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Review paper

Research on gravity field modelling and gravimetry in Poland in 2015–2018

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Abstract: Activities of the Polish research gSDroups concerning gravity field modelling and gravimetry in a period of 2015–2018 are reviewed and summarised in this paper. The summary contains the results of research on the evaluation of GOCE-based global geopotential models (GGMs) in Poland and geoid modelling. Extensive research activities are observed in the field of absolute gravity surveys, in particular for the maintenance of national gravity control in Poland, Sweden, Denmark, the Republic of Ireland and in Northern Ireland as well as for geodynamics with special emphasis on metrological aspects in absolute gravimetry. Long term gravity variations were monitored in two gravimetric laboratories: the Borowa Gora Geodetic-Geophysical Observatory, and Jozefoslaw Astrogeodetic Observatory with the use of quasi-regular absolute gravity measurements as well as tidal gravimeter records. Gravity series obtained were analysed considering both local and global hydrology effects. Temporal variations of the gravity field were investigated using data from GRACE satellite mission as well as SLR data. Estimated variations of physical heights indicate the need for kinematic realization of reference surface for heights. Also seasonal variability of the atmospheric and water budgets in Poland was a subject of investigation in terms of total water storage using the GLDAS data. The use of repeatable absolute gravity data for calibration/validation of temporal mass variations derived from satellite gravity missions was discussed. Contribution of gravimetric records to seismic studies was investigated. The bibliography of the related works is given in references.

Keywords: gravity field, gravimetry, global geopotential model, geoid, absolute gravity measurements

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1. Introduction

Research activities in gravimetry and gravity field modelling performed by Polish research groups in the years 2015–2018 are the continuation/extension of those from the period of 2011–2014. Recent releases of GOCE-based global geopotential models (GGMs) require assessment and validation over the area densely covered with high quality terrestrial data, e.g. the area of Poland, to determine their usefulness for geoid modelling. On the other hand, new data and the use of upgraded strategies of geoid modelling result in the determination of higher accuracy geoid models on both regional and local scales, and their evaluation.

Research activities from the period 2015–2018, that concern the establishment and maintenance of gravity control, were separately summarised (Krynski et al., 2018). New absolute gravity surveys with the FG5-230 gravimeter of the Warsaw University of Technology (WUT) and, in particular, with the A10-020 gravimeter of the Institute of Geodesy and Cartography (IGiK), were conducted in that period for the maintenance of national gravity control in Poland and in a couple of other European countries as well as for investigating geodynamic phenomena of both natural as well as anthropogenic origin.

The installation of the first superconducting gravimeter iGrav-027 in the middle of 2016 in Poland at the Borowa Gora Geodetic-Geophysical Observatory (BG) of IGiK made a major improvement in gravimetric research, in particular in metrological support of absolute gravity surveys to monitor and maintain the gravity standard. Intercomparison of the iGrav-027 record with simultaneous records with LCR gravimeters and A10-020 data was used to determine scale factor of the iGrav-027. Both gravimeters FG5-230 and A10-020 participated in comparison campaigns of absolute gravimeters (local and international). In addition, laser, rubidium oscillator, and the barometer of the A10-020 gravimeter were regularly calibrated in National Metrological Institutes. Scale factors of LCR gravimeters completing gravimetric metrological infrastructure are also regularly determined on the Polish gravimetric calibration baselines.

Continuation of monitoring of long term gravity variations in gravimetric laboratories at the Borowa Gora and Jozefoslaw observatories provides data for the investigation of non-tidal gravity changes due to e.g. atmosphere and hydrology. It also allows investigation of the effect of local water table changes on measured gravity.

Determination of temporal variations of the gravity field with the use of data from satellite gravity missions is of growing interest of scientific community. The performance of filters applied to reduce the noise contained in GGMs as well as the choice of a method for the analysis and modelling temporal variations of geoid heights requires investigation, in particular on local scale. Estimation and modelling physical height changes are fundamental for the kinematic definition of the reference surface for heights. The results of the research in that matter for Poland and Central Europe can be used in corresponding research in other regions of the world.

Investigations concerning the use of gravimetric records from tidal gravimeters for advanced seismic studies were initiated in 2016 in Poland. In particular, they were oriented on the complementary role of seismic surface waves of very long periods recorded with tidal gravimeters may to seismometer data in seismic analysis. Innovative research in that matter was undertaken and first results were presented.

2. Geoid/quasigeoid modelling and study of the gravity field in Poland

2.1. Evaluation of GOCE-based GGMs

The use of data from satellite gravity missions for modelling gravity field was extensively investigated at IGiK (Godah et al., 2015a). The accuracy of 1st – 5th releases of GOCE-based GGMs developed with the use of the direct solution (DIR) and the time-wise solution (TIM) strategies was assessed over the area of Poland using EGM2008 in terms of height anomalies as well as free-air gravity anomalies. Height anomalies obtained from GOCE-based GGMs were additionally compared with the corresponding ones from three different GNSS/levelling data sets (Control Traverse – 184 GPS/levelling stations of high precision, EUVN – 58 sites, and POLREF – 315 sites) with the use of the spectral enhancement method (SEM) (Hirt et al., 2011). Consecutive releases of GOCE-based GGMs investigated exhibit clear quality improvement.

The best performance shows the 5th release GOCE-based GGM developed with the use of time-wise strategy. Its fit to gravity anomalies, and height anomalies in terms of the standard deviation equals 0.84 mGal and 2.8–3.4 cm, respectively (Godah et al., 2015b).

The evaluation of GOCE-based GGMs over such area like the area of Poland which is densely covered with high quality data provides valuable information on the quality of geoid that can be determined from those GGMs in the areas where terrestrial data is sparse and rather low quality. The extended investigation was conducted at the area of Sudan where GGMs calculated from approximately 12 months of GOCE data were compared with the EGM2008 and terrestrial data. Gravity anomalies and geoid heights obtained from the GOCE-based GGMs fit to the corresponding ones from the EGM2008 truncated to d/o 200 with the standard deviation of 3.4–4.2 mGal, and 18–20 cm, respectively. Their fit to the terrestrial gravity anomalies and geoid heights from GNSS/levelling, in terms of standard deviation is of 5.5 mGal, and of 50 cm, respectively. Although the obtained results do not match the nowadays geoid heights accuracy worldwide, the use of geoid models computed from GOCE-based GGMs could be recommended for GNSS levelling in Sudan (Godah and Krynski, 2015).

Fifteen GGMs developed in 2014–2016 with the use of data from satellite gravity missions GRACE and GOCE were evaluated In the Centre f Geodesy and Geodynamic of IGiK. Height anomalies determined from those models were compared with GNSS/levelling data at 98 ASG-EUPOS stations as well as with absolute gravity data at 168 stations of the modernized gravity control in Poland. Standard deviations of differences of height anomalies $\sigma(\zeta)$ and gravity anomalies $\sigma(\Delta g)$ are at the level of 2.2 cm and 1.7 mGal, respectively, for combined (satellite and terrestrial data) models and 16.0 cm and 9.8 mGal, respectively, for satellite-only models (Krynski and Rogowski, 2017).

In the next step, quality of five satellite-only GGMs as well as one combined GGM were evaluated (Krynski and Rogowski, 2018). The results obtained indicate poor quality of spherical harmonics above d/o 200 in satellite-only GGMs investigated.

2.2. Geoid modelling

Two consecutive gravimetric quasigeoid models for Poland: GDQM-PL13 (Szelachowska and Krynski, 2014) and GDQM-PL15 (Krynski and Rogowski, 2015) were developed in IGiK using the same computational strategy. To develop GDQM-PL15 the new gravity data from Czech Republic and Slovakia were used. Accuracy of those models was assessed with the use of precise GNSS/levelling data (Figure 1).

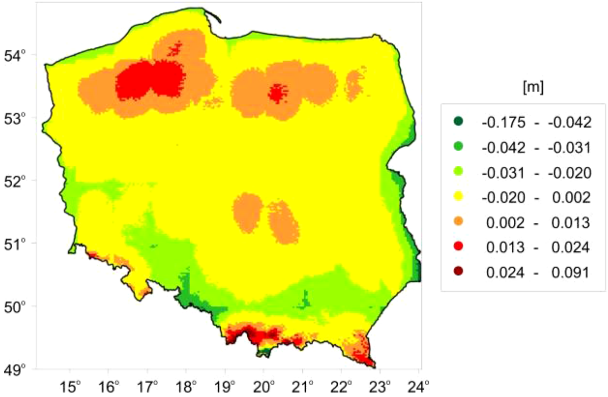

Fig. 1. Comparison of the GDQM-PL13 model with the GDQ08 model (Szelachowska and Krynski, 2014)

The fit of height anomalies from GDQM-PL13 and GDQM-PL15 to the corresponding ones of 1st and 2nd order sites of GNSS/levelling Control Traverse, and the sites of the EUVN, ASG-EUPOS, and POLREF networks, in terms of standard deviations of respective differences, is presented in Table 1.

Table 1. Standard deviations of differences between height anomalies obtained from geoid models and the respective ones at the stations of GNSS/levelling Control Traverse, and of the EUVN, ASG-EUPOS, and POLREF networks [cm]

Geoid model	Traverse 1st order 44 sites	Traverse 2nd order 140 sites	EUVN 58 sites	ASG-EUPOS 98 sites	POLREF 315 sites
GDQM-PL13	1.4	1.6	1.7	1.8	2.3
GDQM-PL15	1.5	1.7	2.9	1.8	2.6
GDQM-PL16	1.3	1.6		1.9	

GGM GECO, which is the combination of GOCE data with the EGM2008, was used to develop the following gravimetric quasigeoid model GDQM-PL16. The fit of height anomalies from GDQM-PL16 to the corresponding ones of 1st and 2nd order sites of GNSS/levelling Control Traverse, and the sites of the ASG-EUPOS, in terms of standard deviations of respective differences, is also given in Table 1 (Krynski and Rogowski, 2017).

It has been shown that scattered/sparse absolute gravity data can efficiently be used of for validation of GGMs as well as for improving quasigeoid heights derived from satellite-only GGMs (Godah et al., 2018a). The spectral enhancement method (SEM) (Hirt et al., 2011) was employed to validate gravity anomalies obtained from combined GGMs: EGM2008, EIGEN-6C4, and GECO with absolute gravity determined with the A10-020 gravimeter at 161 gravity stations of the modernized Polish gravity control.

High accuracy GNSS/levelling data was used for evaluation the quasigeoid heights obtained from the satellite-only GGM and from the satellite-only GGM in combination with absolute gravity data. The short wavelength components, i.e. from d/o 219 onward, of the Earth's gravity field were compensated using the Shuttle Radar Topography Mission (SRTM) model with spatial resolution of $30'' \times 30''$ (i.e. SRTM30, Becker et al., 2009). The results obtained from this evaluation indicate that adding absolute gravity data to the satellite-only GGM leads to improvement of quasigeoid model developed by a factor of 2.5 in terms of its spatial resolution and accuracy. They demonstrate the capability of absolute gravity data determined with A10 gravimeter for the validation of GGMs as well as for improving geoid/quasigeoid heights obtained from satellite-only GGMs.

Research on the determination of geoid in Saudi Arabia was conducted with contribution of IGiK. Geoid heights at 5187 GNSS/levelling stations and gravity anomalies at 3500 stations in Saudi Arabia were used for validation of GOCE-based GGMs. Vertical datum accuracy of 22 cm was estimated. Up to 16% improvement in geoid heights determined from satellite only GGMs can be achieved by adding short wave signal obtained from EGM2008 and SRTM (Elsaka et al., 2015). Among GOCE-based GGMs investigated TIM_R4 and TIM_R5 fit best to terrestrial gravity data in Saudi Arabia and thus they are recommended as reference models when determining gravimetric geoid over the Arabian Peninsula (Alothman et al., 2015).

Research on the use of the geophysical gravity data inversion technique (GGI) for local quasigeoid modelling was further conducted at the Wroclaw University of Environmental and Life Sciences (WUELS). The extents of a DEM and the Moho depth model as well as the extent of gravity data and its density data as parameters of input data used in GGI were estimated (Trojanowicz, 2015a). Accuracy of local quasigeoid modelling using the GGI method was assessed at the level of 1.2 cm in the case study for the area of Poland. Such accuracy can be achieved with input data: GNSS/levelling height anomalies of ±2.0 accuracy, and gravity data of ±1.3 mGal accuracy (Trojanowicz, 2015b).

Geoid modelling was also a subject of research at the University of Warmia and Mazury in Olsztyn (UWM). The least squares modification of Stokes' formula with additive corrections method (LSMSA) was applied to develop a new gravimetric geoid model for Poland. The model was evaluated with height anomalies at the stations of the ASG-EUPOS network (Kuczynska-Siehien et al., 2016). The local average geopotential value of W_0^L was determined at UWM using data at Swinoujscie, Ustka, and Wladyslawowo tide gauges, at the Baltic Sea coast, geoid undulations from the EGM2008 and ellipsoidal heights from revised GNSS data obtained from three campaigns of the Baltic Sea Level Project as well as the new GNSS campaign from 2015 at three investigated tide gauge stations. The best estimation of W_0^L equal to 62636857.45 m^2s^{-2} was obtained from the campaign carried out in 2015 (Kuczynska-Siehien et al., 2017).

Shipborne and airborne gravity anomalies were used for validation of gravity anomalies derived satellite altimetry models, along the Polish coast and Baltic Sea. New gravimetric quasigeoid model for Poland of 1.4 cm accuracy estimated using GNSS/levelling data at ASG-EUPOS stations, was developed with the use of new gravity data from satellite altimetry, EIGEN-6C4, and SRTM models (Kuczynska-Siehien and Lyszkowicz, 2017).

Current state of development of satellite altimetry is sufficiently advanced to allow a number of inland water case studies. Special attention was paid at the Koszalin University of Technology on the use of altimetry for monitoring elevations of continental surface water (Bernatowicz and Lyszkowicz, 2017). Variation of the surface elevation of the Lebsko Lake was investigated. A total of 26 satellite tracks of Jason-2 from the period of 9 months of 2016 were analysed with the use the toolbox BRAT developed by ESA showing that altimetry is a promising tool for true global lake studies with centimetre accuracy.

The quasigeoid determined from the EGM2008 was calibrated at the Rzeszow University of Technology with the use of satellite/levelling data of the following networks: ASG-EUPOS (213 stations and their eccentricities), EUVN (40 stations), EUREF-POL + POLREF (317 stations) creating the quasigeoid model PL-geoid-2011 which became recommended by the surveying and mapping agency in Poland (GUGiK). The fit of height anomalies derived from EGM2008 to the respective ones at the stations of satellite/levelling networks, in terms of the standard deviation can be improved from 3.3 cm to 2.3 cm by using 3D transformation with the estimation of 7 transformation parameters (Kadaj and Swieton, 2016).

The performance of the application of the selected quasigeoid models to satellite/levelling data at more than 100 stations along 1000 km of levelling lines in the area of Lower Silesia in Poland was investigated at UWM. The analysis of the number of quasigeoid models, including the recently developed local satellite/levelling geoid LGOM2015 model, showed that the most accurate is the local model; its accuracy is better than 1 cm (Figure 2) (Stepniak et al., 2017).

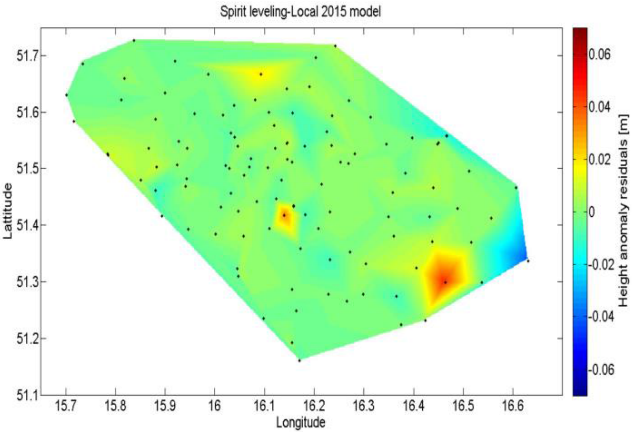

Fig. 2. Height anomaly residuals of the LGOM 2015 model (Stepniak et al., 2017)

The use of classical kriging (cK) and moving window kriging (MWK) on a sphere in modelling geoid based on GNSS/levelling data was investigated at three test areas in USA by the team of the AGH University of Science and Technology in Cracow. It was shown that in the case of high-sampling density the use of MWK instead of cK does not improve accuracy. For more sparse datasets (low-sampling density) MWK provides much better fit to data than cK (Ligas and Kulczycki, 2018).

The new PL-EVRF2007-NH vertical reference system, introduced in the spatial reference system of Poland in 2012, will be the only binding vertical system from 2020. The system is realized by the precise levelling network with the so-called the fourth levelling campaign (measurements from 1997–2001) related to over 45 000 benchmarks of the fundamental and base levelling points, adjusted as a part of the UELN network. Elevations in the new system differ by ca. $+175$ mm from the respective ones in the outgoing PL-KRON86-NH system connected with the tidal gauge in Kronstadt. The introduction of the new vertical reference system causes a necessity to apply a new quasigeoid model in geodetic surveying related to satellite levelling and defined with a common European Vertical Reference System (EVRS).

The introduction of EVRS enables to include the European Gravimetric Geoid model (EGG) developed in the framework of the European Gravity and Geoid Project (EGGP, from 2011 Gravity and Geoid in Europe) (Denker, 2013). EGG2008 as the pure-gravimetric geoid model shifted by a constant value of $\zeta_0 = +302$ mm, resulting from the averaging differences in height anomalies at the stations of the EUVN network (10 in Poland), was implemented. Thus, fitting EGG2008 into the EVRF2007 system was reduced to a parallel (vertical) shift of the gravimetrically determined surface by that mean value.

The accuracy of the EGG2008 quasigeoid model in Poland was estimated using satellite/levelling data at the stations of EUVN and EUVN_DA networks (40 stations), POLREF network (310 stations), eccentric stations of the active GNSS network ASG-EUPOS (109 stations) whose coordinates were determined in PL-ETRF89 and PL-ETRF2000 frames and the heights in the PL-EVRF2007-NH frame.

The PL-EVRF2007-NH system was realized in the zero-tide system, while the ellipsoidal heights of the stations investigated are defined in the non-tidal system. Therefore, the ellipsoidal heights require a correction to the zero-tide based on EVRS system formulae (Mäkinen and Ihde, 2008).

Differences between height anomalies obtained from satellite/levelling data in both reference frames investigated and the respective ones computed from EGG2008 gravimetric quasigeoid model (Figure 3) were analysed (Olszak et al., 2018). Their statistics are given in Table 2.

The EGG2008 quasigeoid model exhibits significantly better agreement with the ETRF2000 than with the ETRF89 system. The fit of EGG2008 to ASG-EUPOS is similar to its fit to EUVN. The results obtained show that the estimated accuracy of EGG2008 model represented by the standard deviation of the differences between the respective height anomalies depends on the quality of the used satellite/levelling dataset. The average accuracy of EGG2008 for the region of Poland for ETRF2000 reference frame is at

Table 2. Statistics of differences between height anomalies obtained from satellite/levelling data and the respective ones computed from EGG2008 gravimetric quasigeoid model [m]

Statistics	EUVN		POLREF		ASG-EUPOS	
	ETRF2000	ETRF89	ETRF2000	ETRF89	ETRF2000	ETRF89
RMSE	0.023	0.084	0.024	0.073	0.020	0.080
Std	0.021	0.031	0.024	0.033	0.018	0.028
Max – Min	0.097	0.142	0.203	0.163	0.085	0.125
Mean	–0.009	–0.078	–0.001	–0.065	–0.009	–0.075
Median	–0.009	–0.078	–0.003	–0.063	–0.011	–0.075

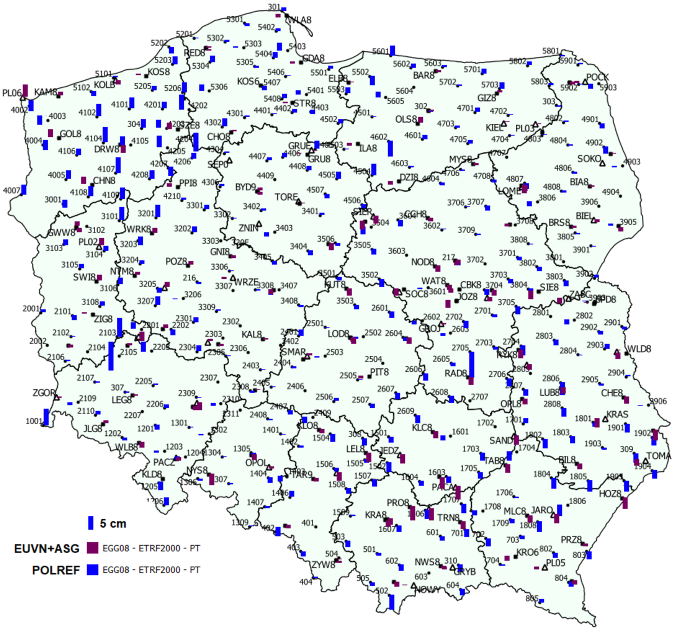

Fig. 3. Differences between height anomalies obtained from satellite/levelling data and the respective ones computed from EGG2008 gravimetric quasigeoid model (ellipsoidal heights in the zero tidal system)

the level of 2 cm. The results obtained proved the limited potential of satellite/levelling data for the validation of high quality gravimetric geoid.

3. Absolute gravity surveys

Two institutions in Poland operate absolute gravimeters: WUT (FG5-230) and IGiK (A10-020). Both gravimeters were used in various projects in Poland and in other European countries for maintenance of gravity control, geodynamical research and metrology.

3.1. Absolute gravity surveys for the maintenance of national gravity control in Poland

The survey related with the modernization of the gravity control in Poland was completed in 2015 (Dykowski and Krynski, 2015a). The modernized gravity control consists of 30 fundamental stations, at which gravity was determined with the use of the FG5-230 gravimeter, and 168 base stations, at which gravity was determined with the A10-020 gravimeter. The total uncertainty of gravity determined in an effective height as well as reduced to the pillar, obtained on the basis of at least double determination of the nonlinear vertical gravity gradient over the benchmark was analysed. It ensures the uncertainty of 4 μGal and 10 μGal of the reduced gravity value for fundamental stations and base stations, respectively.

Differences between absolute gravity values obtained in the last decade of 20th century, during the establishment of the previous gravity control in Poland, and the corresponding ones obtained during the first stage of its modernization from 2006-2007 indicate some interesting phenomena (Barlik et al., 2018).

At selected stations in the mountain region (Zakopane in the Tatra Mountains, Janowice in the Sudeten area) slight changes in gravity are observed in 10 years period. They can reflect the gravity effect caused by the global hydrology changes that can be derived from the GLDAS_NOAH10_M model (Rodell et al., 2004) (Figure 4).

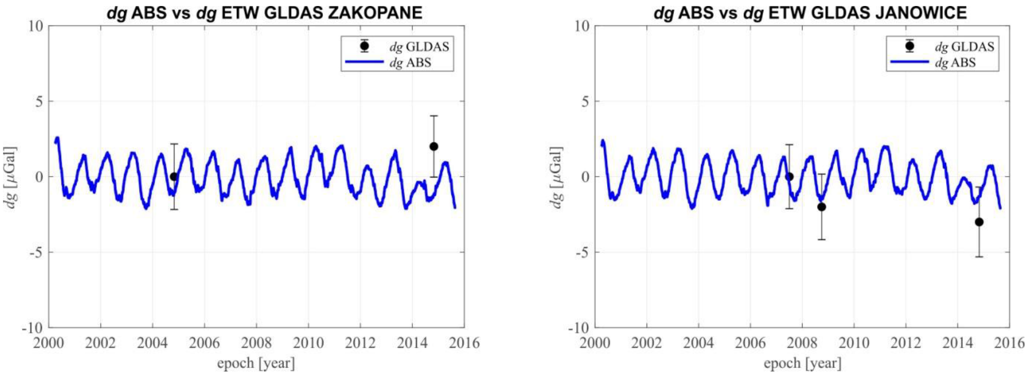

Fig. 4. Absolute gravity changes at Zakopane and Janowce stations with the gravity effect caused by the global hydrology changes derived from the GLDAS_NOAH10_M model

At stations located in central and northern Poland (Ojcow, Lamkowko) no such clear relationship between gravity changes and global hydrological changes were observed. Gravity at those stations also clearly differ from those determined in 1990s mainly due to different types of absolute gravimeters used (JILAg, IMGC, FG5) (Figure 5).

At several stations, rather conspicuous differences in gravity reaching several tens of μGal were obtained. They might be interpreted as the effect of anthropogenic factors, i.e. installation of liquid fuel tanks in the immediate vicinity of the Bialowieza station, and a new building constructed close to the Wroclaw station indicating high sensitivity of absolute gravimeters to “mass rebuild” in the close vicinity of the gravity station.

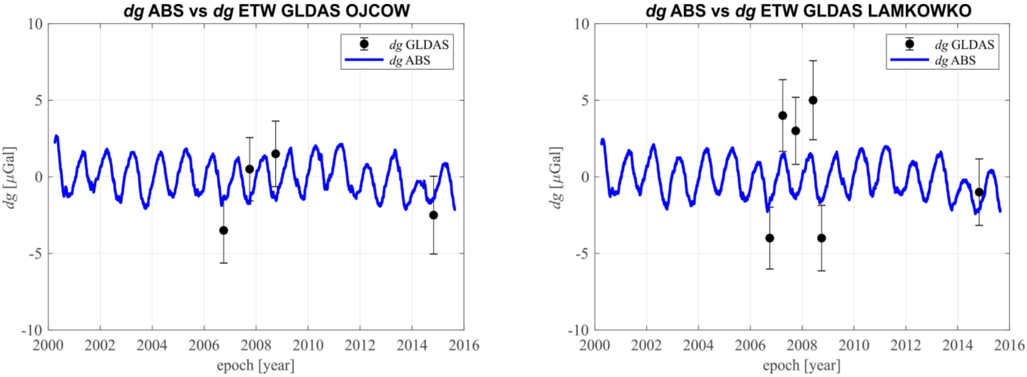

Fig. 5. Absolute gravity changes at Ojcow and Lamkowko stations with the gravity effect caused by the global hydrology changes derived from the GLDAS_NOAH10_M model

Each of these examples justify the conclusion that the maintenance of gravimetric reference system in Poland requires, besides careful metrological control, consideration of the impact of global hydrological variations. At the same time, a conclusion was drawn that national gravimetric reference system should be updated more often than every 20 years, as suggested by the Polish geodetic law.

3.2. Absolute gravity surveys for gravity control maintenance in Europe

Within the period from 2015 to 2018, the gravimetric team of IGiK was involved in gravity maintenance and establishment in several European countries. Gravity surveys with the A10-020 absolute gravimeter were performed in Sweden in 2015 and Denmark in 2018. The team of IGiK also undertook long term cooperation with the Ordnance Survey Ireland (OSi) as well as the Land Property Services (LPS) for the design and establishment of a modern gravity control across the whole island of Ireland in the framework of the AGN Ireland project.

3.2.1. Sweden

In 2015 the team of IGiK performed a single survey campaign in Sweden using the A10-020 absolute gravimeter, determining gravity on 25 stations (Figure 6) within the cooperation with Swedish Lantmäteriet on the establishment of a new gravity system in Sweden called the RG-2000 (Engfeldt et al., 2018). The epoch of RG 2000 is 2000.0, which corresponds well with the epochs of the national Swedish height system RH 2000, and the national 3D system SWEREF 99. In five field campaigns conducted in 2011, 2012, 2013, and 2015, gravity was determined with the A10-020 at 98 sites densifying the gravity reference frame for Sweden primarily based on the observations with FG5 gravimeter. Surveys from 14 FG5 stations, 96 A10-020 gravimeter stations and nearly 200 relative stations were adjusted for the final shape of the RG2000 gravity network. The A10-020 as well as the Swedish FG5-233 (later upgraded FG5X-233) gravimeters participated in absolute gravimeter comparisons on a regular basis during the cooperation, which allowed to include determined offsets in the adjustment process. Additionally, all campaigns in Sweden with the A10-020 gravimeter started and finished in Maartsbo for internal control. The data acquired with the A10-020 at the sites of RG 2000 are available in the International Absolute Gravity Database (AGrav) of the International Association of Geodesy (IAG) maintained by BKG and BGI.

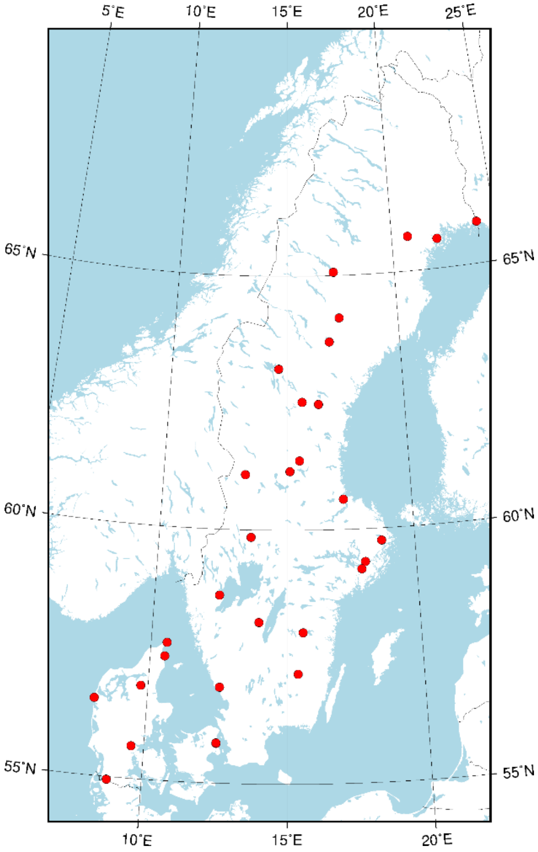

Fig. 6. Stations where absolute gravity was surveyed with the A10-020 in Sweden (2015) and Denmark (2018)

3.2.2. Denmark

In 2018 the team of IGiK supported the activities of DTU Space in the annual maintenance of gravity control in Denmark. In a single survey campaign the absolute gravity was determined with the A10-020 gravimeter at 8 stations (6 of them were located outdoors) (Figure 6).

3.2.3. Republic of Ireland and Northern Ireland

The project on the establishment of the modern gravity control in Ireland (Absolute Gravity Network for Ireland – AGN) by the team of IGiK started in the middle of 2018 (Krynski et al., 2018). The conceptual plan includes gravity surveys on total 62 stations. Nearly 50 of them are located in the open field, 6 stations will serve as the gravimetric calibration baseline, 7 stations are previous gravity reference of IGSN71 which are planned to be resurveyed. First gravity survey campaign was performed in 2018 covering in total 26 stations: 6 IGSN71 stations (3 stations connected with relative gravity survey), 2 stations of the gravimetric calibration baseline, and 18 network stations (Figure 7). On all network stations surveyed vertical gravity gradients were also determined. Further surveys regarding the AGN project are planned for the summer of 2019. Additionally, to evaluate the significant ocean tidal loading effect for the island of Ireland the LaCoste&Romberg G-1084 gravimeter was set up at OSi headquarters near Dublin to serve as a tidal instrument.

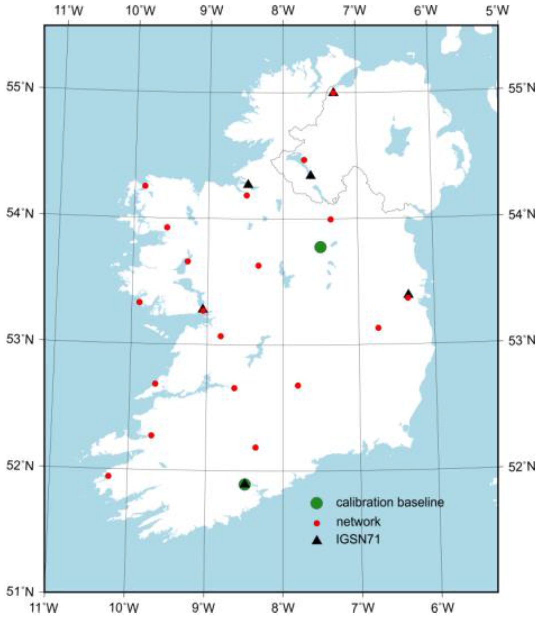

Fig. 7. Gravity stations surveyed in 2018 in the Republic of Ireland and Northern Ireland in the framework of the AGN Ireland Project

3.3. Absolute gravity surveys for geodynamic research

Several activities related to quasi-permanent monitoring of gravity changes in Poland were carried out in the years 2015–2018. Two main activities concerned geodynamical monitoring in Pieniny Klippen Belt (PPK) in southern Poland and mining area monitoring in the Upper Silesian Region (UPR).

A project concerning the geodynamic test field in PPK was completed in 2016. The results obtained with the use of wide spectrum of surveying techniques applied in this area between 2004 and 2015, especially GNSS measurements, precise levelling and absolute gravimetry were summarized (Walo et al., 2016).

In 2017 the first epoch of the absolute gravity measurements at two stations: Dziwie (Wielkopolska Voivodeship), and Holowno (Lublin Voivodeship) of the Monitoring of Geodynamics in Poland (MoGePL) network, newly created by the geohazard section at the Polish Geological Institute, were conducted. These stations are a supplement to 7 seismic stations operating within the Polish Seismological Network. Stations of MoGePL network are equipped with modern wide-band seismic, magnetic, GNSS, meteorological and hydrogeological equipment which is installed in a very stable conditions to provide long term observations. In the near future, tidal gravimeters are planned to complete the equipment at those stations. Simultaneous seismic and continuous gravity record with spring gravimeters (LCR G-986) at Holowno station started in 2018.

Within the framework of the EPOS-PL project, the team of IGiK performs a periodic absolute gravity survey on 10 field stations (Figure 8 – red dots) of the polygons of Multidisciplinary Upper Silesian Episodes (MUSE) located one in non-active and the other in still active mining areas in UPR. The purpose of the periodic absolute gravity surveys (every 6 months) is to provide a reliable gravity reference for periodic relative surveys conducted also every 6 months on nearly 200 stations of MUSE (Figure 8 – black dots). On the same nearly 200 stations, precise GNSS surveys are performed to assess the deformations induced by mining (Mutke et al., 2018; Sośnica et al., 2018). By the end of 2018, three gravity and GNSS campaigns were conducted.

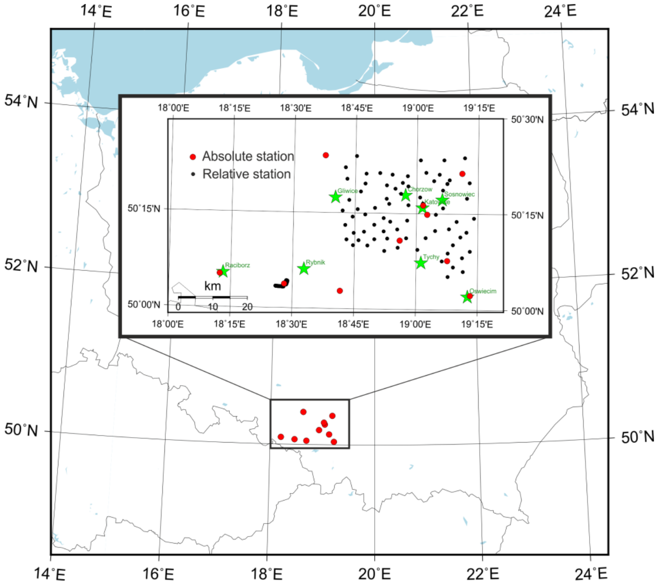

Fig. 8. Gravity stations surveyed within EPOS-PL project at MUSE polygons

3.4. Metrological aspects in absolute gravimetry

To monitor and maintain the gravity standard in Poland the A10-020 and FG5-230 absolute gravimeters (AGs) participate on the regular basis in local, regional and international absolute gravimeter comparisons. Additionally, subcomponents of both instruments (laser, rubidium clock and barometer) are regularly calibrated at the Polish Central Office of Measures (GUM) with respect to corresponding national metrological standards.

Local comparisons of the A10-020 and FG5-230 absolute gravimeters are carried out since 2012 on annual basis. Additionally, since 2009 both gravimeters participated in 3 international comparisons of AGs what allowed for their indirect comparison. In 2016 all current comparisons had been summarised and compared with the results from international comparisons (Dykowski and Olszak, 2016). Gravity determined with both instruments differed over 8 years by values ranging from +11.3 µGal to −4.0 µGal (Figure 9). The results of local comparisons are moreover consistent within a few µGal with indirect offsets determined at the international comparisons of AGs.

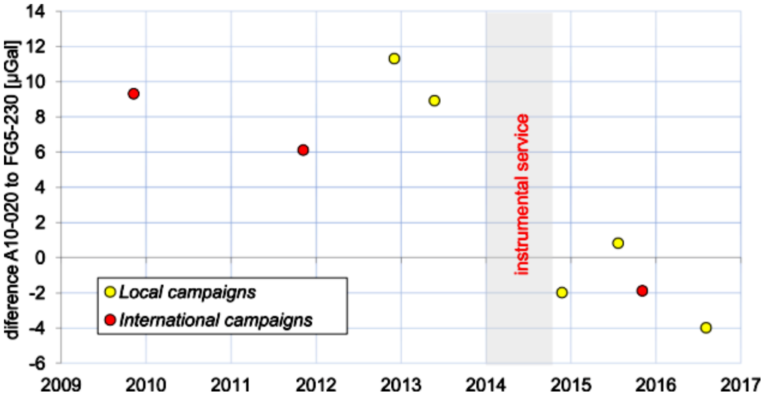

Fig. 9. Results of local comparisons of the A10-020 and FG5-230 absolute gravimeters

Both the A10-020 and FG5-230 gravimeters participated in the EURAMET.M.G-K2 Key Comparison and Pilot Study in 2015 AG comparison in Belval, Luxemburg (Palinkas et al., 2017). The comparison included 17 absolute gravimeters, of which 15 were FG5-type instruments, one A10-type of IGiK (sn 020) and one IMGC-type of INRIM (sn 02). The offsets of the FG5-230 and A10-020 estimated within the Pilot Study (includes all participating instruments) were −4.2 µGal and −6.4 µGal, respectively.

The A10-020 absolute gravimeter of IGiK also participated in the 2018 EURAMET.M.G-K3 Key Comparison and Pilot Study AG comparison in Wettzell, Germany. Data is being processed, and a respective publication is expected to appear early 2019.

The long term stability of the A10-020 absolute gravimeter for establishing modern gravity controls in Europe was investigated (Dykowski et al., 2018a). In order to assure a full reliability of the A10-020 gravimeter several periodic control activities were implemented. The most basic ones concerned calibration of the A10-020 internal components: He-Ne laser, rubidium oscillator, and the barometer. In the period from 2008 to 2018 all three components of the A10-020 gravimeter were calibrated at least once a year. Calibrations were performed in multiple National Metrological Institutes as well as in associated institutions with relevant infrastructure.

Results of the calibrations of the laser of the A10-020 are shown in Figure 10. The red/blue mode drift appears symmetrically with respect to the central frequency which has a linear trend, and after 9 years became smaller than the initial calibration value by ~ 8 MHz, which corresponds to ~160 nm/s^2 difference in the calculated gravity value. It indicates a necessity to monitor laser frequency on a regular basis. Results of the calibrations of the clock of the A10-020 range within 0.015 Hz, which corresponds to ~ 30 nm/s^2 in gravity variation.

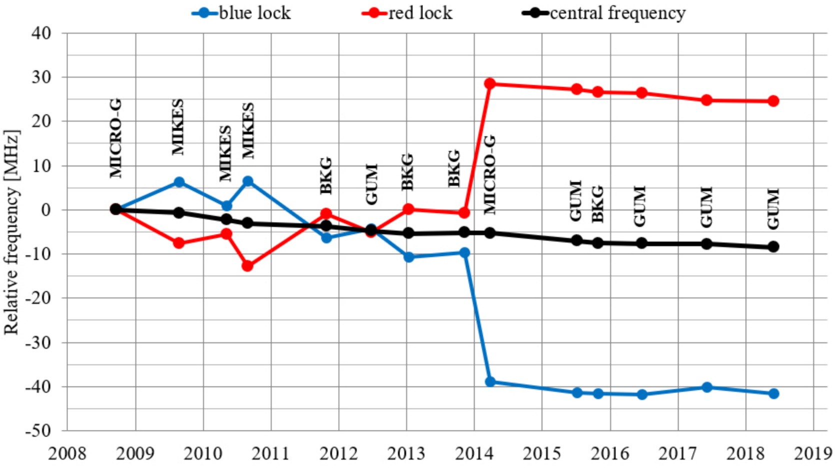

Fig. 10. Results of calibrations of the laser of the A10-020 gravimeter 2009–2018

Within the years 2008-2015, both gravimeters the A10-020 of IGiK and the FG5-230 of WUT took part in four local AG comparisons either at the Borowa Gora Observatory or at Jozefoslaw Observatory. They also participated four times in the International/European Comparison of Absolute Gravimeters Campaigns (ICAG2009, ECAG2011, ICAG2013, EURAMET.M.G-K2 Key Comparison and Pilot Study in 2015). Results of the comparisons for the A10-020 gravimeter (offset values) for Key Comparison and Pilot Study are shown in Figure 11.

To summarise, Polish teams of IGiK and WUT are active in fulfiling the requirements for supporting the new definition of the new International Gravity Reference System (IGRS) as an alternative to IGSN71, currently discussed by IAG Joint Working Group 2.1.1. In the created structure of the IGRF presently two stations were selected in Poland: Borowa Gora and Jozefoslaw.

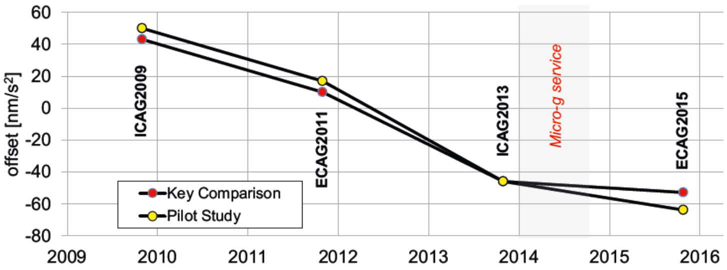

Fig. 11. Offsets of the A10-020 gravimeter during the International Comparison of Absolute Gravimeters Campaigns

3.5. Metrological aspects in relative gravimetry

3.5.1. Polish Gravimetric calibration baseline maintenance

There are two gravimetric calibration baselines in Poland: a Central Gravimetric Calibration Baseline consisting of 11 stations: FROM, LAMK, CHOR, BOGO, JOZE, RADO, CHEC, OJCO, MZAZA, ZAKO, KAWA, and Western Gravimetric Calibration Baseline consisting of 5 stations: KOSZ, BORO, LUBI, JANO, SINI. All those gravity stations belong to the fundamental gravity control of Poland and have a solid monumentation. For each gravity station there is an eccentric station located in its immediate vicinity and the other associated station belonging to different types of geodetic networks (satellite and levelling). Absolute gravity value at the stations of gravimetric calibration baseline stations was determined partly in 2007-2008 and partly in 2014, in different epochs unfortunately.

3.5.2. Scale factor determination for continuous gravimetric records

An important task undertaken by the team of IGiK was to establish as precise as possible the scale factor for the iGrav-027 superconducting gravimeter installed at BG. During the period of operation of the iGrav-027 several calibration experiments were carried out to determine its scale factor. Most of them were performed in a specially planned time period to achieve the highest amplitude of the tidal curve (Dykowski et al., 2016; Sękowski et al., 2016; Dykowski et al., 2017, 2018b). The longest experiment lasted 10 days in June 2017. Within the same time frame the iGrav-027 was calibrated by means of three LCR spring gravimeters (two of which are periodically calibrated on a gravimetric calibration baseline). It was also calibrated against the A10-020 absolute gravimeter (a pair of red/blue sets every 1 hour). In all calibrations (Table 3) a linear least squares fit was applied (Dykowski et al., 2016; Sękowski et al., 2016).

The accuracy of the iGrav-027 scale factor determination with the use of LCR gravimeters was at the level below 0.1% what is within the requirements for superconducting gravimeters. Also a very good accuracy (0.3%) of its scale factor determined

Table 3. Determination of the scale factor of the iGrav-027

Date	Instrument	iGrav-027 [nm/s^2/V]	Error [nm/s^2/V]
2017.06	A10-020	−1065.13	3.51
2017.06	LCR G1012	−1062.08	0.80
2017.06	LCR G1084	−1064.06	0.33
2016.08	FG5-230	−1063.03	3.13
2016.05	A10-020	−1069.74	7.62
2016.05	LCR G1012	−1060.36	0.52
2016.05	LCR G1084	−1064.32	0.31
	average	−1063.27	2.95

with the use of the FG5-230 gravimeter was achieved. Overall all scale factor values determined up to now for the iGrav-027 are within 10 nm/s^2/V, i.e. below 1%.

4. Investigations of non-tidal gravity changes

4.1. Monitoring of long term gravity variations in gravimetric laboratories

4.1.1. Monitoring program in Borowa Gora

The major upgrade in the gravity monitoring program in Poland was the installation of the first superconducting gravimeter – the iGrav-027 produced by GWR Inc. The gravimeter has been installed in February/March 2016 at BG, situated 34 km north of Warsaw, and is operational providing data since the end of April 2016. The iGrav-027 record supplements the LCR tidal records as well as the long term time series of monitoring gravity variations determined with the A10-020 gravimeter at BG. Details concerning the location of the instrument, preparations of installation can be found in (Sękowski et al., 2016). One of the first tasks with the iGrav-027 gravimeter was to determine its scale factor (see section 3.5).

The data collected with the iGrav-027 gravimeter is periodically analysed in terms of internal consistency and long term stability understood as instrumental drift (Dykowski et al., 2016, 2017, 2018b, 2018c). In 2018 more than 2-year long time series of gravity variations recorded with the iGrav-027 was analysed (Dykowski et al., 2018c). Data from the iGrav-027 gravimeter is also regularly submitted to the International Geodynamics and Earth Tide Service (IGETS) database (Dykowski et al., 2018d, 2018e).

The drift of the iGrav-027 was evaluated with respect to monthly measurements with the A10-020 gravimeter (Dykowski et al., 2018c). Two alternative drift estimations were conducted, one considering all A10-020 surveys, and the other – selected ones with the exclusion of apparent outliers (Figure 12). The most important parameter of the drift, i.e. the linear component, was evaluated at −33 nm/s^2/year for all A10-020 gravimeter results and −4 nm/s^2/year for the selected ones.

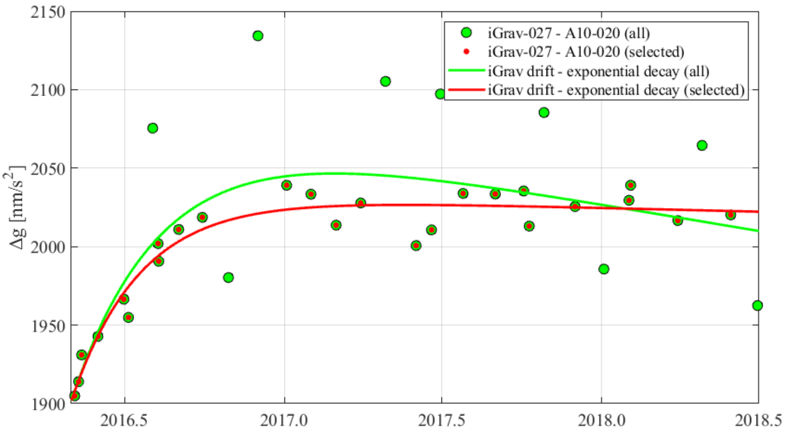

Fig. 12. iGrav-027 drift evaluation over the first 26 months of operation

The fit of gravity determined with the A10-020 to the iGrav-027 record, after removing the evaluated drift, is shown in Figure 13. Annual variation of gravity, most likely caused by large scale hydrological effect, can clearly be observed. Within the last years several studies were conducted to verify the sensitivity of the A10-020 gravimeter to hydrological variations (Dykowski et al., 2015; Dykowski and Krynski, 2015a, 2017). The most recent study (Dykowski et al., 2018c) conducted with the use of the iGrav-027 record allowed to reliably evaluate the sensitivity of the A10-020. From the analysed record of 26 months the standard deviation of gravity determined with the A10-020 equals 75 nm/s^2 but when evaluated against the iGrav-027 record it becomes equal to 35 nm/s^2.

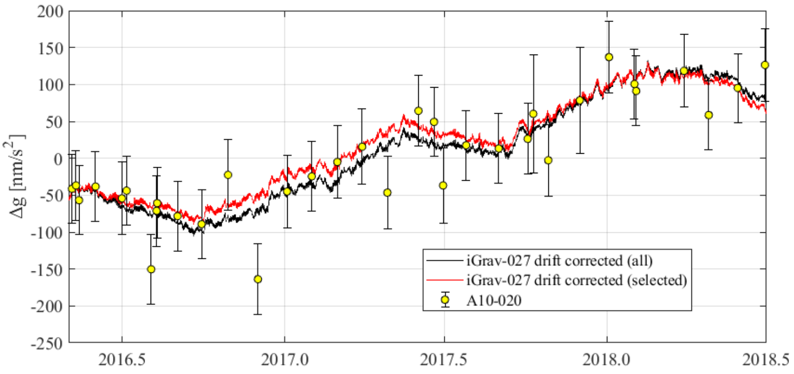

Fig. 13. Combined A10-020 and iGrav-027 records (after drift removal)

Several studies concerning correlation of the iGrav-027 residual signal with atmospheric and hydrological effects (Dykowski et al., 2017, 2018c) obtained from numerical weather models (Boy and Hinderer, 2006; Boy et al., 2009) were conducted.

Figure 14 presents the iGrav-027 residual signal (red curve from Figure 13) corrected with the ECMWF model (provided by EOST Loading Service) together with GLDAS2 and MERRA2 models.

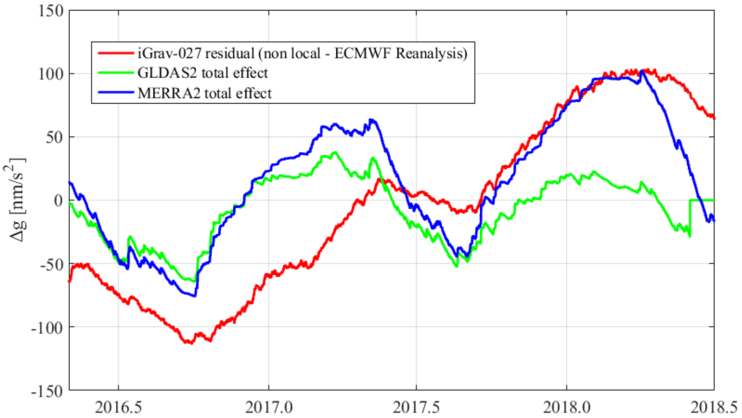

Fig. 14. iGrav-027 residual (red) compared with hydrological loading effect from GLDAS2 (green) and MERRA2 (blue)

Since late 2008, gravity measurements with the A10-020 are performed at three stations at BG: two indoor stations (A-BG and BG-G2), and one outdoor station (156). Results for the BG-G2 station (located next to the iGrav-027) are shown in Figure 15.

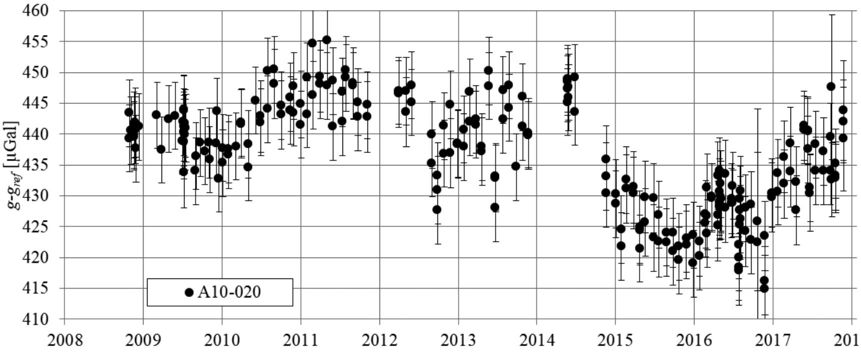

Fig. 15. Time series of A10-020 gravity determinations at BG-G2 station; $g_{ref} = 981\ 250\ 000$ μGal

4.1.2. Monitoring program in Jozefoslaw

The Gravimetric Laboratory at the Astrogeodetic Observatory of WUT in Jozefoslaw is located 6 meters below the ground on the deepest cellar floor in the main building. There are four stations for absolute gravity measurements on a large single pillar and another independent pillar in a separate chamber for tidal measurements. The Laboratory is equipped with the high quality spring tidal gravimeter LCR ET-26 installed in 2002, and the absolute gravimeter FG5-230 installed in 2005. In the immediate vicinity operate a piezometer (upgraded in 2017 to automatic recording) and a vertical soil moisture probe with five sensors at 6 m, 3 m, 1.50 m, 0.75 m, 0.40 m depths below ground level (Brzezinski et al., 2016).

Absolute gravity measurements consisting of 24 sets over 24 hours are quasi-regularly conducted in the Laboratory on monthly basis. Absolute gravity measured is corrected by gravity effects due to Earth' and ocean tides (FES2004), pole tide (IERS Bulletin B), and atmospheric pressure using a constant coefficient of 0.3 μGal/mbar. Reduction for natural vertical gradient and offsets determined during ICAG/ECAG campaigns are applied. Time series of absolute gravity measurements in Jozefoslaw with the record of the water table level are presented in Figure 16.

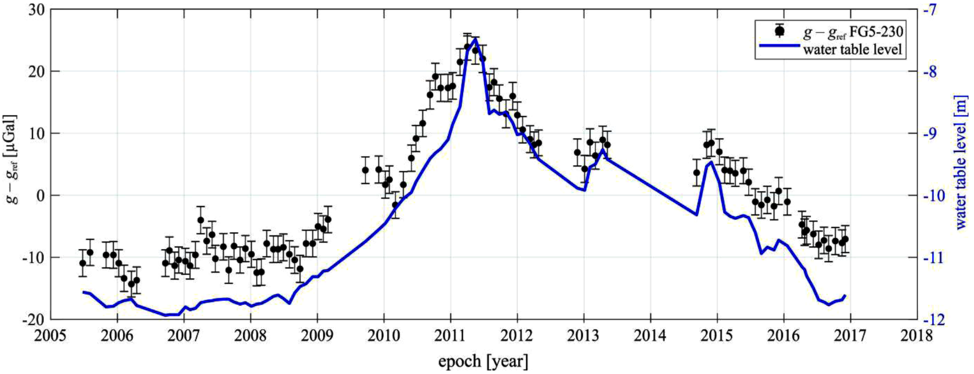

Fig. 16. Time series of absolute gravity and water table level (piezometer) measurements in the Jozefoslaw Astrogeodetic Observatory; $g_{\text{ref}} = 981\,213\,780$ μGal

The global effect of hydrology on gravity, i.e. effect of distant zones beyond 0.125 degree of the spherical distance, and the effect of close zone computed as a simple Bouguer plate of the equivalent water thickness (*EWT*) at the Jozefoslaw Astrogeodetic Observatory were calculated using Global Hydrological Models (GLDAS)-Noah v.2.1 and Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA) – 2 models.

Time series of gravity corrected for the effect of hydrology (global as well as global and local) was then used for empirical determination of the effect of local water table changes on gravity. Determination of gravity change dg_{local} to water table change dH_{WTL} ratio (linear coefficient c)

$$dg_{\text{local}} = c \cdot dH_{\text{WTL}}$$

is the only solution if the proper hydrogeological model of the influence of the water and soil moisture changes on gravity variations is not available. Such linear coefficients for investigated gravity time series corrected with the use of global hydrological effect are at the level of 10 μGal/m; they vary within the range of 1 μGal/m.

The determined coefficients as well as global hydrological effects used to correct the gravity time series are shown in Figures 17a and 17b for GLDAS and MERRA models, respectively.

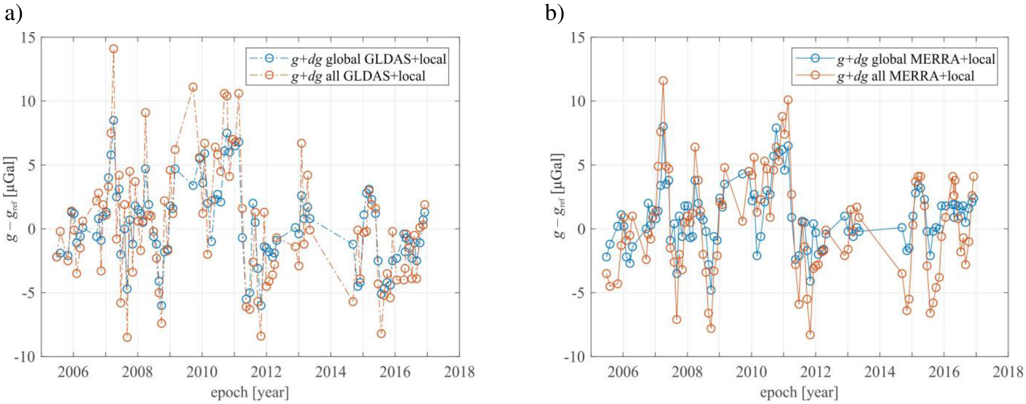

Fig. 17. Gravity series corrected for the effect of hydrology using global GLDAS (a) and MERRA (b) models and local water table changes; $g_{\text{ref}} = 981\,213\,780$ μGal

The residual seasonal effect observed in Figure 17 may be caused by incomplete modelling of soil moisture changes in the zones close to the gravity station. This effect exhibits local maxima in spring, especially in 2007–2011 and in 2015. The statistics of gravity time series corrected for local and global hydrology is presented in Table 4, where g – absolute gravity value, dg_G – hydrological correction from model from global component, dg_A – hydrological correction from model all components, dg_{local} – hydrological correction from local modelling. As it turns out soil moisture changes are a dominant factor in the residual gravity changes. Thus, the vertical soil moisture probe was installed in the vicinity of the gravity station at Jozefoslaw.

Table 4. Statistics gravity time series (2005–2017) at Jozefoslaw station corrected for local and global hydrology [μGal]; $g_{\text{ref}} = 981\,213\,000$ μGal

Statistics	g not corrected	GLDAS model		MERRA model	
		$g{+}dg_G{+}dg_{\text{local}}$	$g{+}dg_A{+}dg_{\text{local}}$	$g{+}dg_G{+}dg_{\text{local}}$	$g{+}dg_A{+}dg_{\text{local}}$
Mean ($g - g_{\text{ref}}$)	788.8	780.3	780.3	780.9	780.3
Std	10.2	3.2	4.6	2.4	4.1
Max-Min	37.5	14.5	22.5	12.7	19.8

4.2. Temporal variations of the gravity field from GRACE data

The extensive research on the use of GRACE data for the determination of temporal variations of the gravity field was conducted by the team of IGiK. The suitability of the newest release GRACE-based GGMs for modelling the temporal gravity field variations over the area of Poland represented by the Vistula river basin and the Odra river basin, and surrounding areas was investigated. Temporal variations of the terrestrial water storage (*TWS*) obtained from the 5th release GRACE-based GGMs, provided by different computational centres, were compared with the corresponding ones derived from hydrological models (Godah et al., 2015c). The performance of the Gaussian filter with different radii as well as DDK1–DDK5 filters applied to reduce the noise contained in those GGMs were investigated on global as well as on local scale. Both the internal and external accuracy of GGMs investigated were assessed. Error degree variances of geoid heights were calculated on the basis of hydrological models. *EWT* variations obtained from GRACE-based GGMs provided by CSR, GFZ, and JPL processing centres are consistent, and exhibit good fit to those obtained from the Water Global Hydrological Model (WGHM) (Figure 18).

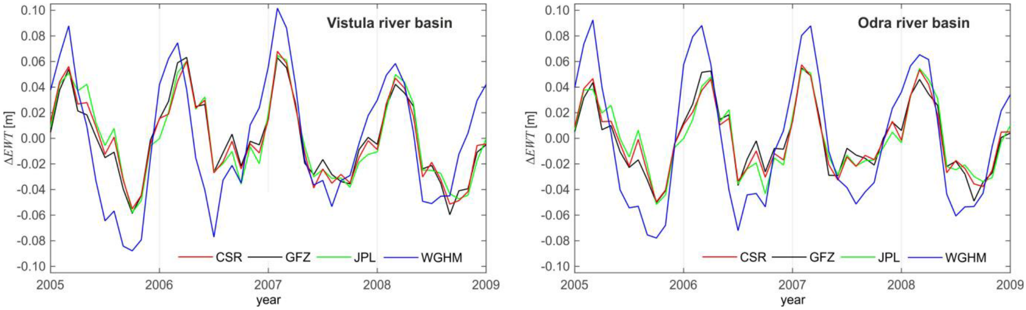

Fig. 18. Time series of equivalent water thickness variations ΔEWT(WGHM) and ΔEWT(GRACE) for the Vistula river basin and the Odra river basin; the DDK1 filter was applied to obtain ΔEWT(GRACE) (Godah et al., 2015c)

Extensive numerical tests show that DDK1 filter removes substantially less signal than the Gaussian filter. Thus DDK1 was found the best for reducing the coloured noise 'strips' in GRACE-based GGMs. The analysis of the results obtained using GGMs from CSR, GFZ and JPL processing centres indicate that for estimating mass variations in the Earth system over the area of Poland, RL05 GRACE-based GGMs developed by the GFZ centre are more recommended than the corresponding GGMs provided by other centres (Godah et al., 2015d). In addition, the comparison of *EWT* determined from GRACE-based GGMs with those from the GLDAS models confirms the suitability of GRACE data for studying short term temporal mass variations over Poland (Godah et al., 2016).

Research on the usefulness of time series of repeatable absolute gravity measurements for calibration/validation of temporal mass variations derived from satellite gravity missions was conducted in IGiK. Temporal gravity variations obtained from RL05 GRACE-based GGMs developed by CSR and GFZ, were compared with the corresponding ones obtained from the time series of smoothed/reduced (moving average/local hydrology) gravity data from the measurements with the A10-020 absolute gravimeter at BG (Godah et al., 2016). Repeatable absolute gravity measurements with the A10-020 gravimeter were found a valuable tool for the calibration/validation of the long term temporal gravity variations at BG.

Temporal variations of geoid heights determined at GFZ from GRACE-based GGMs were computed for four 3° × 5° subareas in Poland. Variations of geoid heights determined are noticeable; they reach 10 mm from one epoch to the other, and their differences between subareas reach 2 mm for the same epoch and 11 mm for different epochs (Godah et al., 2017a).

The Principal Component Analysis/Empirical Orthogonal Function (PCA/EOF) method was applied for both, analysis and modelling temporal variations of geoid heights (Godah et al., 2018c). It was shown that the use of the first PCA mode and EOF loading pattern allows to obtain a large signal of temporal variations of geoid heights over the area of Poland (96.3%, in terms of total variance) while with the first three PCA modes and EOF loading patterns ~ 99.93% of total variance of temporal variations of geoid heights can be obtained. The PCA/EOF method was also found very suitable for developing models of geoid heights temporal variations. The fit such models investigated to RL05 GRACE-based GGMs data in terms is at the level of 0.3–0.4 mm.

The results of study of physical height changes over Central Europe indicate that in the period of 2004–2010, they reach up to 22.8 mm (Godah et al., 2017c). It was also shown that using the seasonal decomposition (SD) method they can be modelled with the accuracy of 1.4 mm.

A case study for Poland was conducted to investigate temporal variations of geoid height and vertical displacements of the Earth surface in relation to the realization of a kinematic vertical reference system (Godah et al, 2017a, 2017b). The temporal variations of geoid heights obtained for the four subareas as well as for the whole area investigated were analysed using two different methods: the spectral analysis method, and the SD method (Fig. 19).

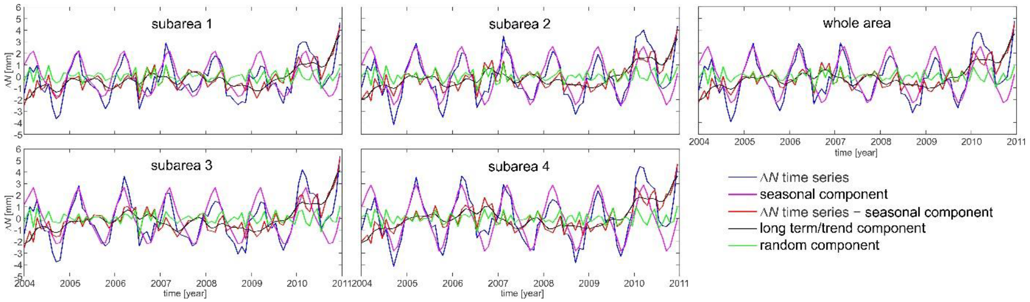

Fig. 19. Temporal geoid height variations and their components obtained with the use of SD method

Seasonal components of amplitudes ranging from 3.5 to 6.0 mm are dominant parts of ΔN; for the area and time period investigated; they show non-linear long term/trend components of ΔN. For some periods, trend values reach the level of 2 mm/year.

A couple of temporal geoid height variations models was investigated and then implemented for predicting variations of geoid heights. It was shown that geoid height variations can be predicted with 1 mm accuracy even 6 months ahead. The results obtained indicate SD method as a recommended one for the analysis and modelling the temporal geoid height variations over the area of Poland (Godah et al., 2017a).

Physical height changes in two study areas: Poland and Turkey, were estimated as a sum of temporal variations of geoid/quasigeoid heights and vertical displacements of the Earth surface using the release 5 (RL05) GRACE-based GGMs and GRACE-based global mass concentration (mascon) products as well as load Love numbers from the Preliminary Reference Earth Model (PREM) as input data, and the standard spherical harmonic synthesis, the Green function and the Terzaghi's Principle method. They were analysed and modelled using two methods: SD method and the PCA/EOF method (Godah et al., 2018b). In the area investigated PCA/EOF method provides slightly better results compared to the Fourier analysis and SD methods (Godah et al., 2018c).

Temporal variations of the Earth gravity field determined from SLR data was investigated by the team of WUELS in cooperation with the University of Bern and Bundesamt für Kartographie und Geodäsie. SLR observations of nine geodetic satellites: LAGEOS-1, LAGEOS-2, Starlette, Stella, AJISAI, LARES, Larets, BLITS, and Beacon-C were used to recover coefficients up to d/o 10, of the time variable Earth's gravity field, for the time span 2003–2013. Monthly low-degree gravity field coefficients were estimated and compared with the respective ones derived from GRACE data. It was shown that using the combination of 1-day arcs for low orbiting satellites with 10-day arcs for LAGEOS satellites all coefficients up to d/o 10 can be well determined – tesseral and sectorial coefficients from LEO data, and zonal from LAGEOS data. The annual signal in their amplitudes obtained from SLR data matches in 77% with that from GRACE data, which indicates a great potential of SLR to fill the gap between the GRACE and the GRACE Follow-On mission for recovering seasonal variations and secular trends of the longest wavelengths in gravity field (Sosnica et al., 2015).

The impact of the selection of GLDAS and WGHM models on gravity change determination was investigated at WUT with the use of GRACE RL05 data and all available time series of gravity changes in the territory of Poland. Differences between models result in gravitational effect of 0.3 μGal. With the exception of the globally variable effect, it was possible to capture gravity changes resulting from the global environmental factors, pointing to their interpretation for the significance of the hydro-geological monitoring (Brzezinski et al., 2016).

The usefulness of observations from GRACE mission and GOCO hydrosphere model for evaluating local hydrosphere conditions, in particular for flood and drought prediction, was investigated in UWM. It was shown that combining gravity and meteorological data provides more reliable modelling of water flows than "gravimetric only" and "meteorological only" models (Birylo et al., 2015). The research was also conducted on the use of high resolution GLDAS as well as GRACE data for evaluation ground water level changes and water budget (Birylo et al., 2016; Rzepecka et al., 2017). Special attention was devoted to the study of accuracy of water budget prediction (Birylo et al., 2017). The mean *TWS*s obtained from GRACE data and GLDAS models were used to investigate variations of groundwater level as well as water balance in the Sudety Mountains in time span of over 10 years (Rzepecka et al., 2017). It was shown the groundwater level declined approximately 1 cm/year over the period investigated.

Research on forecasting future behaviour of time series to find most suitable method for water budget computation and assessment of accuracy of ground water level determination was conducted using the ARIMA (or ARMA) models together with exponential smoothing and structural models (Birylo et al., 2017). Best results for prediction were obtained using ARIMA models. Snow and rain falls (precipitation) contribute most to the final water budget value.

GLDAS, MERRA-2, and GRACE data were used for investigation seasonal variability of the atmospheric (energy) and water budgets in Poland (Birylo, 2017). Good agreement of results from GLDAS and MERRA-2 models was obtained and the lack of linear correlation between the total water storage and the atmospheric budget was observed.

Differences between gravity variations from GRACE monthly solutions provided by three processing centers (CSR, GFZ and JPL) and variations of absolute gravity data for the Jozefoslaw Observatory corrected for local hydrology were analysed in terms of choosing the optimum degree of anisotropic de-correlating DDK filter (Szabo et al., 2018). RMS of the residuals are given in Table 5. The fit of CSR GGMs to absolute gravity at Jozefoslaw is shown in Figure 20.

Table 5. RMS of the differences between variations of absolute gravity determined with the FG5-230 at Jozefoslaw and gravity variations from GRACE-based GGMs provided by CSR [μGal]

Filter	CSR product	GFZ product	JPL product
DDK1	3.0	4.1	3.5
DDK2	3.6	4.2	5.7
DDK3	5.9	5.9	4.7
DDK4	5.0	4.3	3.4
DDK5	4.0	5.0	5.2
DDK6	4.4	6.9	5.4
DDK7	17.2	9.5	5.7
DDK8	31.2	6.9	6.9

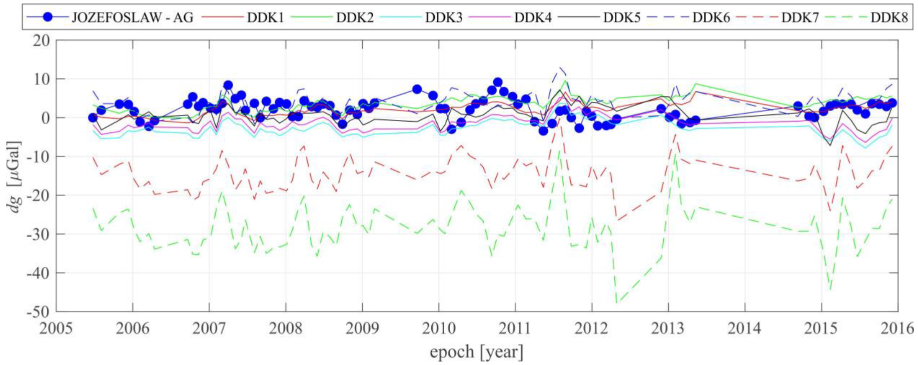

Fig. 20. Differences between variations of absolute gravity determined with the FG5-230 at Jozefoslaw and gravity variations from GRACE-based GGMs provided by CSR

5. Contribution of gravimetric records to seismic studies

Seismic events are a common phenomena recorded by various types of gravimeters, especially instruments designated for Earth tides recording. They are commonly considered as disturbances and removed from gravity records. The ability of recording seismic surface waves of very long periods with tidal gravimeters was investigated within a cooperation of several Polish scientific institutions listed below. Four seismometer-gravimeter pairs were tested at three locations (Figure 21a): Borowa Gora Geodetic-Geophysical Observatory (BG), Jozefoslaw Astro-Geodetic Observatory (JO), and Lamkowko Satellite Observatory (LA), in the framework of cooperation between the IGiK (Centre of Geodesy and Geodynamics), University of Warsaw (Faculty of Physics), WUT (Faculty of Geodesy and Cartography), UWM (Space Radio-Diagnostics Research Centre). From December 2016 to May 2017 several large teleseismic events (Fig. 21c) were observed with well-formed surface waves (Wilde-Piórko et al., 2017, 2018).

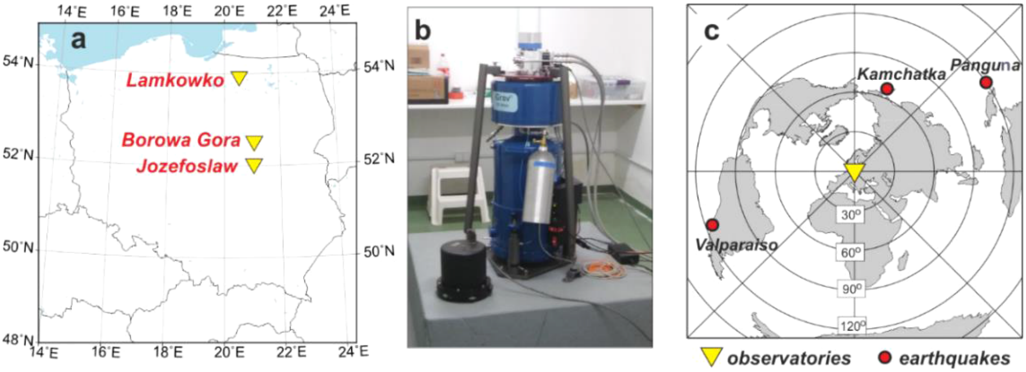

Fig. 21. (a) Location of observatories (yellow triangle); (b) the iGrav-027 superconducting gravimeter (blue instrument) at BG and the REF-TEK Observer 151B-120 seismometer (black instrument) during the operation time; (c) location of epicenters of analyzed earthquakes

A few important issues due to variety of instrumentation used had to be considered, namely different sampling rates (100 Hz to 1.8 Hz), unrecognized transfer functions for all types of instruments.

Spectrograms of M6.9 Valparaiso earthquake (2017-04-24, 21:38:30.82, according to USGS/NEIC PDE Catalogue) for two selected instruments are shown in Figure 22. All records including the seismometer (Figure 22a) were normalized with the maximum range of the event. An excellent signal-to-noise ratio of the iGrav-027 recordings (Figure 22b) up to the period of 1000 s can be observed and seismic signal can be recognized up to periods of 300–400 s.

For the advanced part of seismic analysis the group velocities were calculated dividing the epicentral distance by travel-time of selected envelope maxima for each period (Wilde-Piórko et al., 2017). Group velocities of all gravimeters and seismometers match very well up to the period of 100 s.

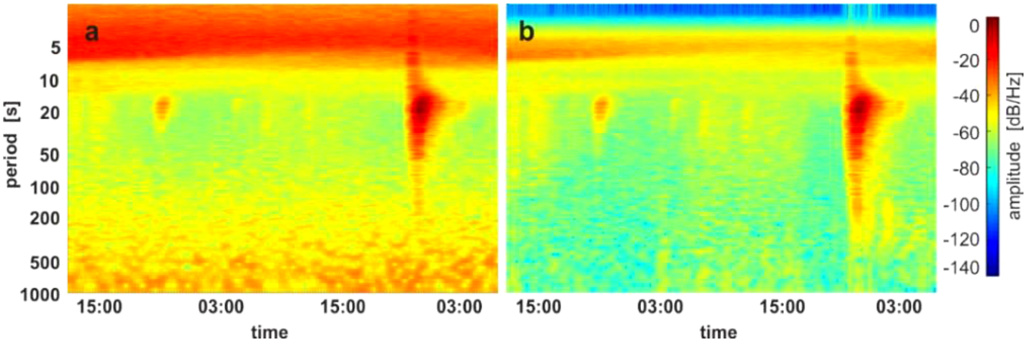

Fig. 22. Spectrograms of the M6.9 Valparaiso earthquake: (a) seismic station B941 (BG); (b) superconducting gravimeter iGrav-027 (BG); Each record was normalized with the maximum amplitude range of the event

The superconducting gravimeter iGrav-027 shows an excellent consistency with the seismometer within the frequency range of a seismometer (up to 120 s periods). Moreover, the iGrav-027 data show great potential for analysing periods of above 120 s. Generally, transfer functions for gravimeters are desirable to improve their usefulness for seismic analysis and gravimeter to seismometer comparisons and first such experiments had been conducted in late 2018 (Dykowski et al., 2018c).

6. Summary and conclusions

The paper presents the activities of Polish research and government institutions in the years 2015–2018 in the areas related to gravity field modelling and gravimetry. In the years 2015–2018, evaluation of newly developed GOCE-based GGMs were continued. Wide use of geoid models computed from GOCE-based GGMs was discussed. The potentiality of absolute gravity data measured with A10 absolute gravimeter for validation of GGMs and for improving geoid heights obtained from satellite-only GGMs was shown and confirmed. In particular, GOCE-based GGMs could be recommended for GNSS levelling of sparse coverage with terrestrial gravity data.

Further progress in modelling gravimetric geoid by Polish research groups is observed resulting in a number of consecutive quasigeoid models developed for Poland and Saudi Arabia, and evaluated. In particular, the geophysical gravity data inversion technique as well as least squares modification of Stokes' formula with additive corrections method were implemented for local gravimetric geoid determination. The quasigeoid model PL-geoid-2011 determined in 2016 from the EGM2008 calibrated by the satellite/levelling data at almost 600 stations was recommended by the surveying and mapping agency in Poland.

An extensive research considering absolute gravity surveys for the maintenance of gravity control was conducted. Both Polish absolute gravimeters the FG5-230 and A10-020 were regularly taking part in the international and European absolute gravimeter comparison campaigns as well as they were calibrated in the institutions equipped with the relevant infrastructure. Installation of superconducting gravimeter iGrav-027 in BG completed the infrastructure required for reliable metrological control of gravity standard in Poland. It was shown that the maintenance of gravimetric reference system requires, besides careful metrological control, consideration of the impact of global hydrological variations and that the national gravimetric reference system should be updated significantly more often than every 20 years. Experience of the team of IGiK in establishment and maintenance gravity control, in particular in the use of the A10 absolute gravimeter, was shared in 2015–2018 with respective institutions in Sweden, Denmark, Republic of Ireland and Northern Ireland. It was also used in the project concerning monitoring deformations in mining areas in the Upper Silesian region in Poland. Gravimetric measurements were also performed for geodynamic research Pieniny Klippen Belt in southern Poland as well as in the Tatra geological region with the FG5-230 gravimeter.

Research on non-tidal gravity changes was successfully continued in two gravimetric laboratories: at the Borowa Gora Geodetic-Geophysical Observatory and the Astrogeodetic Observatory in Jozefoslaw. Acquired time series of tidal gravimeter records and quasi-regular absolute gravity measurements enable analysis of long term gravity variations and investigation of the especially significant hydrological loading effect as well as the relation between gravity change and water table change.

Advanced research on temporal variations of the gravity field from GRACE data was also continued, in particular considering the choice of processing centre's product and optimum filter for the area investigated. In four $3^\circ \times 5^\circ$ subareas in Poland variations of geoid height can reach 10 mm on annual basis. On the other hand physical height changes over Central Europe can exceed 20 mm. It was shown that physical height changes can be modelled with the accuracy of 1.4 mm using the seasonal decomposition method. The attention was paid on the importance of investigation of geoid height variations and vertical displacements of the Earth surface related to the realization of a modern vertical reference system. A case study for Poland as well as for Turkey was conducted with the use of on GRACE-based GGMs and mascon products as well as load Love numbers. PCA/EOF method was found suitable for analysing and modelling temporal variations of geoid heights. It was also shown that SLR has a great potential to recover seasonal variations and secular trends of the longest wavelengths in gravity field, which are associated with the large-scale mass transport in the system Earth.

Mutual research of geodetic and seismic specialists concerning contribution of gravimetric records to seismic studies was initiated. Records of seismometers were analysed together with records of collocated spring gravimeters and the superconducting gravimeter. The superconducting gravimeter iGrav-027 exhibits an excellent consistency with the seismometer within the frequency range of a seismometer (up to 120 s periods). Moreover, it recordings shows excellent signal-to-noise ratio up to the period of 1000 s and seismic signal can be recognized up to periods of 300–400 s what substantially exceeds sensitivity range of the seismometer allowing for new research in this area.

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