertical components, respectively. Characteristics of rapid combination can be found at the BKG product center (ftp://igs.bkg.bund.de/EUREF/products/WWWW/eurWWWWDr.sum).

3.5. Validation of GNSS orbits using SLR

In the framework of the cooperation of the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences with the Astronomical Institute, University of Bern (AIUB, Switzerland), the microwave-based orbits of GNSS satellites were validated using satellite laser ranging (SLR) observations. In case of GPS and GLONASS, the reprocessed orbits provided by the Center for Orbit Determination in Europe (CODE) were used, whereas for other GNSS systems, the operational CODE MGEX products were analysed.

For many years the Empirical CODE Orbit Model (ECOM) was used for generating high-precise GNSS orbits and GNSS products due to its high efficiency in mitigating the impact of solar radiation pressure. Recently, it was found that the classical ECOM is well suited for the near cubic-shaped GPS satellites, whereas the orbit quality of the elongated cylinder-shaped GLONASS-M satellites suffers from some modelling deficiencies. This led to the series of theoretical and empirical investigations resulting in a new extended ECOM model (Arnold et al., 2015). Subsequently, the validation was extended also on operational MGEX products. Figure 10 shows the results of the validation of GNSS orbits using the old and the new ECOM models for different satellite systems. The Galileo orbits are remarkably improved when using new ECOM (by about 44% in terms of SLR residuals). BeiDou orbits show a slight degradation when using the new ECOM (by about 15%). This degradation holds for both, the BeiDou MEO orbits, as well as for BeiDou inclined geosynchronous orbits. QZSS orbits are substantially improved (from RMS = 160 mm to 65 mm) when using the new ECOM and excluding observations for |β|<20° (due to the normal orbit attitude, which is not yet considered in a proper way in the Bernese GNSS Software). All in all, the new ECOM remarkably improves the satellite orbits of GLONASS-M, Galileo and QZSS satellites.

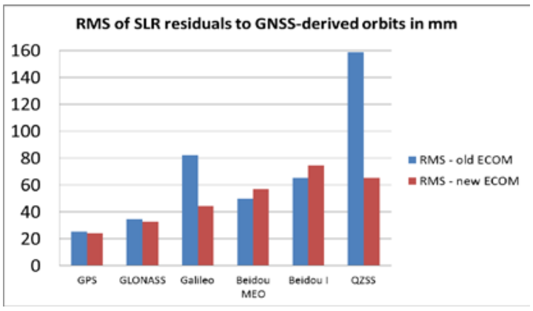

Fig. 10. Mean RMS of SLR residuals to GNSS-derived orbits [mm]; validation of orbits from 2010–2013 (GPS+GLONASS) and 2014 (Galileo+BeiDou+QZSS) is shown

Most of the SLR stations use special narrow-band filters to allow for daytime tracking. Different tracking procedures in the day and night time may possibly induce some systematic effects in SLR data. Figure 11 (left) shows that the SLR residuals for Galileo-102 for the daytime tracking are at the level of +50 mm (in magenta), whereas for the night time tracking the residuals are at a level of –150 mm (in cyan). Figure 11 (right) shows that this systematic effect disappears when using the new ECOM. Using the new ECOM removes the elongation-dependency and thus also the differences between SLR observations acquired during day- and night time, which also proves that the new ECOM substantially reduces the systematic effects and deficiencies in solar radiation pressure modelling of the GNSS orbits.

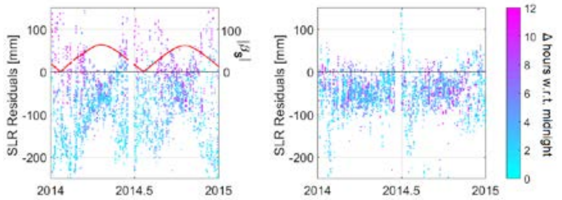

Fig. 11. SLR residuals to Galileo-102 as a function of the local time of collected data at a station. Daytime observations are shown in magenta, whereas night time observations in cyan. Left figure is generated using classical ECOM, whereas the right one using extended ECOM (for the same satellite)

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 conducted in 2015 in the Warsaw University of Technology. Long time series of IPW on IGS permanent stations (calculated from tropospheric delay estimates) averaged daily can serve as climate change indicators (Kruczyk, 2015a). The seasonal model of IPW change has been adjusted to the multi-year series using the least squares method. Different modes have been applied: sinusoidal and composite (two or more oscillations), trend fitting together with seasonal model or to residuals. Information potential of IPW for climate research depends on series length and homogeneity. To fit linear trend to long IPW series the seasonal model of 1–4 oscillations is also included (Fig. 12).

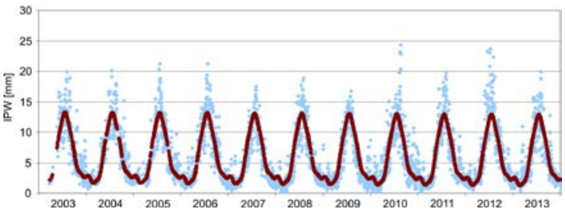

Fig. 12. IPW for THU2 (Thule, Greenland) and a model with 3 oscillations (annual and 1/2, 1/3 of a year) for 2003-2013 period

Usually it is sufficient to model seasonal changes by annual and semi-annual oscillation as confirms the analysis of a periodogram (Fig 13). The exact method does not affect considerably the value of linear trend. The IPW trend value is mostly influenced by a series length, completeness and data (also meteorological) overall quality.

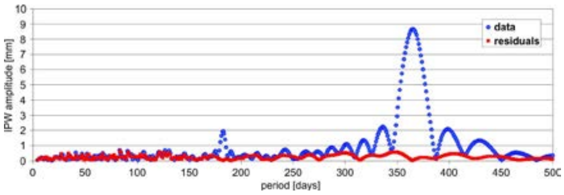

Fig. 13. Periodogram of IPW series and residuals after subtracting annual and semiannual oscillations for JOZE (Poland), multi-year series: 1997-2013

Areological techniques of water vapour retrieval in polar regions were assessed in the Warsaw University of Technology. Three independent techniques to obtain integrated precipitable water (GPS solution, radiosounding and CIMEL sunphotometer) have been tested at four points in Greenland (Kruczyk, 2015b). CIMEL sunphotometer IPW, and IPW values derived from standard solutions of IGS and EPN (combined solution) show relatively good agreement but also some biases of 2–7 %. IPW bias shows seasonal dependence, especially in case of Thule station what signals some systematic deficiencies in solar photometry as IPW retrieval technique. Probable this effect is caused by a change of optical filter characteristics in sunphotometer working in extreme polar conditions. Averaged IPW difference for RAOB (radiosounding observation) – GPS is relatively small and shows no dependence on temperature. The attempt to compare aerological techniques (CIMEL and RAOB) brings similar temperature – IPW difference dependence (Fig. 14).

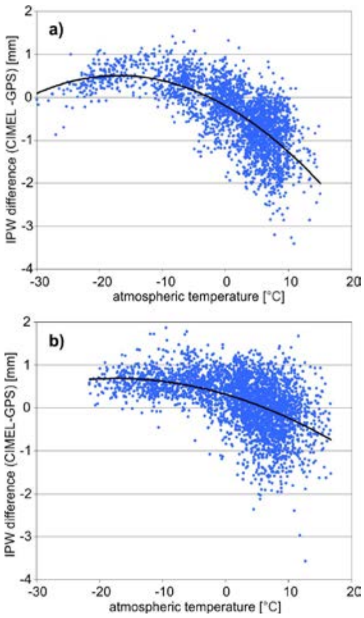

Fig. 14. IPW difference (CIMEL-GPS) for Thule-THU2 for 2009–2011 a) and Ittoqqortoormiit – Scoresbysund (SCOR) for 2012–2014 b) as a function of atmospheric temperature, IGS tropospheric solution

In the first step of building the integrated model of troposphere, in the Wroclaw University of

Environmental and Life Sciences (WUELS) the NWP model outputs were inter-compared with the reference data consisting of: high-quality ground-based meteorological observations, radiosonde profiles and GNSS products and the accuracy of the provided parameters were evaluated (Wilgan et al., 2015). The radiosonde and the GNSS observations have been found to be consistent (ZTD discrepancy below 10 mm), whereas the ground-based observations and soundings detect in NWP data: 1) a negative bias in air pressure, 2) a negative bias in water vapour partial pressure, and 3) a positive bias in temperature. The standard deviation of ZTD residuals of reference data and the NWP model is at the level of 20 mm. The NWP model COAMPS (Coupled Ocean/Atmosphere Mesoscale System) used does not provide meteorological parameters with acceptable accuracy for positioning, therefore the use of the WRF model (Weather Research and Forecasting) is recommended.

Next the total refractivity profiles and ZTDs were integrated using the collocation software COMEDIE (Collocation of Meteorological Data for Interpretation and Estimation of Tropospheric Pathdelays) developed at ETH Zurich for two regions: western part of Switzerland and Poland (Wilgan et al., 2016). For Switzerland the data set with the best agreement with the reference radiosonde (RS) measurements is the combination of ground-based meteorological measurements and GNSS zenith delays. Mean biases of the total refractivity residuals varies from –7 to 3 ppm with standard deviations from 3 to 8 ppm (data averaged up to 4 km). It has been presumed that introducing the horizontal gradients improves the vertical interpolation, but the data set with gradients has slightly larger biases and standard deviations. In terms of the total refractivity interpolation in Poland, data set based on meteorological parameters from NWP WRF model and from a combination of NWP model and GNSS zenith delays show the best agreement with reference RS data. Mean biases vary from –2 to 2 ppm and standard deviations from 1 to 6 ppm (data were averaged up to 31 km). The ZTDs were compared with the reference GNSS data during one week with severe weather event. Figure 15 shows such comparison for the sample station KRAW. The combined NWP-GNSS observations and GNSS-only set exhibit the best accuracy with average bias (from all stations) of 2.6 mm and average standard deviations of 17.5 mm w.r.t reference GNSS stations.

To provide fully operational service for real-time PPP (Precise Point Positioning) it is essential to calculate real-time ZTD estimates or short-term forecasts from near real-time estimation. There are several methods to predict future values of zenith total delay. The statistical approach was used. The ZTD time series was fitted into the autoregressive (AR) and autoregressive moving average (ARMA) models (Wilgan, 2015). The forecasts (statistical and also from NWP COAMPS) were compared with the in-situ values of ZTDs. In up to 5-hour forecasts (Fig. 16), statistical models show a small discrepancy between in-situ observation and a forecast. The average absolute biases for 5-hours global forecasts for the entire country are: 0.6 mm for AR model, 0.54 mm for ARMA model and 9.36 mm for COAMPS and average standard deviations are: 6.72 mm for AR model, 6.76 mm for ARMA model and 7.26 mm for COAMPS. The statistical and the COAMPS predictions can be complementary, first one is suitable for shorter (1–5 hours) forecasts and latter for longer (24 hours) forecasts.

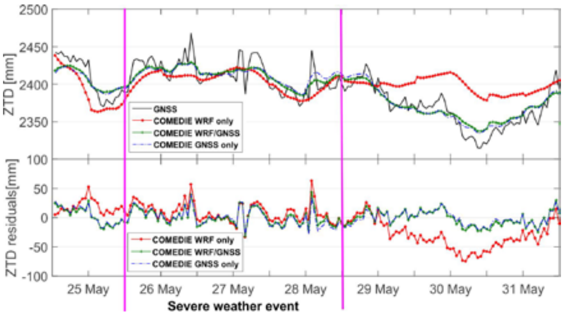

Fig. 15. Comparison of ZTD from GNSS station KRAW with ZTDs from COMEDIE from 3 data sets: WRF only (red), WRF/GNSS (green) and GNSS only (blue) (top) with corresponding residuals of ZTDGNSS – ZTDCOMEDIE [mm] for all data sets (bottom); data period 25 – 31 May 2014

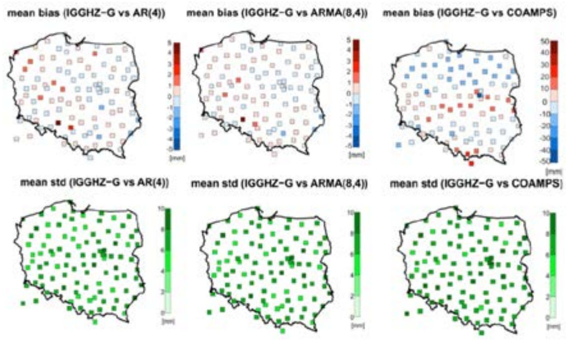

Fig. 16. Mean biases and standard deviations from residuals ZTDIGGHZ-G – ZTD model, where 'model' is one of the following: AR(4), ARMA(8,4) or COAMPS for 121 ASG-EUPOS stations; data are averaged between 1.12.2012 – 15.03.2013

Analysis centre at Institute of Geodesy and Geoinformatics (WUELS) continues its near real-time (NRT) GNSS data processing activities for meteorology applications since 2012. Computing services were upgraded in 2015 to the latest version of Bernese GNSS Software v.5.2 and two new networks except of ASG-EUPOS were included. The networks are ASG-EUPOS, SmartNet in Poland and LitPOS in Lithuania (Fig. 17).

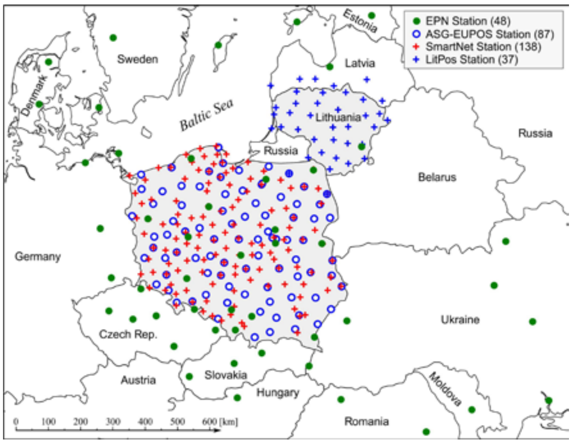

Fig. 17. GNSS network processed by the WUELS AC in NRT mode for troposphere parameter estimation

Processing is performed in hourly intervals. Of 310 processed stations 48 EPN stations are used as reference. Troposphere results (ZTD and its horizontal gradients) are delivered to the E-GVAP (http://egvap.dmi.dk) data repository. The NRT troposphere products are used for calculation of integrated water vapour content (IWV) in the atmosphere above the GNSS stations and both products (ZTD and IWV) are utilized for severe weather studies according to the COST ES1206 Action as well as for improving the weather prediction. As the result of WUELS NRT processing expertise, the NRT troposphere parameter estimation service was established at RMIT University in Australia for Victoria state in 2015 (Fig. 18). This service is used by the Australian Bureau of Meteorology for GNSS troposphere parameters assimilation into NWP system ACCESS studies.

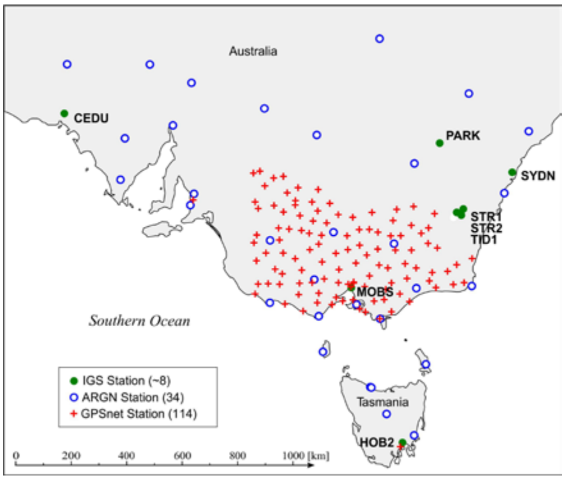

Fig. 18. GNSS network processed in NRT mode for troposphere parameter estimation by the RMIT University in cooperation with WUELS

Time series of radio signal wet tropospheric delays was analysed for short-term forecast (Rzepecka et al., 2015). Data from 2010–2013 and two permanent stations located in Central Europe region were used. After removing annual, semi-annual components and a linear trend appropriate parameters of the ARIMA model were evaluated and the accuracy of forecast values was analysed. One-step forecasts based on the above models are estimated to be within ±2.5 cm for 80% of confidence level, and ±3.8 cm for 95% of confidence.

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 recently developed at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn (IG/UWM). The LSC method frequently applied in geophysical sciences, e.g., in magnetic or gravity field modelling is proposed here for epoch by epoch TEC interpolation. For total electron content (TEC) estimation, dual-frequency carrier phase GPS data from both Polish national GNSS network (ASG-EUPOS) and the EPN were used. The new regional ionospheric model (UWM-rc1) is computed using only precise, absolute (undifferenced) carrier phase GNSS measurements, a few order of magnitude more precise comparing to pseudorange measurements. In the first step of the data processing, carrier phase bias parameters for each observation arc are estimated together with parameters of the local polynomials. The carrier phase bias includes undifferenced carrier phase ambiguities and hardware – satellite and receiver – delays. Once the bias parameters are known it is possible to calculate precise TEC values at the ionospheric pierce points (IPP) using geometry-free linear combination (L4). In order to represent the ionospheric vertical TEC (vTEC) at IPP locations, a single layer model (SLM) was used. The estimated vertical TEC (VTEC) values at IPPs are then processed by parametrized LSC to obtain regular VTEC maps (grids) that are precise in the least squares sense. An additional advantage of LSC in relation to non-parametric methods is the accuracy analysis of the obtained maps. The model allows for providing ionospheric TEC maps with high spatial and temporal resolutions – 0.2°×0.2° and 1 minute, respectively (Fig. 19).

In order to investigate the quality of the new regional TEC model (UWM-rc1), the GNSS data collected under different ionospheric conditions were processed. For the study, seven days from 14 to 20 March 2015 were selected. For numerical tests two perpendicular baselines of 77 km and 90 km were selected (Fig. 20). The test baselines were located in central Poland and directed in north–south (N-S) and west–east (W-E) directions. The UWM-rc1 model was tested by creating double-differenced (DD) ionospheric delay corrections and comparing them to high accuracy reference values derived from the reference network data processing at selected test baselines. The residuals between the UWM-rc1 and the reference DD ionospheric corrections were analysed as metrics of the model quality. In addition, similar comparison at DD level was carried out, but using CODE regional (COE) and IGS global TEC maps.

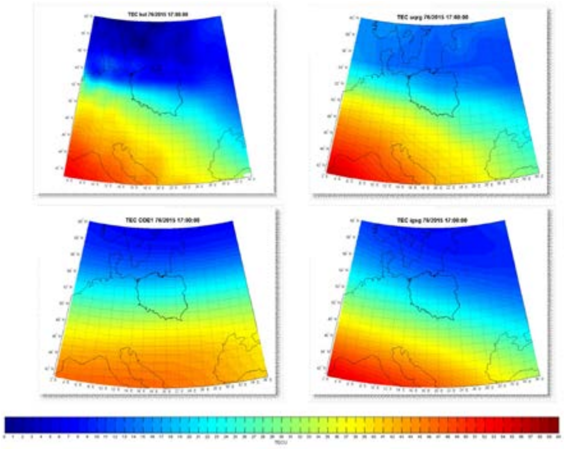

Fig. 19. Comparison between the ionosphere maps derived using the new regional TEC model UWM-rc1, IGS, COE and UQRG model for the active day (17 March 2015)

Fig. 20. Test baselines for investigating the quality of the UWM-rc1 regional TEC model

The statistics concerning the average DD correction accuracy for all days and maps for each baseline are shown in Table 2. Numerical tests confirmed good performance and high accuracy of UWM-rc1 TEC maps, which performed better that IGS global and COE regional TEC maps. The resulting accuracy of the DD corrections was usually better that 10 cm, even during the ionospheric disturbances. This proves suitability of UWM-rc1 regional TEC maps for supporting fast ambiguity resolution in kinematic GNSS positioning.

Table 2. Average accuracy of DD ionospheric corrections (% of the residuals within the predefined limits)

	SOCH-CCHN			SOCH-MIMA		
	UWM-rc1	IGS	COE	UWM-rc1	IGS	COE
±0.025m	54.7	38.9	37.0	48.7	36.6	34.7
±0.050m	79.7	66.5	61.7	75.8	62.4	59.1
±0.100m	94.3	86.2	83.2	93.2	87.6	83.9

The Faculty of Civil Engineering and Geodesy of MUT in Warsaw in collaboration with 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. 21) that allows visualization of the ionospheric irregularities (Zanimonskiy et al., 2016a).

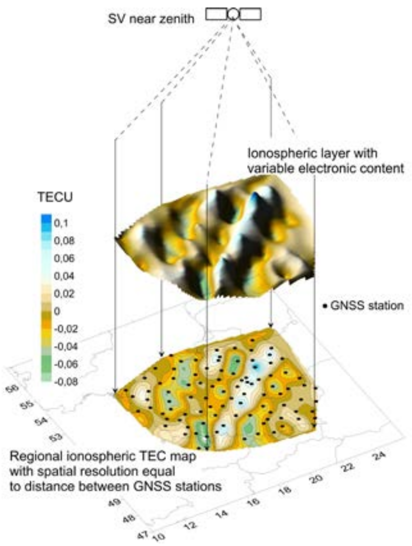

Fig. 21. Scheme of TEC mapping by the method of orthogonal parallel-beam projection

The method was applied to detect travelling ionospheric disturbances (TIDs), as well as model and measure their parameters such as direction and speed of movement, the spatial period using observational data from the ASG-EUPOS network. TIDs are 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. The amplitude of TEC variations during the passage of TID is proportional to the background TEC value and grows with the level of geomagnetic disturbances (Zanimonskiy et al., 2016b).

4. Advanced methods for satellite positioning

The quality of IGS Real-Time Service (RTS) products that affects the accuracy and precision of PPP derived coordinates was investigated in the Wroclaw University of Environmental and Life Sciences (Hadas and Bosy, 2015). It was confirmed that for GPS and GLONASS systems the availability of corrections was over 92%, however for a few satellites the availability was below 30%. The latency of correction was between 28 s and 30 s, which is much more than declared by RTS. Real-time satellite coordinates (in radial, along track and cross track directions) and satellite clock offsets were compared with IGS final products. A high quality of GPS products was confirmed. 3D orbit accuracy was 48 mm and clock accuracy was 0.28 ns. For GLONASS, 3D orbit accuracy was 132 mm and clock accuracy was 0.82 ns. The classification of GLONASS products as unofficial is thus well justified (Fig. 22).

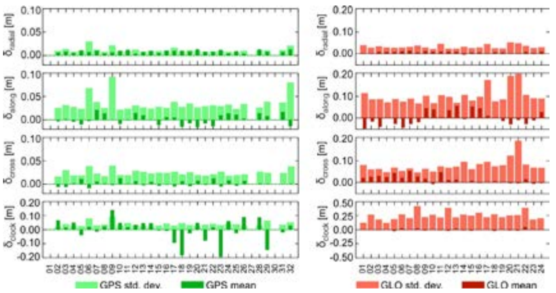

Fig. 22. RTS orbits and clocks quality with respect to ESOC final products during DOYs 208-214, 2013

An original real-time PPP software GNSS-WARP was developed at Wroclaw University of Environmental and Life Sciences (WUELS). The software allows to process GPS and GLONASS data in real-time (from RTS stream), simulated real-time (using recorded orbits and clocks from RTS stream) and postprocessing (with final products) modes, to estimate static and kinematic coordinates. The analysis of the quality of real-time static and kinematic PPP using GPS and GPS+GLONASS data was performed (Hadas, 2015). It was found that in static positioning the inclusion of GLONASS data degrades the results due to the limited quality of RTS products for GLONASS. However, in kinematic mode the common processing of data from both GNSS results in slightly worse accuracy, but the convergence time is reduced from more than 1 hour to around 15 minutes.

The application of high-resolution troposphere delay models into real-time kinematic positioning was also investigated. The modification with respect to standard strategy of data processing was that the external ZTD model provided not only the a priori ZTD value that is used at the beginning of data processing, but also allowed to constrain the estimated correction to a priori ZTD. An improvement of up to 40% was noticed for Up component during the unusual, rapidly changing weather conditions – the mean standard deviation of coordinate residuals was reduced from 14 cm to 8 cm. A significant reduction of coordinate residuals was also noticed at the very first epochs of data processing, even though the estimated error was relatively large. This will be exploited in further research on phase ambiguity resolution in real-time GNSS positioning based on PPP technique.

Extensive studies on precise GNSS-based positioning have been carried out at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn (IG/UWM). Several scientific issues related to multi GNSS and multi frequency positioning have been studied. One of the scientific achievements was the development of algorithms and software for precise relative positioning with the use of multiple GNSS antennas and receivers configuration on a common moving platform (Paziewski, 2015). This rigid platform configuration with nearby antennas can be used to form several constraints which may be applied in order to improve the redundancy and strengthen of the least squares solution. The objective of the developed methodology was to take advantage of the known baseline length, relationships between ambiguities over dependent baselines as well as similar atmospheric delays constraints in order to improve the ambiguity resolution performance. The performance assessment of the developed methodology was based on the processing of medium length baselines up to several tens of kilometers in the instantaneous (single-epoch) mode. The results show clear improvement in ambiguity resolution domain in comparison to commonly used ionosphere-weighted model.

The study on integration of multi GNSS observations in relative positioning was continued at UWM in Olsztyn. The overlapping frequencies in GNSS systems, i.e. L1/E1 & L5/E5a in GPS and Galileo systems support creating between systems double-differences in a tightly combined positioning model. In this approach it is necessary to take into account receiver Inter System Biases (ISB), which are the difference in the receiver hardware delays for separate GNSS systems present in both carrier-phase and pseudorange observations. The research showed that using an a priori knowledge on earlier calibrated ISB for correcting GNSS observations has significant impact on the ambiguity resolution performance (Paziewski and Wielgosz, 2015). However in the study, small oscillations in the phase ISB time series were discovered (Fig. 23). Short-term temporal stability of ISB, its dependence on the number of Galileo satellites used, the amplitude and frequency of the detected ISB time series oscillations as well as their potential source were investigated (Paziewski et al

2015). The presented results were based on between GPS-Galileo-IOV phase ISB time series derived from real observational data collected on a zero baseline with the use of different sets of GNSS receivers.

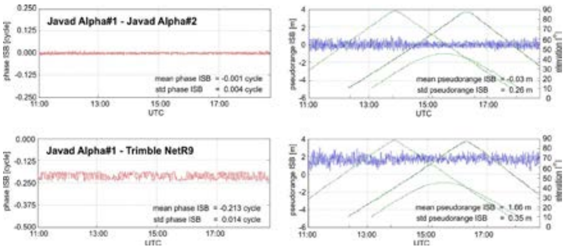

Fig. 23. Phase and code ISB time series obtained using all available GPS and Galileo satellites for different receiver pairs: 1st row – homogenous receivers (Javad Alpha), 2nd row inhomogeneous receivers (Javad Alpha – Trimble NetR9). Source: Paziewski et al. (2015)

The different-origin disturbances in the ionosphere are still one of the main unresolved problems of GNSS positioning. Their occurrence causes the increase of Total Electron Content (TEC) gradients and consequently degrades ambiguity resolution. In order to mitigate this effect a new algorithm – RTC, which allows the elimination of temporal TEC fluctuations in rapid static positioning, was developed at the Institute of Geodesy of the University of Warmia and Mazury in Olsztyn. The novel approach consists in the modification of raw dual-frequency observations using the ROT corrections and ensures that the ionospheric delay variations can be levelled to the one, reference epoch. As a result the ionospheric delays for each satellite can be treated as constant during the entire observational arc. The example of original and modified double-differenced ionospheric delays in 10 minute sessions is given in Figure 24.

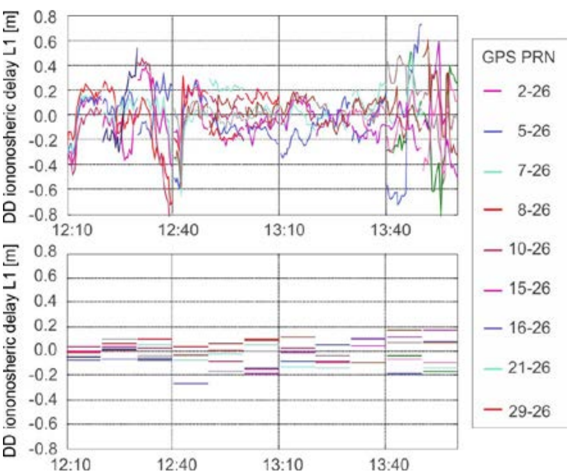

Fig. 24. Double-differenced ionospheric delays on L1 frequency for TREO–LYNS baseline obtained from geometry-free solution with fixed ambiguities for original observations (top) and RTC-corrected observations (bottom) (Sieradzki and Paziewski, 2015a)

The new algorithm was evaluated on the basis of static multi-baseline positioning using ionosphere-weighted model performed for different latitudes and ionosphere conditions (Sieradzki and Paziewski, 2015a, 2015b). The analyses executed both for high latitudes during geomagnetic storm and mid latitudes, affected by medium scale travelling disturbances (MSTIDs), have proved its high efficiency. In the case of the test carried out for circumpolar region, the application of the proposed RTC algorithm resulted in almost 10 time increase of the integer ambiguity resolution success rate (ASR) – up to 59%.

The study performed for the latter, less challenging case, has confirmed the improvement of ASR to 90%. The more detailed analysis has also demonstrated that under no cycle-slip conditions, the solution is stable and led to the continuous increase in ASR depending on session length. It should be mentioned that the proposed algorithm does not require any an external modelling of ionospheric conditions and can be easily implemented in multi-GNSS positioning, including both relative and absolute methods.

The impact of ocean tides loading on precise point positioning based on FES2004 model was investigated basing on observations from 50 days acquired at 24 globally distributed permanent stations. For the stations with high amplitudes of the loads the improvement in the solution in height component reach the level of 19% or 7.3 mm (Kalita and Rzepecka, 2015).

The advantages of using combination of different global navigation satellite systems constellations, i.e. GPS, GLONASS, Galileo and BeiDou with respect to using only GPS were indicated. They concern the improvement of RTK accuracy and the possibility of elimination systematic errors from RTK solutions in particular in the determination of height (Siejka, 2015).

The extensive analysis of visibility and geometry of global navigation satellite systems constellations, i.e. GPS, GLONASS, Galileo and BeiDou was performed (Januszewski, 2015).

Research on stochastic modelling of GNSS observations was carried out at the Warsaw University of Technology (WUT). It was focused on the development the stochastic model for instantaneous Network RTK positioning, called the Network-Based Stochastic Model (NBSM) (Prochniewicz et al., 2016). The NBSM is a weighted model which used a network correction variance estimations as an accuracy characteristic of ionospheric and geometric residual errors. This model uses correction term variances estimated directly in the network solution, together with estimations of the corrections themselves. Such a solution enables capturing of current residual error values on the basis of observations from a single epoch without using observations from the monitoring station, which is the essential difference compared to the existing models. This approach predisposes the NBSM for application in instantaneous Network RTK positioning. Figure 25 illustrates the scheme of the Network RTK performance model composed of three groups of algorithms: network solution, network correction and positioning model. Color red denotes new elements of this model which were added by NBSM.

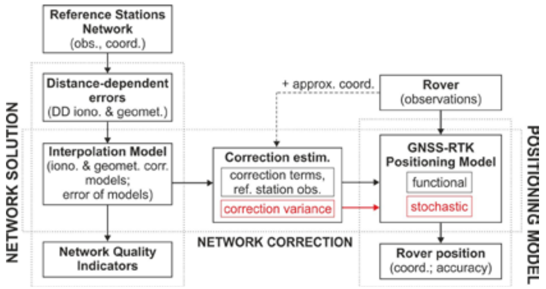

Fig. 25. Network RTK positioning model based on NBSM; in red – new elements of the model added by NBSM

Comparison of weighted positioning model based on NBSM with the ionosphere-fixed troposphere-fixed model, which is the standard model for the Network RTK shows that both the ambiguity integer estimation and the validation are characterized by a significantly higher success rate. Application of the NBSM reduced also the rover positioning errors down to the level of 15-30% (Prochniewicz et al., 2016).

Algorithms for the computation of orbital elements and positions of GLONASS satellites based on the asymmetric variant of the generalized problem of two fixed centers have been developed. The numerical tests show that the proposed analytical method is an interesting alternative for presently used numerical methods for computation of position and velocity of GLONASS satellites (Goral and Skorupa, 2015).

Selected data acquisition methods for GNSS terrain obstacles modelling were intercompared. The accuracy of data acquisition methods was examined by taking as the reference the coordinates from classical tacheometric survey (Pelc-Mieczkowska et al., 2015).

An innovative solution to increase the reliability of determining the coordinates of building corners, by modernizing the results obtained from the indirect method of measurement of line-line intersection by the so-called half-angle method has been presented (Krzyzek, 2015a) including the algorithm developed on the basis of vectors translation method (Krzyzek, 2015b) and the method of vector addition (Krzyzek, 2015c).

A study on along-track and cross-track noise of altimetry data by maximum likelihood was conducted using the data of Mars Orbiter Laser Altimetry (Jarmolowski and Lukasiak, 2015). The results obtained confirm substantial influence of different data resolution in along-track and transverse directions on the covariance parameters.

5. ASG-EUPOS network

5.1. Status of the ASG-EUPOS network

At the end of 2015 the network of the ASG-EUPOS system consisted of 125 operating permanent reference stations (108 GPS/GLONASS stations) (Fig. 26) (www.asgeupos.pl).

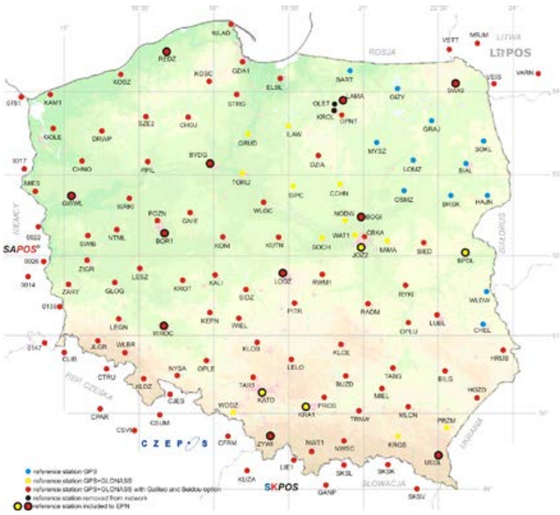

Fig. 26. Reference stations of the ASG-EUPOS system (31 December 2015)

The number of changes in the ASG-EUPOS stations took place in 2015. Receiver and antenna have been replaced at 34 stations in northern and southern regions of Poland. Four new RTN data streams were created for providing GPS+GLONASS Network RTK data for most area of Poland. A new OPNT station in Olsztyn was established and launched. It replaced OLST station which was removed from the network. One Lithuanian station VSTT was included into the ASG-EUPOS network.

Since 12 July 2014 all services in ASG-EUPOS system are fully payable as a new act on geodetic and cartographic law was introduced into force (earlier all services and data were available free of charge). At the end of 2015 a total number of active users for RTN, RTK and DGNSS services was at the level of 3100.

In 2016 the modernization of ASG-EUPOS is to be continued and equipment replacement on another 12 stations is to planned. Additionally a new Gellin reference station from Germany's GREF system will be included into the Polish network. Also it is planned to launch a system for automatic payments for ASG-EUPOS services. Area of coverage of RTN correction data from GPS+GLONASS observations will be extended to cover whole area of Poland.

6. Modelling precise geoid

Activities of the team of the Institute of Geodesy and Cartography on the improvement of precise quasigeoid model for Poland were continued. Following the gravimetric quasigeoid model GDQM-PL13 (Szelachowska and Krynski, 2014) a new model GDQM-PL15 was developed with the use of the new gravity data from Czech Republic and Slovakia. The 1'×1' mean Faye gravity anomalies, deflections of the vertical for the territory of Poland, gravity anomalies from the neighbouring countries and the EGM2008 were used as input data. The remove-compute-restore (RCR) method and the least squares collocation approach with the planar logarithmic covariance function of gravity anomalies were applied. Accuracy assessment of the GDQM-PL15 with the use of precise GNSS/levelling data proved its high quality. The fit of the quasigeoid heights from GDQM-PL13 to the corresponding ones of 1st and 2nd order sites of GNSS/levelling control traverse, the ASG-EUPOS, POLREF and EUVN networks sites represented by the standard deviations of respective differences is of 1.5 cm, 1.7 cm, 1.8 cm, 2.6 cm, and 2.9 cm, respectively.

Works on local quasigeoid modelling using the geophysical gravity data inversion technique (GGI method) were continued at the Wroclaw University of Environmental and Life Sciences. Optimal quantitative parameters of selected input data used in GGI were estimated (Trojanowicz, 2015a). Assessment of the Accuracy of local quasigeoid modelling using the GGI method was assessad in the case study for the area of Poland (Trojanowicz, 2015b).

Research on geoid modelling was also conducted at the University of Warmia and Mazury. A new gravimetric geoid model for Poland using the method based on least squares modification of Stokes' formula with additive corrections method (LSMSA) developed at the Royal Institute of Technology (KTH) in Stockholm, Sweden. Terrestrial gravity anomalies, EGM2008 and SRTM v.4.1 were used in computations. The gravimetric geoid model determined was evaluated with GPS/levelling points of the Polish ASG-EUPOS network. After fitting the geoid model to the GPS/levelling data using a 7-parameter model, the standard deviation of differences was estimated to 2 cm (Kuczynska-Siehien et al., 2016).

7. The use of data from satellite gravity missions

The extensive work on the use of data from satellite gravity missions for modelling gravity field was conducted in the Institute of Geodesy and Cartography (IGiK). The accuracy of 1st – 5th releases of GOCE-based Global Geopotential Models (GGMs) developed with the use of the direct solution and the time-wise solution strategies were assessed over the area of Poland where there is a dense coverage with high quality terrestrial data. Free-air gravity anomalies and height anomalies computed from those GGMs have been compared with the corresponding ones obtained from EGM08. Moreover, height anomalies determined from GOCE-based GGMs were compared with the corresponding ones obtained from three different GNSS/levelling data sets with the use of the spectral enhancement method (SEM). The results obtained reveal clear improvement for the consecutive releases of GOCE-based GGMs investigated. The 5th release GOCE-based GGM developed with the use of time-wise strategy shows the best performance. Its fit over the area of Poland to the terrestrial data in terms of the standard deviation is 0.84 mGal for gravity anomalies and in the range of 2.8–3.4 cm for height anomalies (Godah et al., 2015a, 2015b).

Similar research has been performed for the area of Sudan where terrestrial data is sparse and rather low quality. The GGMs based on approximately 12 months of GOCE satellite gravity gradiometry (SGG) data have been compared over the area of Sudan with the EGM08 and terrestrial data. Geoid heights and free-air gravity anomalies from four GOCE/GRACE satellite-only GGMs, and one GOCE/GRACE GGM combined with terrestrial/altimetric gravity data were compared with the corresponding ones obtained from the EGM08, terrestrial free-air gravity anomalies and GNSS/levelling data. The results reveal that geoid heights and free-air gravity anomalies obtained from the GOCE-based GGMs agree with the corresponding ones from the EGM08 truncated to d/o 200 with standard deviation of 18–20 cm, and 3.4–4.2 mGal, respectively. Their agreement with the terrestrial free-air gravity anomalies and the GNSS/levelling geoid heights, in terms of standard deviation is about 5.5 mGal, and about 50 cm, respectively (Godah and Krynski, 2015).

The team of IGiK participated in the research on the usefulness of GOCE-based GGMs for the improvement of geoid model in Saudi Arabia. Geoid heights determined from several recent GOCE-based GGMs were validated against GNSS/levelling data at 5187 benchmarks in Saudi Arabia. It has been shown that completing the missing high-frequency component of geoid heights in GOCE-based GGMs, using EGM2008 and SRTM data, results in an improvement of about 16% in the reduction in the standard deviation of the differences. This is provided by DIR_R5 at SH d/o 230, which shows improvement from 37.5 cm, without applying the spectral enhancement method (SEM), compared to 31.4 cm when applying the SEM. The analysis of the results of the use of transformation models (four-, five-, and seven-parameter transformations) to fit geoid heights obtained from GOCE-based GGMs to GNSS/levelling reveal that the standard deviation of vertical datum over the region of Saudi Arabia is at the level of about 22 cm (Elsaka et al., 2015).

The team of IGiK also contributed to a comparative study of gravity field functionals from recent GOCE-based GGMs and terrestrial data over Saudi Arabia. Free-air gravity anomalies and geoid heights determined from EGM2008 and several recent GOCE-based GGMs have been compared with the corresponding ones obtained from available 3500 terrestrial gravity measurements over the study area. The SEM method was used to compensate the missed high frequency component of geoid heights in GOCE-based GGMs using EGM2008 and a high-resolution SRTM digital terrain model. The estimated standard deviations of gravity anomalies and geoid heights differences are: 5 mGal (20 cm), 6–7 mGal (22–24 cm), and 8 mGal (25.9 cm) at d/o 200, 240 and 280, respectively. Investigation of various releases of GOCE-based GGM, up to d/o 200, reveals that TIM_R4 and TIM_R5 GOCE-based GGMs developed with the use of time-wise solution strategy approximate the gravity field well over Saudi Arabia. Those two models are suggested as reference models for recovering the long wavelength up to d/o 200 and 240, respectively, when modelling the gravimetric quasigeoid over Saudi Arabia (Alothman et al., 2015a).

The suitability of the 5th release, GRACE-based GGMs for modelling the temporal gravity field variations over the area of Poland and surrounding areas was investigated in IGiK. The study area was represented by the Vistula river basin and the Odra river basin. The GRACE-based GGMs provided by different computational centers have been examined. The analysis has been based on the comparison of temporal variations of terrestrial water storage (TWS) obtained from the 5th release GRACE-based GGMs with the corresponding ones derived from hydrological models. The Gaussian filter with different radii as well as DDK (de-correlating in post-processing approach) filters were investigated on both global and local scale. Applying the DDK1 filter, as well as Gaussian-700 km filter substantially reduce the coloured noise 'strips' in GRACE-based GGMs. However, the Gaussian filter removes substantially more signal than the DDK1 filter. The DDK1 was found an optimum filter for reducing the noise contained in those GGMs (Godah et al., 2015c).

The Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences together with the Astronomical Institute of the University of Bern comprise the analysis of Earth rotation parameters (in particular the length-of-day LOD parameter) and the temporal changes of the Earth's gravity field as a consequence of the mass redistribution. In case of the gravity field recovery, the monthly gravity field models based uniquely on SLR observations were generated up to degree and order 10. Moreover, the SLR-derived gravity field models were compared and combined with GRACE GPS-based gravity field models as well as GRACE K-Band models.

The impact of El Niño occurrence was found in geodetic parameters, such as LOD, geocenter coordinates, as well as in the low-degree gravity field parameters. Figure 27 illustrates a comparison of the Southern Oscillation Index (SOI) provided by the Bureau of Meteorology of the Australian Government, intradecadal variations of LOD extracted using the wavelet decomposition and intradecadal variations of the effective axial angular momentum function for the period 1962–2015.

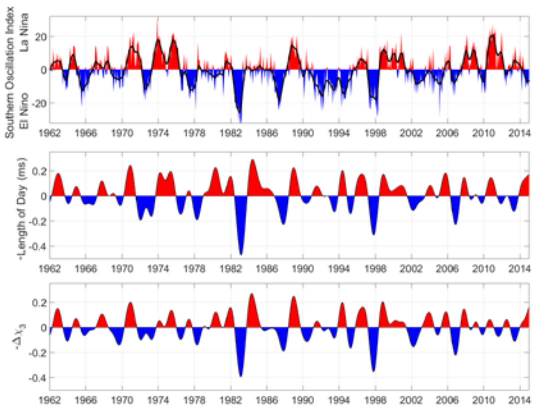

Fig. 27. Comparison of southern oscillation index (top), intradecadal variations of LOD (middle), and intradecadal variations of the effective axial angular momentum function (bottom)

All three series contain similar signals, although they are based on completely different observation principles: SOI is based on meteorological data, LOD is based on geodetic space and satellite observations, whereas the angular momentum function is derived based on geophysical models. The correlation coefficient between SOI and LOD is 0.497, however, when taking only the epochs during El Niño or La Niña events (|SOI|>8), the correlation coefficient increases to 0.648. Figure 27 shows that the extreme El Niño events from 1983 and 1997 generate variations in LOD of the order of 0.48 and 0.29 ms, respectively, whereas La Niña events from, e.g., 1972 or 1974–1976 induce the LOD anomalies of –0.28 and –0.19 ms, respectively. The value of the largest LOD fluctuations of 0.48 ms due to the El Niño occurrence corresponds to the displacement of about 0.223 m on the Earth's surface on the equator.

8. Monitoring of gravity changes

Earth tides were continued to be monitored in 2014 at the Borowa Gora Observatory of IGiK with the LCR G1036 gravimeter equipped with the LRFB-300 feedback system (Fig. 28).

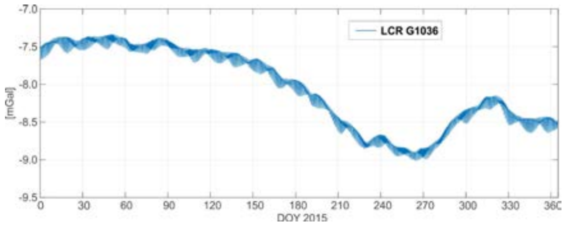

Fig. 28. Gravity record with LCR-G gravimeter in Borowa Gora Observatory averaged in 1 hour window

Basing on the parameters of the local tidal model for Borowa Gora Observatory developed in 2014 time series of tidal corrections for the Observatory was generated with the use of TSoft software. Local tidal model was then compared with the model used for gravity determination with the A10-020 absolute gravimeter and the differences between local and global tidal ephemeris was calculated (Fig. 29). The differences range between –10 nm/s^2 (1.0 µGal) and +13 nm/s^2 (1.3 µGal) (Dykowski et al., 2015a).

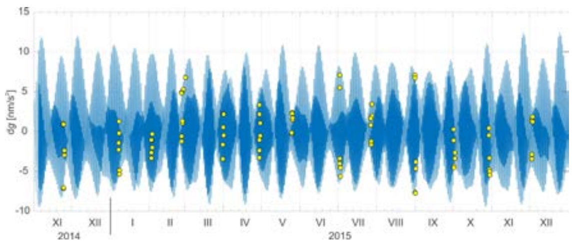

Fig. 29. Differences between local and global tidal ephemeris in 2015; differences for epochs of gravity determination with the A10-020 gravimeter marked with yellow dots

The results obtained indicate the need for considering those differences when interpreting the results of absolute gravity determination.

9. Activity in Satellite Laser Ranging and their use

The Satellite Laser Ranging station at Borowiec (7811) resumed laser measurements in the framework of the International Laser Ranging Service (ILRS) and EUROLAS Consortium since 2 March 2015 after 5 years break in activity. Satisfactory results were obtained two months later, i.e. 6 May 2015. Since 17 June all results of observations were sent to the EUROLAS Data Center (EDC). SLR station 7811 became fully operational within ILRS. Starting from 1 February 2016 its observations are available in SLR data banks.

In 2015 the Borowiec SLR station tracked 377 successful passes (6061 normal points and 248 699 good single shots) of 21 SLR satellites with the single shot average RMS of 2.4 cm. The Borowiec SLR station is currently in ILRS quarantine mode. This operation will be completed when at least 20 good LAGEOS-1, LAGEOS-2 and LARES passes are observed by the station and the results are confirmed by Analysis Centers. Currently 6 LAGEOS-1 passes remained to the fulfilment of the quarantine conditions. In 2015, activity focused also on the Space Surveillance Tracking (SST) programme of space debris laser observations. The Borowiec SLR station observed successfully several space debris satellites ENVISAT, TOPEX/POSEIDON and JASON-1. The results were sent to Space Debris Study Group in Graz.

Processing of the SLR observations by means of GEODYN-II software were continued in Borowiec Observatory. The station positions and velocities for all SLR stations (149 points) in the period from September 1983 to December 2012 were computed. The improvement of the accuracy of SLR station position determination is visible, especially in 1983 – 1996. The comparison of the station velocities obtained from SLR and GNSS results in 1996–2012 were presented in Szafranek et al. (2015). The study concerning the determination of velocity of Arabian tectonic plate from results of 21 GNSS stations distributed evenly around the Arabian Peninsula was presented (Alothman et al., 2015b). The results show a good agreement for the most of the GNSS stations.

Research on orbits of SLR satellites as conducted in WUELS. LAGEOS sensitivity to ocean tides was investigated (Sosnica, 2015a). Also the impact of the atmospheric drag on STARLETTE, STELLA, AJISAI, and LARES orbits was analysed (Sosnica, 2015b).

SLR data of LAGEOS 1, LAGEOS 2 and two low satellites, STARLETTE and STELLA acquired by 18 globally distributed ground stations over a period of 2.5 years were analysed in terms of their potentiality to estimate global elastic parameters of the Earth. A major discrepancy between the solutions from high and low satellites was only found for the Shida number l_2 (Rutkowska and Jagoda, 2015).

10. Geodynamics

Coordinate changes of selected EPN stations based on weekly solutions were analysed and parameters of approximating function by assuming an existence of periodic, annually repeatable trend were suggested. Fitting functions for two different periods of two ITRF frames of routine time analysis and reprocessing were applied (Maciuk, 2016).

Several models of relative vertical crustal movements in Poland were developed using data from ASG EUPOS network and evaluated (Kowalczyk, 2015).

Study of mechanisms of contemporary tectonic activity of the Sudetes region based on current observations of phenomena (in real time), which is unique in the Polish conditions are conducted in the underground Geodynamic Laboratory (GL) of the Space Reseach Centre, Polish Academy of Sciences (SRC PAS) in Ksiaz, which has exceptionally favorable natural conditions. The established spatial geodetic control and survey network in connection with measuring instruments will provide a holistic and comprehensive information of the processes that occur in the Ksiaz Massif: tectonic deformation, the bed rock tilts, vertical movements and displacements on faults. The multi-component model enables to estimate the compensation effect of tectonic deformation and the main direction of stresses. It will also provide information about the multi-phase nature of the tectonic event (Kaczorowski et al., 2015).

Based on long-term observations from ASG-EUPOS stations the new GNSS strain rates map was developed in the Military University of Technology. Since Poland is not a tectonically active region the analysis of GNSS measurements provide only deformations of the geodetic network itself. To increase the reliability of the results a special filtering approach was used to identify unreliable motion of stations. The basis of presented approach is the pattern in local strain rate field generated be anomalous movements (Araszkiewicz et al., 2016). In total, half of the analysed stations showed the unsuited motion and were excluded from further analysis. The verified strains show much better consistency between surrounding segments and a new map shows also striking similarity to present-day horizontal stress directions (Fig. 30).

IGiK, WAT and WUELS, integrated into the GGOS-PL network, together with the Institute of Geophysics of the Polish Academy of Sciences together with some other institutions made a substantial progress in activities towards establishing a common geodynamics research in the framework of the European Plate Observing System Programme (EPOS) (Bosy et al., 2015).

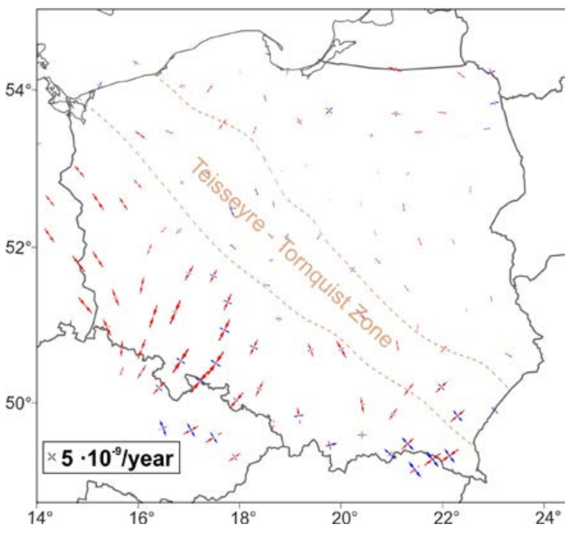

Fig. 30. The GNSS strain rate map over Poland

The application of space techniques for the determination of surface deformation is already for some time a subject of interest of a number of research groups in Poland. The project 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 is recently conducted in IGiK in cooperation with two other institutions. First results of IPTA analysis obtained from ENVISAT data registered from various orbits in the period between 2002 and 2008 demonstrate that most of the area of the central part of Warsaw is stable from the geological point of view, however small deformations (level of mm/year are observed in the western part of the city. The reasons of these movements are currently under (Ziolkowski et al., 2015).

Observations from permanent GPS stations are used to monitor surface deformations and mining induced seismic events at Legnica–Glogow Copper District (LGCD). The spatial-temporal evolution of the surface vertical displacement of these areas demonstrated relations with seismic tremors or rock burst induced by mining. Temporal and spatial characteristics and distribution of the displacements are found not accidental, which means that the coordinates of some permanent GNSS stations of ASG-EUPOS network about 40 km distant could be affected by tremors (Szczerbowski and Jura, 2015).

Similar research has been conducted for the area of Bochnia. The deformations observed are linked to by old mining but also to the orientation of tectonic stress and tectonic structures. It has been concluded that reliable investigations should be carried out both on the surface (GNSS) and underground with the use of a combination of geophysical and geodetic methods (Szczerbowski et al., 2016).

The analysis of time series of permanent GNSS stations coordinates was continued by the team of the Military University of Technology. The reliable determination of the velocities of those stations along with their uncertainties is indispensable for maintaining kinematic reference frames as well as for the interpretations of geodynamic effects. Klos et al. (2015c) searched for an optimum criterion to remove outliers. It has been shown the importance of removing seasonal signals from the time series prior to noise analysis causing the residuals to be non-normally distributed (Klos et al., 2015a). Bogusz and Klos (2015) proposed a method of the efficient elimination of the periodicities, based on the Least Squares Estimation. The method applied resulted in the improvement of velocity uncertainty even by 56% for some GPS stations investigated. The periodicities in the coordinate time series are not stable in time. The non-parametric method of year-to-year stacking was proposed to model the time varying curves (Bogusz et al., 2015b). The JPL topocentric time series for more than 300 globally distributed IGS stations were stacked the into data sets from January to December and then decomposed and approximated with a Meyer wavelet. An observed quasi-annual signal for a set of European stations prompted to divide them into different sub-networks called clusters. Each cluster was characterized by a similar amplitude and phase shift of quasi-annual signal. This approach allowed to investigate the changes of amplitudes in time for different regions in Europe (Fig. 31).

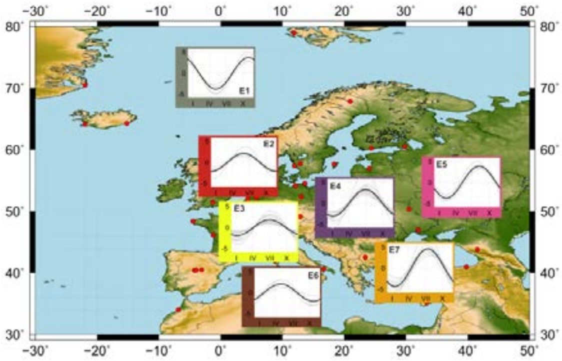

Fig. 31. The mean quasi-annual signal for individual European clusters

The analysis of daily solutions from 5 years for the ASG-EUPOS stations provided by MUT LAC show that spatio-temporal behaviour of the GPS-derived time series is not purely random; there is an evident uniform spatial response (Bogusz et al., 2015a). An extensive noise analysis of coordinate time series for 18 permanent GPS stations in Poland that belong to the EPN, using Maximum Likelihood Estimation (MLE) was conducted (Klos et al., 2015b). The results obtained indicated that concrete pillars are much better than buildings for GPS antenna locations. The same kind of analysis was applied to weekly GPS solutions from more than 150 EPN stations. The amplitudes of a white noise ranged from 0.5 to 3 mm for horizontal components and from 1.5 to 9 mm for vertical component. The amplitudes of white and flicker noise showed a clear geographical latitude dependence with a correlation with its minimum centered approximately at 50°N. The assumption of white plus flicker plus random-walk noise led to stations' velocity errors from 0 to 3 mm/year for the flicker noise and from 0 up to 7 mm/year for the random-walk. They proved that the spatial filtering applied (weighted stacking method) resulted in a decrease of power-law amplitudes by 1–2 mm/year-κ/4 in average and a shift in spectral indices to zero, with amplitudes and indices decreased of about 5%, compared to the time series before stacking (Fig. 32).

Bogusz (2015) applied a non-parametric wavelet decomposition proving its usefulness to investigate the non-linear motion of GNSS stations (Fig. 33).

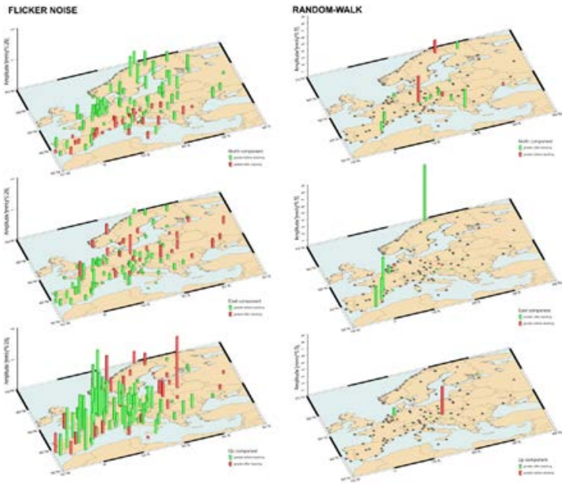

Fig. 32. Amplitudes of flicker (left) and random-walk (right) processes for selected EPN network stations' time series before and after filtering with stacking; the plots correspond to (from the top) North, East, Up components, respectively; the green colour represents a decrease in noise amplitudes when filtration was performed, whereas the red colour shows an increase which was observed mainly for short time series

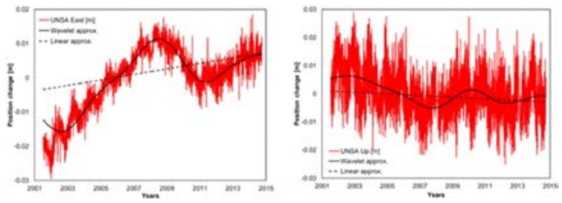

Fig. 33. Variations of UNSA (Salta, Argentina) East (left) and Up (right) components; the solid line represents the wavelet approximation, while the dashed line – a linear fit

Although the peak-to-peak amplitudes of non-linearity obtained in the last approximation were not found to be high (several centimetres) in comparison to linear approximation, they still remain variable in time. It was found that the trend of the coordinates of the stations located in the tectonically active areas is definitely non-linear for the selected (North, East or Up) components.

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