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Review paper

Research on gravity field modelling and gravimetry in Poland in 2019–2022

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Abstract: The article presents the reviewed and summarised research activities of the Polish research groups on gravimetry and gravity field modelling in the period of 2019–2022. It contains the results of absolute gravity surveys for the maintenance of the international gravity reference level in Poland and Europe, and for geodynamic research with an emphasis on metrological aspects. It also contains relative gravimetry issues as well as the results of marine gravity surveys in the southern Baltic Sea. Non-tidal gravity changes were extensively investigated. Long-term gravity variations were monitored at the Borowa Gora Geodetic-Geophysical Observatory and in a few other locations in Poland. The contribution of gravimetric records to seismic studies was investigated. Temporal variations of the gravity field from GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (GRACE Follow-On) data, in particular, deformations of the Earth's surface as well as temporal variations of heights, total water storage and groundwater storage were investigated. Moreover, GRACE-based products and the performance of monthly Global Geopotential Models (GGMs) were a subject of research. GGMs developed in last years were evaluated. The research on developing new approaches in geoid modelling and their validation was conducted. New regional and local geoid models were determined for Poland and Ethiopia. The use of different techniques for estimating the absolute sea level at sites of the selected network in the Baltic Sea was investigated.

Keywords: geoid, gravity field, absolute gravity measurements, gravimetry, GRACE/GRACE-FO satellite missions

1. Introduction

Research activities of the Polish research groups in the years 2019–2022 in gravimetry and gravity field modelling are a consequent continuation/extension of those from the period of 2015–2018 (Krynski et al., 2019).

The new definition of the International Terrestrial Gravity Reference System/Frame (ITGRS/F) challenges activities related to the maintenance of gravity control (Wziontek et al., 2021), especially at the Borowa Gora Geodetic-Geophysical Observatory (BG) of the Institute of Geodesy and Cartography (IGiK) utilizing the continuous operation of the iGrav-027 superconducting gravimeter. In particular, it concerns gravimetric metrology. Multiple initiatives have been started for periodic absolute gravity surveys with two absolute gravimeters (AGs): the FG5-230 and the A10-020 at several locations in Poland selected for geodynamic monitoring. The capabilities of absolute gravimetry at IGiK have been expanded in late 2021 by the absolute quantum gravimeter AQG-B07 installed at the BG Observatory. All three AGs operating in Poland: FG5-230, A10-020, and AQG-B07 participated in 2022 in an absolute gravimeter comparison campaign.

The calibration of gravimeters is necessary to ensure consistency and reliability of gravimetric survey, in particular, to efficiently monitor non-tidal gravity changes. Relative LaCoste&Romberg (LCR) gravimeters of IGiK, calibrated on the gravimetric calibration baseline, were successfully used to calibrate spring gPhoneX tidal gravimeters in Poland within the EPOS-PL (European Plate Observing System – Poland) and EPOS-PL+ (continuation/extension of EPOS-PL) projects. Joint measurements of AGs and the iGrav-027 gravimeter at the BG Observatory allowed for an updated drift evaluation and long term stability assessment providing an insight into long term gravity variations at the Observatory.

The combination of tidal gravimetric and seismic records provides promising material for advance seismic studies. Detail analysis showed that the stability of tidal gravimeters allows deeper insight into Earth structure than the one from standard seismic records.

The products of GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (GRACE Follow-On) satellite missions provide extremely valuable information for monitoring temporal variations of the Earth's gravity field. These variations can further be interpreted in terms of hydrological mass change (e.g. temporal variations of total water storage and groundwater storage), deformations of the Earth's surface (i.e. ellipsoidal height change) induced by temporal mass loadings, and temporal variations of geoid/quasigeoid heights resulted from gravity change. They are a subject of growing interest among worldwide scientific community in terms of both analysis and software development.

The newly developed Global Geopotential Models (GGMs) require evaluation, before being used for geoid modelling. It is particularly important for quality estimate of modelled geoid. Also new approaches to geoid modelling on regional and local scale are the subject of research of numerous research groups.

2. Gravity measurements

The research in Poland applying gravity survey for geodesy and geodynamics was related in the last years to terrestrial gravity surveys (absolute gravity surveys and tidal gravity records) as well as marine gravity surveys. Within the period of 2019–2022, major developments in recording Earth tides in Poland were observed, up to a large extend due to the involvement in the EPOS-PL and EPOS-PL+ projects (Dykowski et al., 2021a). Majority of repeated gravity surveys with AGs were performed at the BG Observatory. New marine gravity surveys were conducted with a Micro-g Marine Gravity System by the team of the Gdansk University of Technology in the Baltic Sea region in Poland. Research utilizing gravity tidal records for seismic studies was continued by IGiK.

2.1. Absolute gravity surveys

For over a decade, two institutions in Poland: the Warsaw University of Technology (WUT), and IGiK were conducting gravity surveys with AGs: FG5-230, and A10-020, respectively. Both gravimeters were used in various projects in Poland as well as in a number of European countries for the maintenance of gravity control, geodynamic research and metrology. Starting from October 2021, a new AG – the Absolute Quantum Gravimeter (AQG-B07) of IGiK – is used in Poland (Dykowski et al., 2022b; 2022c). It is the first commercial type of gravimeter based on a quantum sensor with a variety of applications in the field of geodesy and geophysics (Ménoret et al., 2018). Thus, three AGs are currently operational in Poland allowing to utilize all of them for research in the field of geodesy and geophysics.

Absolute gravity surveys for the maintenance of the international gravity reference level in Poland and Europe

Current status of the new definition of the ITGRS/F essentially states that AGs now define the system (Wziontek et al., 2021). Within the period of 2019–2022, absolute gravity measurements related to the maintenance of the international gravity reference level were performed with all three AGs in Poland (A10-020, AQG-B07, FG5-230) at the BG Observatory.

In mid-2021, the team of IGiK concluded absolute gravity surveys in the Republic of Ireland and Northern Ireland within the AGN Ireland project related to the establishment of a modern gravity control on the island of Ireland. Aspects of absolute gravity measurements related to the maintenance of the international gravity reference frames for Poland and other European countries with a contribution of Polish teams are discussed in Krynski and Liwosz (2023).

Absolute gravity surveys for geodynamic research

Multiple activities oriented towards quasi-permanent monitoring of gravity changes in Poland were carried out in the years 2019–2022. Three main research and infrastructure projects contributed to activities concerned geodynamical monitoring the EPOS-PL (2017-2021), EPOS-PL+ (2020-2023), and the Monitoring of Geodynamics in Poland (MGP) (started in 2012, AG measurements since 2018).

Within the framework of the EPOS-PL project, the team of IGiK performed a periodic (every 6 months) absolute gravity survey with the A10-020 gravimeter on 10 field stations (Fig. 1 – red dots) of the Multidisciplinary Upper Silesian Episodes (MUSE) polygons, one in a non-active and the other in still active mining areas in the Upper Silesian Region (UPR). Those absolute gravity determinations provided a reliable gravity reference for periodic relative gravity surveys conducted also every 6 months on nearly 200 stations of MUSE (Fig. 1 – black dots) by the Central Mining Institute (GIG). On those nearly 200 stations, precise GNSS (Global Navigation Satellite System) surveys were performed to assess the deformations induced by mining (Dykowski et al., 2019). Measurements were completed by the end of 2021. Results of gravity survey at two stations (also being points of national gravity control PBOG) of the 10 absolute gravity stations for the period of the EPOS-PL project as well as a gravity value from 2012 to 2015 measurements for the realization of the Polish gravity control are presented in Figure 2 (Dykowski et al., 2022a). Variability of gravity changes at Oswiecim station (Fig. 2 – bottom) indicates the need for repeatable periodic gravity measurements for continuous monitoring of the state of the gravity control.

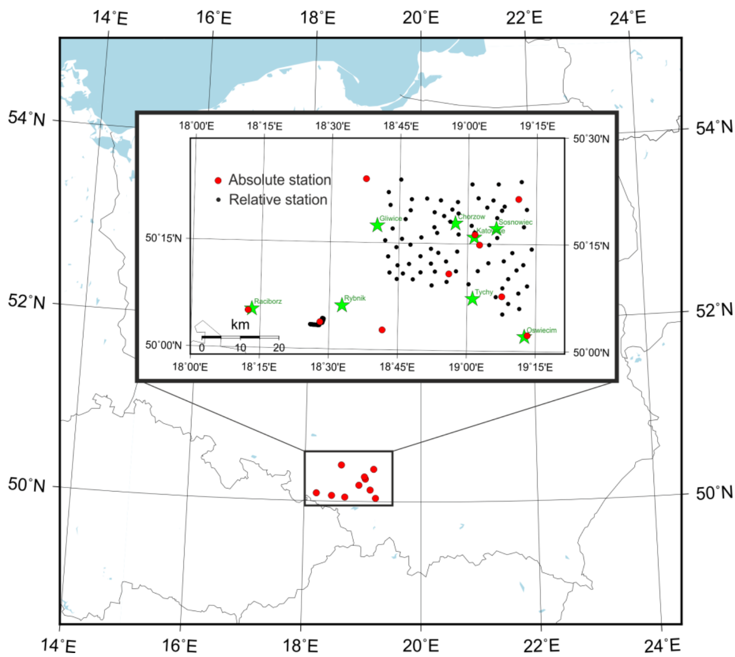

Fig. 1. Gravity stations surveyed within the EPOS-PL project at MUSE polygons

Repeated absolute gravity measurements are being conducted within the EPOS-PL+ project by the team of IGiK every 6 months for GIG and for the Space Research Centre of the Polish Academy of Sciences (SRC PAS). Gravity surveys for GIG which are carried out on an active exploration site in Marklowice in UPR provide absolute gravity reference for relative gravity measurements at nearly 100 field stations in that area. Gravity surveys for SRC PAS are conducted at the Astrogeodynamic Observatory in Borowiec, mainly with the A10-020, but also with the AQG-B07 gravimeter, to monitor gravity long term supporting tidal records by the gPhoneX-161 gravimeter (Nastula et al., 2022).

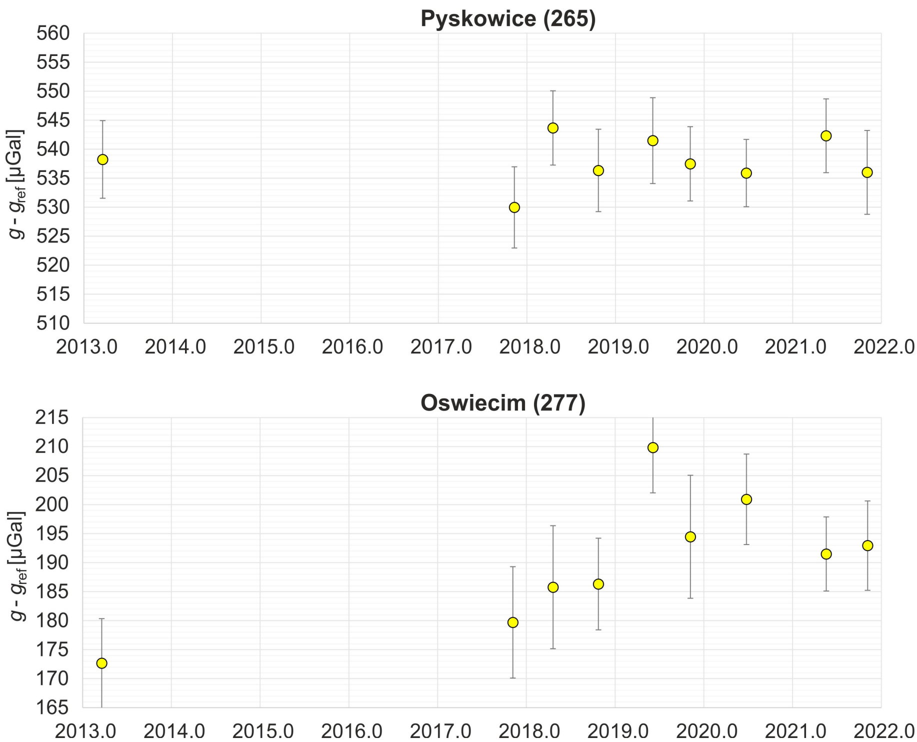

Fig. 2. Absolute gravity measurements conducted within the EPOS-PL project at PBOG stations in Pyskowice (g_{ref} = 981 069 000; top) and Oswiecim (g_{ref} = 981 034 000; bottom); error bars indicate the total uncertainty of gravity value determined with A10-020 gravimeter, reduced to benchmark level, single coverage k = 1.67%

Since 2017 the absolute gravity measurements with the FG5-230 gravimeter were performed by WUT at two permanent stations: Dziwie (Wielkopolska Voivodeship), and Holowno (Lubelskie Voivodeship) of MGP, a project maintained by the Geohazards Centre at the Polish Geological Institute – National Research Institute. Those locations supplement 7 seismic stations operating within the Polish Seismological Network. The MGP stations are equipped with modern broad-band seismic, magnetic, tidal gravimetric (only Holowno station), GNSS, meteorological and hydrogeological infrastructure, installed in very stable conditions to provide long-term observations. Results of repeated absolute gravity measurements with the FG5-230 gravimeter on both stations are shown in Figure 3.

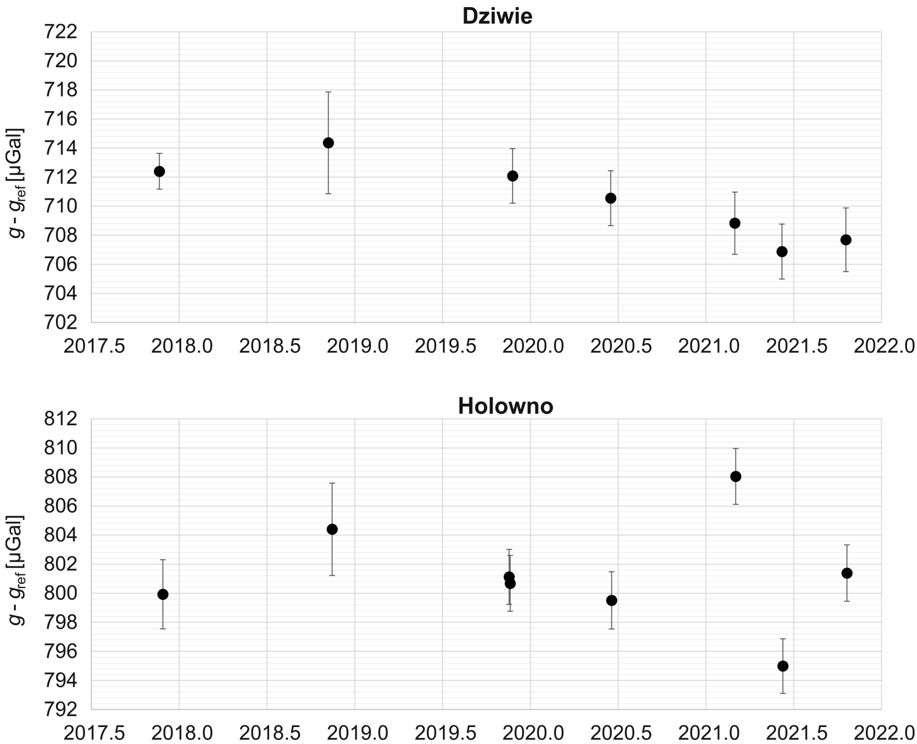

Fig. 3. Absolute gravity measurements within MGP project at stations in Dziwie (g_{ref} = 981 216 000; top) and Holowno (g_{ref} = 981 115 000; bottom); error bars indicate the total uncertainty of gravity determined by the FG5-230 gravimeter at 125.0 cm height above benchmark level, single coverage k = 1.67%

Metrological aspects in absolute gravimetry

Absolute gravimeters in Poland undergo regular metrological control, internally at the level of calibration of gravimeter's subcomponents, and externally either against reference gravity values and/or against the gravity reference function at the BG Observatory as well as international comparisons of AGs. Metrological control is crucial for maintaining and keeping a high quality gravity standard in Poland with the use of all three AGs: A10-020, AQG-B07 of IGiK and FG5-230 of WUT. This control is on one hand carried out by calibration of subcomponents (laser, rubidium clock and barometer) of AGs at the Polish Central Office of Measures (GUM) with respect to national metrological standards of length, time, and pressure, respectively. This type of control cannot be performed with the AQG-B07 quantum gravimeter. Master laser and quartz oscillator calibration used to control the measurement in the quantum gravimeter is performed internally, using spectroscopy against rubidium Rb^{87} atoms (Ménoret et al., 2018).

The long term stability of the A10-020 absolute gravimeter is continuously monitored and analysed (Dykowski et al., 2021b). In order to assure a full reliability of the A10-020 gravimeter several periodic control activities were implemented. The most basic one concerned calibration of the A10-020 internal components: a helium–neon (He-Ne) laser, rubidium oscillator, and the barometer. In the period from 2008 to 2022, 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 equipped with a relevant infrastructure.

Results of the calibrations of the laser of the A10-020 gravimeter are shown in Figure 4. In 2019 the A10-020 gravimeter underwent a laser exchange, hence the gap in Figure 4. For both lasers, the red/blue lock drifts are symmetrical with respect to the central frequency change, which has a linear trend, and after 10 years became smaller by ~9 MHz than the initial calibration value (corresponds to ~18 µGal difference in the calculated gravity value) which is very significant. Laser drift after laser exchange shows a similar character, yet stronger in terms of linear drift of central frequency of ~7 MHz in only 3 years of operation. This indicates the necessity for monitoring laser frequency on a regular basis.

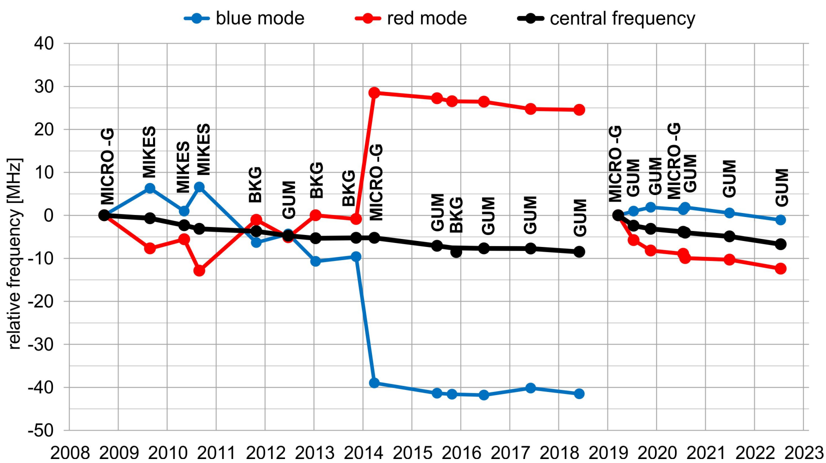

Fig. 4. Results of calibrations of the laser of the A10-020 gravimeter in 2009–2022; MICRO-G – Micro-g LaCoste Inc., MIKES – National Metrological Institute of Finland, GUM – National Metrological Institute of Poland, BKG – Federal Agency of Geodesy and Cartography, Germany

On the other hand, AGs can be metrologically controlled on regular basis against a gravity reference function, e.g. at the BG Observatory (Krynski and Liwosz, 2023). The gravity reference function needs to be constrained by results of participation in international comparisons of AGs.

In mid-2018, the EURAMET.M.G-K3 Key Comparison (Falk, et al., 2020) took place at the Wettzell Observatory. From Poland, only the A10-020 gravimeter participated in that comparison campaign; its resulting offset was estimated as −8.9 µGal (Key Comparison solution). Due to the Covid-19 Pandemic, multiple initiatives of organizing international AGs comparisons in Europe were either cancelled or postponed. It did not allow for effective maintenance of the international gravity reference level. In May–July 2022, a regional AG comparison campaign (NKG-CAG-2022 Additional Comparison) was conducted by the Nordic Commission of Geodesy (NKG) at the Onsala Space Observatory. All three AGs from Poland: A10-020, AQG-B07 (Fig. 5), and the FG5-230 participated in the comparison. Results from the comparison will be publicly available in 2023. They will allow for a comprehensive elaboration of the gravity reference function at the BG Observatory.

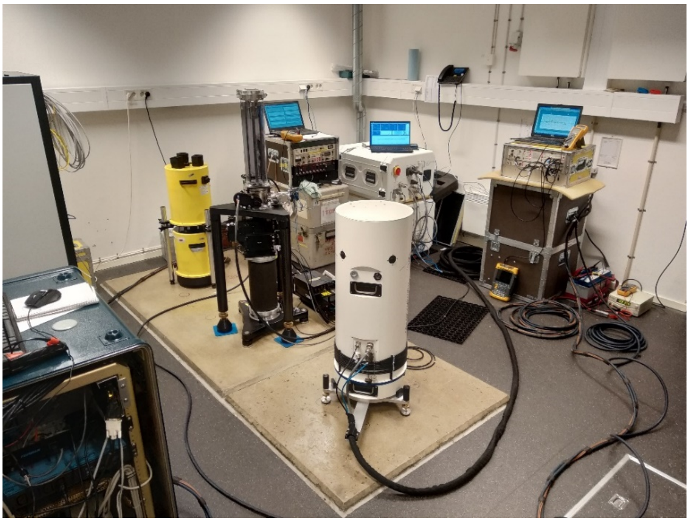

Fig. 5. NKG-CAG 2022 AG comparison at the Onsala Space Observatory. From the left: A10-020 (IGiK, Poland), FG5X-206 (EOST, France), AQG-B07 (IGiK, Poland)

To summarize, Polish teams of IGiK and WUT are active in fulfilling the requirements for supporting and maintaining gravity reference levels of their designated gravity infrastructure toward fulfilling the new definition of the new International Terrestrial Gravity Reference System (ITGRS) as a future replacement to IGSN71 (Wziontek et al., 2021). In the currently being established structure of the ITGRF, presently two stations in Poland: Borowa Gora and Jozefoslaw have the required gravimetric infrastructure to serve as reference stations.

2.2. Metrological aspects in relative gravimetry

Metrological control of relative gravimeters is essential for the most precise terrestrial gravimetric measurements, especially for tidal records. Within the period of 2019–2022, the tidal gravimetric infrastructure in Poland expanded by multiple gPhoneX gravimeters (Dykowski et al., 2021a). All tidal gravimetric records of at least 3 months in length conducted in the recent years are shown in Figure 6. The iGrav, and four gPhoneX gravimeters marked green provide near real time data to the Gravimetric Observations Research Infrastructure Centre (CIBOG) maintained by IGiK. One LCR gravimeter, marked green in Figure 6, is no longer used for continuous tidal records; its tidal gravity series from 2012 until 2018 are, however, collected within CIBOG.

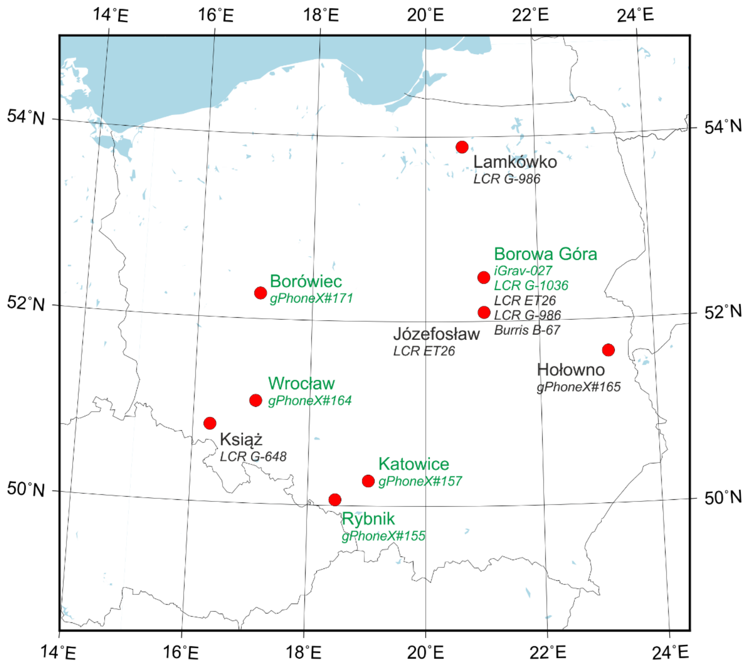

Fig. 6. Tidal gravimeters in Poland, marked green, are active instruments providing data to CIBOG (status by the end of 2022)

All tidal gravimeters providing data to CIBOG went through a consistent scale factor determination procedure by joint records with a pair of relative spring gravimeters, as important parts of the EPOS-PL and EPOS-PL+ projects (Dykowski et al., 2021a; Nastula et al., 2022). The procedure utilized two LaCoste&Romberg model G gravimeters with automatic feedback systems, for joint gravimetric records with the calibrated tidal gravimeter. Joint records lasted at least 60 days (up to 120 days). The scale factor for the tidal gravimeter was calculated using the least squares adjustment. Results of these calibrations for the iGrav-027 and four gPhoneX gravimeters are summarized in Table 1. Because of the methodology applied, an essential part of the procedures included

Table 1. Summary of scale factor determinations for tidal gravimeters in the framework of the EPOS-PL and EPOS-PL+ projects

Gravimeter	Date	$k \pm m_K$
iGrav-027 (Borowa Gora)	2022.06–2022.09	−1060.25 ± 0.24
gPhoneX-155 (Rybnik)	2019.04–2019.06	1.00337 ± 0.00033
gPhoneX-157 (Katowice)	2019.06–2019.07	0.99642 ± 0.00037
gPhoneX-164 (Wroclaw)	2020.10–2021.01	0.99949 ± 0.00010
gPhoneX-171 (Borowiec)	2021.10–2022.01	0.99743 ± 0.00018

calibration of the LaCoste&Romberg gravimeters on gravimetric calibration baselines in Poland, supplemented with absolute gravity measurements with the A10-020 gravimeter (Nastula et al., 2022). The achieved accuracy of the scale factor determinations of tidal gravimeters with the use of LCR gravimeters was below 0.1% which is the threshold to be achieved for precise tidal records analysis.

2.3. Marine gravity surveys

In recent years, the team from the Gdansk University of Technology has conducted a number of marine gravimetric measurements in the Baltic Sea within the MORGRAV project. The internal accuracy of these shipborne gravity data in the Gulf of Gdansk was assessed by using a cross-section analysis (Pyrchla et al., 2020). Internal consistency of the measurements was estimated as 1.13 mGal. The free-air anomalies determined on the basis of the acquired marine gravimetric data compared with the corresponding ones determined from the SGG-UTM-1 combined GGM exhibited some significant differences. The analysis showed that those discrepancies were caused by data deterioration due to external conditions.

3. Investigations of non-tidal gravity changes

Non-tidal gravity changes investigated are related to tidal gravity records and focused either on long term gravity variation or on the use of high frequency raw tidal gravity records for seismic studies. A consistent program of monitoring long term gravity changes is currently being carried out at the BG Observatory of IGiK with the use of AGs and a superconducting gravimeter. With the extension of the tidal infrastructure by a number of gPhoneX gravimeters (mentioned in Section 2.1) more stations in Poland are now suitable for monitoring gravity variations in the non-tidal frequency band, seasonal and longer periods as well as for seismic studies. Separate studies were carried out specifically to use tidal gravity records for in-depth seismic studies.

3.1. Monitoring of long term gravity variations at tidal gravity stations

Monitoring gravity variations at the Borowa Gora Geodetic-Geophysical Observatory

In the period of 2019–2022, the iGrav-027 superconducting gravimeter continued, with no major interruption, high precision gravimetric records started in 2016. Throughout the period from 2016 to 2022 the records of the iGrav-027 gravimeter have been supplemented with absolute gravity determinations with the use of all three AGs currently operating in Poland. The FG5-230 gravimeter of WUT performed survey several times in that period, the A10-020 gravimeter – on a regular monthly basis (Dykowski et al., 2021b) and the AQG-B07 quantum gravimeter – also on a regular monthly basis (Dykowski et al., 2022c). Data from the iGrav-027 gravimeter is partially submitted to the International Geodynamics and Earth Tide Service (IGETS) database (Dykowski et al., 2018a; 2018b).

Several years of continuous operation with the iGrav-027 gravimeter, supplemented with absolute gravity surveys with the use of gravimeters that participated in international AG comparisons allowed not only to evaluate the drift of the superconducting gravimeter, but also to tie the gravity record to the ITGRF gravity level.

In 2021, a joint analysis of gravity records from the A10-020 and iGrav-027 gravimeters at the BG Observatory was performed (Dykowski et al., 2021b). The drift of the iGrav gravimeter was evaluated with the distinction of its two periods of operation. First eight months (~200 days 2016.05 – 2017.01, the end marked with a green dashed line) were considered as an exponential decay due to internal temperature stabilization of the iGrav-027. Second period of the iGrav drift from 2017.01 – 2019.01 (the end marked with a green dashed line) when the A10-020 gravimeter did not undergo service was considered as a linear trend. For both periods drift rates were evaluated using two solutions with respect to the A10-020 result, i.e. utilizing all A10-020 gravimeter results and selected results (within single total uncertainty of the A10-020 gravimeter with respect to the iGrav-027 gravimeter). Both solutions are presented in Figure 7 with indication of the described periods. Using all A10-020 results, the exponential decay resulted in a time constant (tc) of 35.5 days with a linear fit of –0.11 μGal/year while using selected A10-020 gravimeter results, the exponential decay resulted in a time constant of 34.1 days and a linear fit of +0.49 μGal/year. Both solutions indicate exceptional stability of the iGrav-027 superconducting gravimeter, yet in a long term period of several years they considerably drift apart from each other indicating a need for further evaluation.

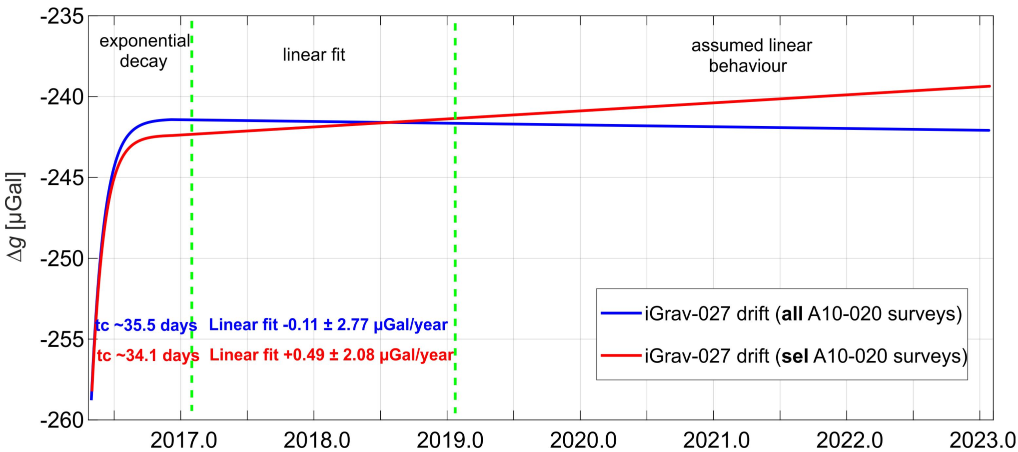

Fig. 7. Drift evaluation of the iGrav-027 gravimeter over first couple of years of operation (all A10-020 results – blue, selected – red)

Beyond 2019, the iGrav-027 drift is assumed linear and has not yet been evaluated due to the lack of participation of AGs operating at the BG Observatory in absolute gravimeter comparisons, mostly postponed and/or cancelled due to the Covid-19 pandemic. In May–July 2022 a regional AG comparison campaign – NKG-CAG-2022 Additional Comparison – was conducted with the participation of the A10-020 and AQG-B07, yet results were not available at the time of preparation of this paper.

The residual signal (after removing Earth tides – Tamura, ocean tides – FES04, barometric effect, polar motion) obtained from the iGrav-027 gravimeter tidal record for both above-mentioned solutions to remove the gravimeters drift are presented in Figure 8. They provide very interesting insights at long term non-tidal gravity change: small scale annual signals, and strong several yearlong trends, both of which are suspected to be of hydrological origin related specifically to the location of the BG Observatory. Within the period of 2016–2022, the peak to peak gravity variation exceeds 25 μGal. The long term gravity variation available from the iGrav-027 gravimeter is a very important tool for the evaluation of AGs, especially the A10-020 and AQG-B07, in terms of their performance and stability, thus may play an important role in defining the ITGRF.

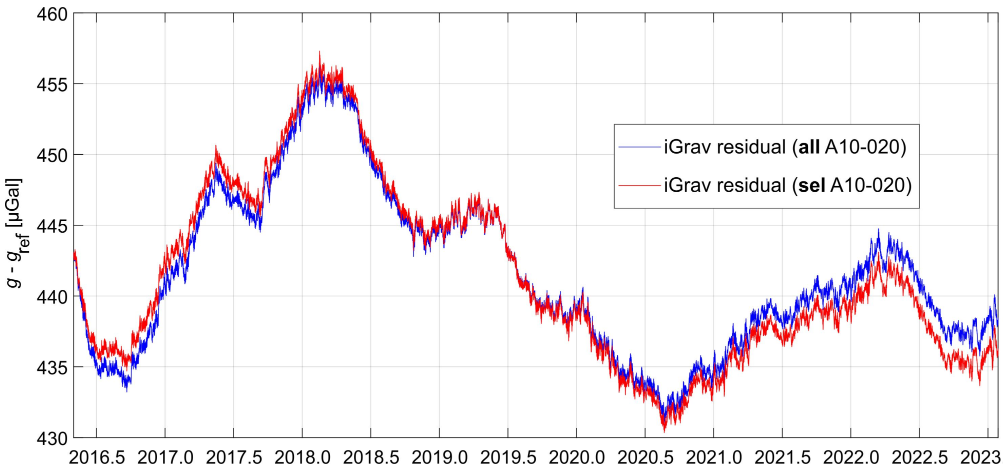

Fig. 8. Residual signal of the iGrav-027 (after drift removal and tie to ITGRF); all A10-020 results – blue, selected – red

Monitoring gravity variations in other locations in Poland

As already mentioned in Section 2.1, within the period of 2019–2022, the tidal gravimetric infrastructure in Poland expanded to five gPhoneX type gravimeters with the support of the EPOS-PL, EPOS-PL+, and MOG projects, hence giving new capabilities for monitoring gravity in Poland.

On selected gPhoneX locations, i.e. Holowno, and Borowiec, periodic absolute gravity surveys are being conducted (Nastula et al., 2022), however, no studies using the long term gravity change from the tidal gravimeter have yet been performed.

Currently, the use of the gPhoneX#165 in Holowno of the Polish Geological Institute – National Research Institute focuses on its capability of recording seismic signals within the MGP project. Events recorded by the instrument are used to prepare periodic reports on seismicity in Poland and around the world.

Tidal gravimeters gPhoneX #155 (Rybnik) and #157 (Katowice) owned by GIG are mainly used to evaluate seismic tremors in mining areas caused by mining exploration (Kotyrba et al., 2020). Using gravimeters to such studies supplements research on understanding the effects of mining exploration, especially in terms of evaluation of tremor strength as a function of distance and magnitude.

The use of the gPhoneX gravimeter at the Borowiec Astrogeodynamic Observatory of SRC PAS primarily focuses on utilizing the results to support the activities related to the Cesium Fountain operating currently at the Observatory. This includes as well short term and long term gravity variation analysis which is undergoing with the support of the IGiK (Nastula et al., 2022).

3.2. Contribution of gravimetric records to seismic studies

Gravimetric recordings of earthquakes show excellent capabilities in long-period seismology. Tidal gravimeters can detect surface waves of periods even up to 500–600 s, while a typical broad-band seismic sensor, due to its mechanical limitation, can detect them only up to periods of 200–300 s. Consequently, gravimetric data can complement seismic recordings for longer periods, depending on what seismometer the station is equipped with and what the seismometer's cut-off period is. A superconducting gravimeter can act as a single-dimension of a very broad-band seismometer (only the vertical component).

Research conducted at the IGiK allowed for the detailed analysis of the transfer function of gravimeters and, as a result, to define a period range when a sensitivity coefficient (calibration factor) and a time lag value only, can be used to adequately describe the properties of instruments (Karkowska et al., 2022a). A joint analysis of the gravimetric and seismometric recordings allows for studying a wider response for incoming seismic wave. Methods developed during the seismic-gravimetric experiment at the BG Geodetic-Geophysical Observatory (Karkowska et al., 2021) have been adopted to selected worldwide stations with co-located typical broad-band seismic sensors and superconducting gravimeters (Karkowska et al., 2022b). Simultaneous seismic and gravity recordings at the same location allow for exploring a broader response for incoming seismic waves. In this way, one joint group-velocity dispersion curve of Rayleigh surface waves for a broader range of periods has been estimated for all stations. All curves were then inverted by linear inversion (together with the determination of resolution matrices, Fig. 9a and Monte Carlo methods to calculate a distribution of shear-wave seismic velocity with depth in the Earth's mantle (Fig. 9b). Analyses of the fundamental mode of Rayleigh surface waves recorded by typical broadband seismometers (120 s) can give information about the Earth's structure up to 600 km (periods up to 300 s), while in the case of tidal gravimeters up to 1200 km (periods up to 500 s).

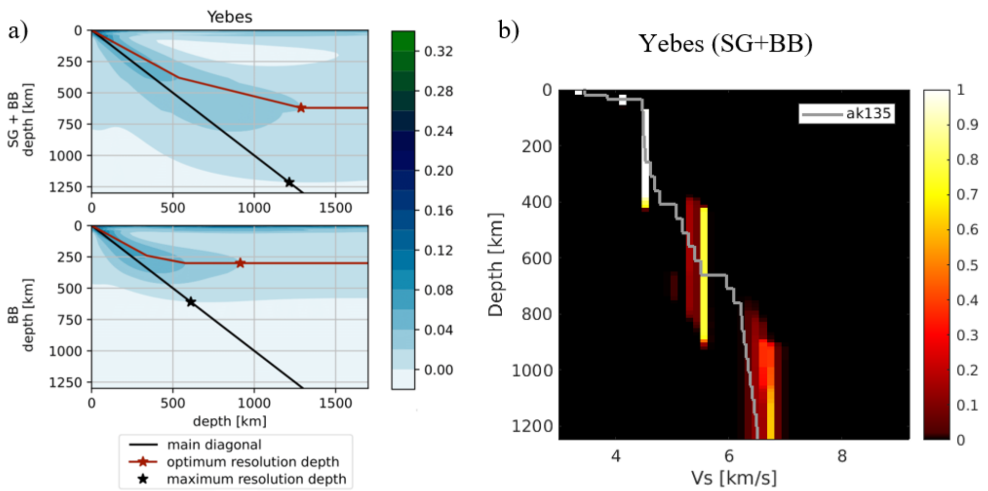

Fig. 9. a) Resolution matrices of the inversion scheme for the joint dispersion curve (SG+BB) and only seismic data dispersion curve (BB). The maximum resolution depth is marked with a black star and the optimum resolution depth with a red star. A resolution matrix relates the estimated model to the true one. A resolution matrix is an identity matrix when the true model and estimated one are identical. b) Results of Monte Carlo inversion performed for Yebes station on joint dispersion curve. The plot represents the a posteriori probability of S-wave velocity (Vs) at each depth; white color shows high probabilities, and red one – low probabilities

3.3. Temporal variations of the gravity field from GRACE/GRACE-FO data

Software for the determination of temporal variations of the Earth gravity field

A novel scientific software, named IGiK–TVGMF (Instytut Geodezji i Kartografii – Temporal Variations of Gravity/Mass Functionals) for the determination of TVGMFs within the Earth's system using GRACE data as well as for analysing and modelling TVGMFs using the seasonal adjustment (SA) and the Principal Component Analysis/Empirical Orthogonal Function (PCA/EOF) methods was developed as a computing tool in the Gravimetric Observations Research Infrastructure Centre of the EPOS-PL project (Godah, 2019). The MATLAB R2017a App Designer was used to develop this software. Three Graphical User Interfaces (GUIs): TVGMF–Computation, TVGMF–Analysis (PCA/EOF), and TVGMF–Analysis (SA) were included in the IGiK–TVGMF software. The TVGMF–Computation allows to calculate thirteen TVGMFs from monthly release 05 GRACE-based GGMs. The user can select monthly GGMs from those provided by seven different computation centres and setup different parameters, e.g. degree-2 spherical harmonic coefficient, reference model, reference system, maximum degree and order (d/o), decorrelation (DDK) filters, and Gaussian filter. The TVGMF–Analysis (PCA/EOF) and the TVGMF–Analysis (SA) allow to analyse and model the TVGMF using PCA and seasonal adjustment methods, respectively. A good agreement, e.g. sub-mm level in terms of temporal variations of geoid height (ΔN), between TVGMFs determined using the IGiK–TVGMF software and the corresponding ones determined using the GRAVSOFT and the International Centre for Global Earth Models (ICGEM[1]) interactive online tool were obtained.

Research on deformations of the Earth's surface and temporal variations of heights

An extended research on vertical displacements and deformations of the Earth's surface, temporal variations of geoid heights and orthometric/normal height changes was conducted by the IGiK's team. Vertical displacements of the Earth's surface (Δh) in the period of 2008–2013 at 25 sites (of presently 129 stations) of the Active Geodetic Network of the European Position Determination System (ASG-EUPOS) in south-eastern Poland determined using GRACE products were compared with those determined using GNSS data (Godah et al., 2020a). The results obtained revealed that monthly Δh obtained from GRACE data are generally in good agreement with the corresponding ones obtained from GNSS data. The Pearson coefficients of correlation between those Δh were in the range from 0.6 to 0.9. Standard deviations of differences between Δh obtained from GRACE and GNSS data were in the range of 2.6–5.7 mm. Overall, the results obtained indicated the need for further investigations concerning Δh determined using GNSS data from the remaining ASG-EUPOS stations as well as for a longer period, i.e. more than 5 years, that are needed to better understand geodynamic processes, and to monitor mass transport within the Earth's system (MTES) over the area of Poland.

The use of GNSS data from national Continuously Operating Reference Stations (CORS) networks, in particular, all GNSS stations of the ASG-EUPOS network, for the determination of MTES and for improving GRACE solutions was investigated (Godah et al., 2020b). The results obtained revealed good agreement between the annual seasonal pattern of Δh from GNSS (Δh_{GNSS}) and the respective one from GRACE/GRACE-FO data ($\Delta h_{G/GF}$). The median values of peak-to-peak variations of Δh_{GNSS} and $\Delta h_{G/GF}$ were at the level of ca. 20 cm. Strong correlations (i.e. Pearson correlation coefficients ranging from 0.6 to 0.9) between Δh_{GNSS} and $\Delta h_{G/GF}$ at 93% of ASG-EUPOS sites investigated were observed. In terms of secular variations of Δh, the results obtained exhibited disagreement between linear trends of Δh_{GNSS} and the respective ones of $\Delta h_{G/GF}$ as GNSS data can include additional local deformations signal. Furthermore, the combination of ΔEWT determined by inverting Δh_{GNSS} with the corresponding ones from GRACE/GRACE-FO data improve the determination of ΔEWT over the area of Poland; the differences between ΔEWT obtained from this combination and ΔEWT from the WGHM (WaterGAP Global Hydrology Model) exhibited strong correlations at 83% of the ASG-EUPOS sites investigated and their standard deviations were of 4 cm. Overall, the results obtained clearly showed that national GNSS CORS networks may provide valuable information for modelling MTES. However, the use of other national GNSS CORS networks operated worldwide for determining MTES as well as for improving GRACE/GRACE-FO satellite missions' solutions can be recommended as subjects for future research.

[1]http://icgem.gfz-potsdam.de/

Significant efforts of the IGiK's team have been put into the estimation of orthometric/normal height changes ($\Delta H/\Delta H^{*}$) over 24 large river basins (Godah et al., 2020c) as well as for the areas of Turkey (Öztürk et al., 2020) and Poland (Szelachowska et al., 2022) using GRACE satellite mission data. For the river basin of a weak hydrological signal, such as the Orange river basin, $\Delta H/\Delta H^{*}$ do not exceed ±1 cm, while $\Delta H/\Delta H^{*}$ can reach 8 cm in the case of the river basin of strong hydrological signal, e.g. the Amazon river basin (Godah et al., 2020c). The analyses of $\Delta H/\Delta H^{*}$ obtained indicated that due to spatio-temporal patterns such as unusual floods, extreme drought, and rainfall seasonality within the entire river basin as well as the location of the upstream and downstream areas of the river basin, clear differences (e.g. ±2 cm in the Amazon river basin) for $\Delta H/\Delta H^{*}$ can be found within subareas of the same river basin (Godah et al., 2020c). For the area of Turkey, the differences between $\Delta H/\Delta H^{*}$ in the same area at different epochs reach up to 25 mm, while those differences at the same epoch and different areas reach up to 9 mm (Öztürk et al., 2020). The seasonal decomposition (SD) method was selected as the appropriate one for analysing $\Delta H/\Delta H^{*}$ over Turkey; the correlations and standard deviations of the differences between $\Delta H/\Delta H^{*}$ data and $\Delta H/\Delta H^{*}$ models developed using the SD method were at the level of ca. 96 ± 1%, and the range from 0.9 to 1.2 mm, respectively. Moreover, the use of Green's function for the determination of $\Delta H/\Delta H^{*}$ from ΔEWT obtained from the WGHM was recommended (Öztürk et al., 2020). For the area of Poland, the need for monitoring $\Delta H/\Delta H^{*}$ to correct orthometric/normal heights was investigated (Szelachowska et al., 2022). Firstly, the relation between temporal mass variations within the Earth system with respect to geoid/quasigeoid height changes, Δh, and $\Delta H/\Delta H^{*}$ was described. Then, the procedure for the determination of orthometric/normal height corrected from their dynamics was formulated. The $\Delta H/\Delta H^{*}$ were determined at the sites of the ASG-EUPOS network using GRACE data and the NKG2016LU (Nordic Commission of Geodesy Land Uplift 2016) model. It was shown that $\Delta H/\Delta H^{*}$ over the area of Poland reached up to 23 mm. Those $\Delta H/\Delta H^{*}$ can be modelled and predicted for the next 6 months with an accuracy of 1 mm and ca. 1–2 mm, respectively. Overall, the results obtained indicate the need of $\Delta H/\Delta H^{*}$ for the determination of accurate orthometric/normal heights that fulfil the contemporary geodetic scientific requirements and high-precision applications associated with physical heights (Szelachowska et al., 2022).

With the use of GPS (Global Positioning System) and GRACE data, the seasonal horizontal deformations of the Earth's surface for the period 2003–2014 were investigated at 36 GPS stations located mostly in northeast India and Nepal Himalaya (Ray et al., 2021). Positive coefficient of correlations between time series of horizontal seasonal deformations of the Earth's surface in the north component obtained from GPS and GRACE data was determined at nearly 89% of GPS stations investigated. The median values of correlation coefficients in the east and north components are 0.20 and 0.61, respectively. They also revealed a positive reduction of Weighted Root Mean Square (WRMS) at ~83% of GPS stations investigated in the case of the north component. In the case of the east component, this positive reduction of WRMS was observed in 58% of GPS stations investigated. Median values of Nash-Sutcliffe model Efficiency (NSE) in the east and north components are -0.01 and 0.28, respectively.

The suitability of GGMs developed using data from Non-Dedicated Gravimetric Satellite Missions (NDGSM) for determining ΔN was investigated (Godah et al., 2019b). Two areas, i.e. Poland and the Amazon river basin, which are characterized by different signal strengths of temporal mass variations within the Earth's system were considered. The results obtained indicated that GGMs developed on the basis of data from TanDEM-X, Swarm-comb, Swarm-2 and Sentinel-3A seem, to some extent, suitable for the reliable determination of ΔN for the Amazon river basin but unsuitable for the determination of ΔN for areas with a weak mass transport signal as in the case of Poland.

Temporal variations of total water storage and groundwater storage

Temporal variations of total water storage (ΔTWS) and groundwater storage were investigated by the team of the University of Warmia and Mazury in Olsztyn (UWM). ΔTWS from GRACE-FO data, monthly precipitation and evapotranspiration as well as sea level change from tide gauge data over Venezia Islands were analysed (Birylo and Rzepecka, 2020). The lack of dependence between ΔTWS obtained from GRACE-FO data and the temporal variations of evapotranspiration and evapotranspiration was observed, however, those ΔTWS and mean sea level change exhibited a similar phase change. The authors concluded that atmospheric budget analysis of the MERRA (Modern-Era Retrospective analysis for Research and Applications) model can provide a good prediction for the availability of fresh water.

Variations of groundwater level obtained from direct measurements in wells located in Poland were compared with temporal variations of groundwater storage (ΔGWS) determined using GRACE products and global land data assimilation (GLDAS) models (Rzepecka and Birylo, 2020). It was found that ΔTWS from GRACE and wells data were highly correlated; the cross-correlation function values reached up to 0.9. The ΔGWS obtained from GRACE data and GLDAS model were shifted (delayed) with respect to measurements in wells by three months. The values of cross-correlation function between those ΔGWS ranged from ca. 0.2 to 0.6. Amplitudes of variations in water levels in the wells are much higher than the amplitudes of ΔTWS from GRACE data and ΔGWS from GRACE and GLDAS data. This might be ascribed to disagreement between mean soil porosity values, as the amplitudes of the thickness of the unsaturated zone at the well locations are about four times larger than the corresponding amplitudes of ΔGWS from the GRACE products and GLDAS models.

The ΔTWS and ΔGWS over main river basins in Poland, i.e. the Vistula river and Odra river basins, determined from GRACE data, GLDAS hydrological sub-models (the Community Land Model (CLM), the Mosaic (MOS) model, the Variable Infiltration Capacity (VIC) model and the Noah model-, CMIP5 (World Climate Research Programme's Coupled Model Intercomparison Project Phase 5) climate models (the Flexible Global Ocean-Atmosphere-Land System Model Grid-point Version 2 (FGOALS-g2), the Geophysical Fluid Dynamics Laboratory Earth System Model Version 2G (GFDL-ESM2G), the NASA Goddard Institute for Space Studies E2-H Model (GISS-E2-H), the Russian Institute for Numerical Mathematics' model (inmcm4), the Model for Interdisciplinary

Research on Climate version 5 (MIROC5), and the Max Planck Institute Earth System Model (MPI-ESM-LR) and direct measurements in wells were determined and analysed (Sliwinska et al., 2019). The results obtained showed that the CLM, GFD-ESM2G and MIROC5 models agree well with GRACE data. The highest agreement between in-situ well measurements and ΔGWS from the combination of GRACE and hydrological and climate models was found for the CLM, FGOALS-g2 and MPI-ESM-LR models.

RL06 GRACE-based products and the performance of monthly GGMs

Researchers from Polish research institutions participated in examining RL06 GRACE-based products and investigating the performance of monthly GGMs. The variance of signal contained in two types of RL06 GRACE-based products: spherical harmonics (SH) solution and mass concentration blocks (mascons) was examined (Lenczuk et al., 2020). For SH solution, spherical harmonics coefficients (SHCs) up to d/o 96, provided by JPL (Jet Propulsion Laboratory), GFZ (GeoForschungsZentrum) and CSR (Center for Space Research at University of Texas, Austin) were used. For the mascons values of ΔTWS provided by the CSR, JPL, and the Goddard Space Flight Center (GSFC) computing centres converted to SHCs (GRACE-M-based GGMs) up to d/o 96 were utilized. It was found that applying the anisotropic DDK3 filter to SH solutions maintain more signal compared to the use of the isotropic Gaussian filter. For mascons, GSFC solution contains much more gravity signal than those of CSR and JPL ones. Differences in signal variance arise from different background models as well as various shape and size of mascons used during processing GRACE observations. It was proved that GGMs obtained from mascon solutions are more appropriate to retrieve the change of gravity signal on a local scale. Furthermore, degree variances and signal contained in GRACE solutions were compared for individual d/o of SHCs. The lowest signal variance was obtained for low SHCs up to d/o 34 of GRACE-based GGMs filtered with DDK3. It was concluded that the method of GRACE-based GGMs filtering has a stronger impact on the final signal than various processing approaches and background models used. The differences in variances were identified for GRACE-based GGMs and GRACE-M-based GGMs.

The research on selecting a proper filter, i.e. an isotropic Gaussian filter and anisotropic decorrelation filters, for RL06 and RL05 releases of monthly GRACE-based GGMs was conducted (Szabó and Marjanska, 2020). The square root of degree variances of spherical harmonics for RL05, RL06 and the difference between RL06 and RL05 for CSR centre using different filters were calculated. The DDK filter shows better stability for higher degrees/orders of spherical harmonic coefficients than the Gaussian filter. For Gaussian filters with radii 500 and 600 km, a better agreement between RL06 and RL05 is noted. Moreover, gravity disturbances determined from filtered GRACE-based GGMs were compared with the corresponding ones obtained from the FG5-230 absolute gravimetric measurements conducted in Jozefoslaw Astro-Geodetic Observatory of WUT. RL05a and RL06 solutions from CSR, GFZ and JPL centres filtered with the use of DDK1–DDK8 filters as well as Gaussian filters with radii 200, 300, 400, 500 and 600 km were analysed. For both releases (except RL6 GGMs from GFZ) very good consistency with the FG5-230 measurements was obtained. The best fit, i.e. a cross-correlation coefficient of 0.7–0.8 and the RMSE (Root Mean Square Error) at the level of 4–5 µGal, was found for GRACE-based solutions filtered using DDK3 – DDK6 filters (Szabó and Marjanska, 2020).

Mass changes and vertical displacements from Swarm satellite mission data were assessed (Richter et al., 2021). A new approach of such an assessment with two variants was considered. In the first one, the entire observed mass change signal was decomposed using the PCA method. In the second variant, the GRACE and Swarm residuals were used as an input for the PCA method, giving solutions that can be considered as the combination of GRACE interpolation/extrapolation with the Swarm reconstruction method. Following this assessment, global temporal variations of equivalent water height (ΔEWH) were reconstructed. It was found that the reconstructed ΔEWH were much closer to GRACE-based solutions than Swarm-only-based ones. For d/o 40, monthly Swarm-only ΔEWH have a global RMSE of 1.39 m at the beginning of the Swarm mission, then decreasing to 0.29 m. The reconstructed ΔEWH have a lower RMSE of 0.02–0.08 m. The reconstruction approach enables to obtain reliable monthly ΔEWH for d/o 40 which is not possible in the case of the Swarm-only monthly solutions.

The performance of monthly GGMs developed up to d/o 90 using satellite laser ranging (SLR) and high-low satellite-to-satellite tracking (HLSST) data from 20 Low Earth Orbit (LEO) satellites and 9 SLR satellites including data from CHAMP (CHAllenging Minisatellite Payload), GRACE, and GOCE (Gravity Field and Steady-state Ocean Circulation Explorer) satellite missions was analysed (Zhong et al., 2021). The accuracies of combined HLSST+SLR solutions were found comparable to the respective ones obtained from GRACE for SHCs below d/o 10, and significantly better than the solutions from SLR-only and HLSST-only. The effective spatial resolution of the combined solutions can reach d/o 20, and is higher than that of the HLSST-only solutions (Zhong et al., 2021). Moreover, the global mass redistribution and its magnitudes can be well identified from combined HLSST+SLR solutions at 1000 km spatial resolution. The seasonal mass variations over the Amazon river basin and the long-term trend of mass variations over Greenland, in terms of ΔEWT, determined from combined HLSST+SLR solutions match to the respective ones from the GRACE solutions. The RMS of mass variations was estimated to 282 Gt for the Amazon river basin, and 192 Gt for Greenland.

The influence of solar, geomagnetic, and ionospheric activities on the quality of kinematic and reduced-dynamic GOCE orbits using SLR residuals of GPS-based GOCE orbits was investigated (Strugarek et al., 2019). A substantial sensitivity of kinematic orbit solutions to the F10.7 Solar Radio Flux Index and the ionospheric activity measured by the variations of the Total Electron Content (TEC) values as well as the minor sensitivity of kinematic orbits to the magnetic field activity index Kp was observed. The reduced-dynamic orbits were almost insensitive to indices describing ionospheric, solar, and geomagnetic activities. Moreover, the quality of data provided by individual SLR stations detecting time biases by the use of ascending and descending sun-synchronous GOCE orbit passes was investigated as well as the analysis of SLR station residuals as a function of the nadir angle and horizontal angle of the SLR observations was conducted. It was shown that some of them are affected by time bias errors. The analysis of SLR station residuals as a function of the nadir angle and horizontal angle of the SLR observations indicated a variability of 2–4 cm for stations Monument Peak, Greenbelt and Mount Stromlo. Moreover, differences of SLR residuals between kinematic and reduced-dynamic orbits indicated that kinematic orbits were frequently affected by radial, along-track and cross-track errors. For some stations, incorrect station coordinates and insufficient troposphere delay modelling can be noted.

Time series of monthly gravity field solutions derived by satellite laser ranging (SLR) observations to geodetic satellites, by GPS observations and a dual frequency K-band range-rate measurements of the GRACE mission, and by GPS observations of the three Swarm satellites were determined, evaluated and mutually compared (Meyer et al., 2019). The combined monthly gravity field solutions obtained from Swarm and SLR data generated on the normal equation level that can be helpful to bridge the gap between GRACE and GRACE Follow-On satellite missions were proposed (Meyer et al., 2019). The combined Swarm and SLR solutions were validated using GRACE solutions. The best fit between the SLR/Swarm combination of mass estimation and GRACE-based mass estimation for the mentioned period was achieved when SLR and Swarm normal equations are combined with almost equal weights. The combined gravity field solutions match GRACE ones significantly better than solutions based on SLR-only.

4. Research on static gravity field

4.1. Evaluation of Global Geopotential Models

GGMs developed in years 2019–2022, i.e. satellite-only GGMs: GO_CONS_GCF_2_TIM_R6, GO_CONS_GCF_2_DIR_R6, GO_CONS_GCF_2_TIM_R6e, and Tongji-GMMG2021S, as well as combined GGMs: SGG-UGM-2 and XGM2019e, were validated at IGiK. Those models are available on the website of the ICGEM. They were assessed over the area of Poland in terms of height anomalies with the use of GNSS/levelling data at ASG-EUPOS network stations, and in terms of free-air gravity anomalies with the use of absolute gravity data at the stations of the Polish gravity control.

For satellite-only GGMs: GO_CONS_GCF_2_TIM_R6, GO_CONS_GCF_2_DIR_R6, GO_CONS_GCF_2_TIM_R6e, standard deviations of differences of height anomalies at d/o 200 are at the level of 25 cm and they decrease to ca. 3 cm when the omitted gravity signal, i.e. the signal in the spectral range from applied d/o 200 to d/o 2190, is compensated using the Earth Gravitational Model 2008 (EGM2008). In the case of Tongji-GMMG2021S model the standard deviation of differences of height anomalies at d/o 200 is 2.9 cm when the omitted gravity signal is taken from the EIGEN-6C4 combined GGM.

The accuracy of the combined GGM SGG-UGM-2, in terms of the standard deviation of the gravity anomaly differences, is ca. 1.8 mGal which is almost at the same level as the ones of the EGM2008, EIGEN and GECO combined GGMs. Standard deviations of differences of height anomalies obtained from XGM2019e and from GNSS/levelling data are 3 cm at d/o 2159 and 2190. However, the accuracy of XGM2019e, in terms of the standard deviation of the gravity anomaly differences at maximum d/o, i.e. 5540, is almost 4 mGal which is twice larger than the corresponding standard deviations obtained for the EGM2008 and EIGEN-6C4 models (Krynski and Rogowski, 2021). The lower quality of the XGM2019e model compared to the quality of the EGM2008 and EIGEN-6C4 models for Poland may result from the use of terrestrial gravimetric data with a resolution of $15' \times 15'$ from the resources of the National Geospatial-Intelligence Agency (NGA) of the United States.

The contribution of dedicated gravity satellite missions to the modelling of the Earth's gravity field over East Africa, in particular, the area of Sudan, Ethiopia and Uganda, was assessed. Gravity functionals, e.g. geoid/quasigeoid height, gravity anomaly, and gravity disturbance, obtained from recent combined and satellite-only GGMs were evaluated using terrestrial gravity data available in Sudan and Ethiopia as well as GNSS/levelling data in Uganda. The results obtained revealed substantial improvements in GGMs developed with the use of GOCE satellite mission data compared to GGMs that do not include GOCE data, e.g. the EGM2008. In the area of Ethiopia and Uganda, these improvements reach ca. 40% and ca. 50%, respectively. This may reflect and confirm the contribution of dedicated gravity satellite missions to improve the modelling of the Earth's gravity field over East Africa (Godah et al., 2019a).

The European Gravimetric Geoid models EGG2008 and EGG2015 were validated on the territory of Poland. Height anomalies determined from these models were compared with those obtained from GNSS/levelling data. In the case of EGG2015 model the fit is at the level of 2 cm and it decreases to 1.3 cm when the trigonometric polynomials fit is additionally applied (Marjanska et al., 2019).

4.2. Geoid modelling

The research team from Wroclaw University of Environmental and Life Sciences (UPWr) continued their investigations concerning geoid modelling and issues related to this process. In particular, they investigated the use of the Geophysical Gravity data Inversion (GGI) method for modelling the disturbing potential and quasigeoid surface over the area of Poland. Different reference crust's densities as well as two types of GGI models: (1) type A – with the disturbing potential from the EGM2008, and (2) type B – without the disturbing potential from EGM2008, were considered. It was concluded that height anomalies and gravity disturbances can be determined with high accuracy from both model types applied in the GGI method as well as the accuracy of height anomalies determined depends on the reference crust's density applied (Trojanowicz, 2019).

The GGI method was applied within the Colorado geoid experiment to model the quasigeoid using terrestrial and airborne gravity data as well as SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM) of a spatial resolution of 3 arc-second, and the XGM2016 (the experimental global gravity field model 2016). In order to model the geoid surface, geoid-to-quasigeoid separation (GQS) was estimated. Over 700 height anomalies from GPS/levelling data: ~500 points from historical data and over 200 points for the Geoid Slope Validation Surveys 2017 profile (GSVS17) were used to validate quasigeoid/geoid models developed. Standard deviations of the differences between geoid/quasigeoid heights determined using the GGI method and their corresponding ones from historical and GSVS17 profile GPS/levelling data are at the level of 1–2 cm. The results obtained exhibited the robustness of the GGI method for modelling the local geoid/quasigeoid surface (Trojanowicz et al., 2021).

The UPWr team also focused on the interpolation methods implemented for local geoid/quasigeoid modelling. In particular, they investigated (1) the effect of neglecting terrestrial gravity data in the geoid/quasigeoid modelling process (2) the effect of the accuracy of the GGM on the quality of a local geoid/quasigeoid model, and (3) the density of GNSS/levelling points to keep the accuracy at the level of the gravimetric geoid/quasigeoid model. An analysis based on comparisons of four approaches for modelling the local geoid/quasigeoid surface was performed. The 1st and 2nd approaches were based only on GGM and GNSS/levelling data interpolated using the least squares collocation method (LSC) and the thin plate spline, respectively. The 3rd and 4th approaches incorporate in addition terrestrial gravity data and elevations from DEM. The 3rd approach was based on Molodensky's theory and the LSC method, while the 4th approach was based on the GGI method. The differences between the results obtained from all four methods investigated do not exceed 1 mm when using a high-quality GGM and a dense network of GNSS/levelling data (ca. 1 point per 30 km^2). In such a case, there is no need to use gravity data and develop advanced geoid/quasigeoid modelling methods. The differences between the results from the four methods implemented became notable when using coarse GNSS/levelling data and lower-quality GGM (Trojanowicz et al., 2020a).

The use of the global topographic mass density model developed by the University of New Brunswick (UNB_TopoDens) for determining the differences between geoid/quasigeoid heights ($\delta = N - \zeta$) and Bouguer anomalies over the area of the Western Carpathians was also investigated by the UPWr team. The results obtained indicated that Bouguer anomalies without using data from UNB_TopoDens model range from approx. –74 to +23 mGal, and δ range from ca. –10 to +5 cm. When data from UNB_TopoDens model are considered, these ranges can be reduced by ~40 mGal for Bouguer anomalies, and ~8 cm for δ. For the highest areas of the Western Carpathians, the difference between δ determined using complete Bouguer anomalies and simple Bouguer anomalies can reach 9 cm (Trojanowicz et al., 2020b).

The research team from IGiK continued their activities towards precise geoid/quasigeoid modelling for the area of Poland. New mean gravity anomalies were generated in two spatial resolutions $5' \times 5'$ and $1' \times 1'$. The coarser grid represented mean free-air gravity anomalies was developed to be included in the EGM2020. The finer grid represented mean Faye anomalies was generated for geoid modelling for the territory of Poland (Krynski and Rogowski, 2021). More accurate formula for the free-air gravity gradient was applied instead of the commonly used constant coefficient equal to 0.3086. The new gravimetric quasigeoid model GDQM-PL-19 for Poland was calculated using the updated mean Faye anomalies. The accuracy of that model, in terms of standard deviations of differences between height anomalies with respect of GNSS/levelling data, is at the level of 1.5 cm.

Gravimetric quasigeoid models GDQM-PL13 and GDQM-PL19 developed in the last decade by the IGiK team were compared with two official Polish quasigeoid models. One is gugik-geoid2011-PL-KRON86-NH – based on the PL-KRON86-NH vertical reference frame, and the other is gugik-geoid2011-PL-EVRF2007-NH – compatible with the PL-EVRF2007-NH vertical reference frame. Both were obtained by fitting height anomalies from the EGM2008 into the corresponding ones determined using GNSS/levelling data. Both GDQM-PL13 and GDQM-PL19 quasigeoid models were developed using the EGM2008, mean $1' \times 1'$ Faye gravity anomalies for the area of Poland (different ones for GDQM-PL13 and GDQM-PL19), free-air gravity anomalies for territories surrounding the country, deflections of the vertical for Poland and applying the remove-compute-restore technique with the LSC method. Standard deviations of differences between height anomalies obtained from GDQM-PL13 and GDQM-PL19 models and the corresponding ones determined from fitted gugik-geoid2011-PL-KRON86-NH and gugik-geoid2011-PL-EVRF2007-NH models are at the level of 1.5 cm (Krynski and Rogowski, 2021).

The IGiK's team participated in the research on geoid modelling for the area of Ethiopia. A new gravimetric geoid model over Ethiopia (named the ETH–GM21) was developed. The model is based on terrestrial and airborne free-air gravity anomalies as well as the SRTM3 DEM and EIGEN-6C4 combined GGM. The LSC method and the remove-compute-restore technique were implemented to develop the ETH–GM21. Geoid heights obtained from this model range from 3 m in northern Ethiopia to –35 m in southeast Ethiopia. The estimated accuracy of geoid heights from the ETH–GM21 gravimetric geoid model, in terms of the standard deviation of differences dN between geoid heights from this model and the corresponding ones obtained from 46 GNSS/levelling, is ca. 15 cm. After applying the 7-parameter transformation model, this accuracy improved to 13 cm (Belay et al., 2021).

Then, a GQS model for the area of Ethiopia (ETH-GQS) with the use of airborne free-air gravity anomalies and the topographic information retrieved from the SRTM3 DEM, was developed. Sjöberg's strict formula was used to compute the ETH-GQS. The use of GQS values obtained from the ETH-GQS substantially improved the agreement between geoid heights obtained from GNSS/levelling data and the corresponding ones determined from GGMs. In terms of the standard deviation of differences between geoid heights from GNSS/levelling data and the ones from the EIGEN-6C4 GGM, this improvement is ~75%, i.e. from ~24 to ~6 cm (Belay et al., 2022).

The local quasigeoid model QuasigeoidKR2019 was developed for the area of Krakow. The model is based on repeatable static GNSS observations at 66 points and normal heights referenced to the detailed vertical control network. Height anomalies derived were used to develop an approximation function that models the residual quasigeoid heights with respect to the EGM2008; planar coordinates in the PL-2000 coordinate frame are the input data to that approximation function. The quality of GNSS and levelling measurements was evaluated based on the repeatability of height anomalies from two independent determinations at 22 points. The estimated accuracy of the local QuasigeoidKR2019 model in the Krakow area is higher than that of the PLgeoid2011 national model. The maximum difference between models and empirical GNSS/levelling data reaches up to 14 mm for the local model and 44 mm for the national model. The mean absolute difference of 5 mm for the local model and 16 mm for the national model was obtained (Banasik et al., 2020).

The problem of interpolation in modelling a local geoid using GNSS/levelling data was investigated. Two methods of interpolation were intercompared: the ordinary kriging/LSC with constant trend and inverse distance weighting (IDW) using leave-one-out and random (Monte Carlo) cross-validation. Ordinary kriging and IDW performance was tested using various planar covariance function models for kriging and various exponents for IDW. Practically no difference between interpolation results of kriging/LSC and IDW with suitably chosen parameters was observed for analysed dataset. However, differences between results within a method and between methods in the whole range of steering parameters may become significant. Generally, for the area investigated, the accuracy in terms of absolute, root mean square and median absolute errors, is below 1 cm (Ligas et al., 2022).

The new quasigeoid model for the Baltic Sea area was determined with the Helmert method (Lyszkowicz et al., 2021) using airborne gravity anomalies from the Baltic Sea and terrestrial gravity anomalies from Denmark, Finland, Latvia, Lithuania, Poland, and Sweden. The terrain corrections were calculated using SRTM30 digital terrain model. Three different GGMs, i.e. GOCE-DIR6, GOCO06s, and EIGEN-6C4 were used; thus three solutions were obtained. The quasigeoid models determined were validated using GNSS/levelling data at the stations of the ASG-EUPOS network. Their accuracy was assessed as 4 cm.

A quasigeoid model for the area of Poland developed by the team of the Wroclaw University of Environmental and Life Sciences was selected in the competition announced by the Head Office of Geodesy and Cartography in 2021, and on 4 April 2022 was established as the official quasigeoid model PL-geoid2021 for Poland. The theoretical part, i.e. the description of the adopted methodology and the cohesion of the models with the vertical geodetic control network, was assessed. The model was first verified using satellite/levelling data at 24 control points located throughout the country and then at 62 points of the geodetic control network which were surveyed in two 12-hour GNSS sessions. It was also compared with the PL-geoid2011 – previous official quasigeoid model for Poland (Table 2).

Table 2. Statistics illustrating the verification of the PL-geoid2021 quasigeoid model for Poland

quasigeoid model	24 control points		62 control points	
	mean (m)	std (m)	mean (m)	std (m)
PL-geoid2011	0.005	0.023	–0.015	0.038
PL-geoid2021	–0.002	0.019	–0.012	0.026

At both sets of control points the new PL-geoid2021 quasigeoid model performs better than the PL-geoid2011 model (GUGiK, 2022).

The influence of noise variance in the prediction of geophysical phenomena was investigated using methods based on the least squares theory, such as Kriging and LSC (Jarmolowski, 2019). In particular, the relation between signal spectral range and uncorrelated noise (e.g. noise induced by measurement error and noise resulted from high frequency signal in the spectral bands beyond the spatial resolution of the data) variance was verified. Two data sets of Bouguer anomalies were utilized: the first one presenting terrestrial data obtained from the United States of America gravity database, and the second one determined from the EGM2008. Three different estimators were used to assess the noise variance size. They were based on the average of a priori noise standard error, the minimum of the differences between the data used and their prediction, and a posteriori noise standard error, respectively. The results obtained revealed that the noise in Bouguer anomalies was related to the spatial resolution of the data used rather than the measurement errors.

The contradictions between the guidelines concerning aeronautical data quality requirements (DQR) and the geodetic legal regulations in Poland were pointed out (Marjanska, 2022). The differences between the coordinates data obtained from the ASG-EUPOS network stations and the corresponding ones documented in the aforementioned guidelines were determined. The results obtained indicated that these differences reach up to of 30 cm for the horizontal position and 1 cm for the ellipsoidal height. Moreover, the differences between quasigeoid heights obtained from the EGM96 (Earth Gravitational Model 1996) GGM that is used in the aviation and the respective ones from the official quasigeoid models for Poland were found at the level of up to 1 m (Marjanska, 2022).

4.3. Estimation of sea level

The research associated with the use of the Synthetic Aperture Radar (SAR), GNSS, tide gauge (TG), and geoid heights data for estimating the absolute sea level at sites of the selected network in the Baltic Sea (SNBS) were conducted within the ESA's project entitled "Geodetic SAR for Baltic Height System Unification (SAR-HSU)" (Gruber et al., 2022). Within the project, ten active electronic corner reflectors (ECRs) tied to the existing TGs and/or permanent GNSS stations, were installed at the SNBS. In order to determine the absolute sea level and height system unification for the SNBS, positions obtained from SAR and GNSS as well as geoid/quasigeoid heights obtained from gravimetric geoid/quasigeoid model, and mean sea level obtained from TG data were combined considering the technique-specific processing standards for each geodetic technique. Moreover, the ECR stations were connected with the TG or GNSS stations using conventional spirit levelling. The absolute sea level obtained from SAR, GNSS, and TG data as well as gravimetric quasigeoid models for the SNBS are not fully consistent; the difference reaches up to 0.5 m. Thus, further research concerning the performance of the ECRs and the instrument calibration as well as the methods and procedures applied by SAR positioning technique to meet the contemporary accuracy of the geodetic measurements were recommended (Gruber et al., 2022). All data and products associated with the SAR-HSU project as well as their supplementary information are available for public use via the website[2].

[2]https://www.asg.ed.tum.de/iapg/baltic/

5. Summary and conclusions

The article contains the summary of activities of Polish research and government institutions in the years 2019–2022 in gravimetry with special emphasis on its metrological aspects, and in modelling gravity field with considering its temporal variations.

Extensive research activities were conducted toward the implementation of ITGRF in Poland. In mid-2022 all three absolute gravimeters operating in Poland i.e., FG5-230, A10-020, and AQG-B07, participated in AG comparison campaign in Onsala, organized by the Nordic Commission of Geodesy. As all gravimeters also performed joint surveys together with the iGrav-027 superconducting gravimeter at the Borowa Gora Geodetic-Geophysical Observatory, results from the comparison will allow a reliable traceability to the ITGRF reference level. It was shown that the maintenance of the international gravity reference system requires, besides careful metrological control, consideration of the impact of non-tidal gravity variations and that the true gravity variations are larger than the accuracies currently achievable with AGs.

Installation of the absolute quantum gravimeter AQG-B07 in the BG Observatory further expanded the gravimetric infrastructure required for reliable realization of the gravity standard in Poland as well as for supporting the operation of the iGrav-027 gravimeter.

The A10-020 absolute gravimeter was used in the EPOS-PL and EPOS-PL+ projects related to monitoring deformations in mining areas in the Upper Silesian region in Poland. Gravimetric measurements with the FG5-230 gravimeter were performed for geodynamic research at stations Dziwie and Holowno in multiple survey campaigns within MOG project.

Research on non-tidal gravity changes was successfully continued with the use of data recorded at the BG Observatory as well as at multiple stations newly equipped with gPhoneX gravimeters. Time series of tidal gravimeter records together with quasi-regular absolute gravity measurements at the BG Observatory allowed for analysis of long term gravity variations reaching peak to peak values of 25 μGal. Linear drift estimates at the level of below ±1 μGal/year confirm great stability of the iGrav-027 gravimeter over the period of 2017–2022.

Joint research in the fields of geodesy and seismicity concerning contribution of gravimetric records to seismic studies was continued. Transfer functions of gravimeters used in the seismic analysis were determined. Monte Carlo methods were used to calculate a distribution of shear-wave seismic velocity with depth in the Earth's mantle. It was shown that signals recorded by typical broadband seismometers (120 s) can give information about the Earth's structure up to 600 km (periods up to 300 s), while in the case of tidal gravimeters up to 1200 km (periods up to 500 s).

Temporal variations of the gravity field were subject of extensive research. A novel scientific software IGiK–TVGMF for the determination, analysis and modelling temporal variations of gravity/mass functionals (TVGMF) from GRACE/GRACE-FO data was developed as a computing tool in the Gravimetric Observations Research Infrastructure Centre of the EPOS-PL project. Vertical displacements and deformations of the Earth's surface, in particular temporal variations of geoid heights and orthometric/normal height changes, were widely investigated with the use of GRACE/GRACE-FO and GNSS data. Also the suitability of non- dedicated gravity satellite missions were examined. In general, results from GNSS data match to those from GRACE data. Variations of orthometric/normal heights were investigated in large river basins of both weak and strong hydrological signal on five continents and specifically in Poland, Turkey, northeast India and Nepal Himalaya. Seasonal signals obtained vary from 1 cm to 8 cm. It was shown that national GNSS CORS networks provide valuable information for modelling TVGMF and can efficiently complement those functionals modelled with the use of GRACE data. Some research was focused on temporal variations of total water storage and groundwater storage with the use of GRACE/GRACE-FO data. An important conclusion was that atmospheric budget analysis of the MERRA model can provide a good prediction for the availability of fresh water.

RL06 GRACE-based products and the performance of monthly GGMs were investigated. GGMs obtained from mascon solutions were found more appropriate to retrieve the change of gravity signal in a local scale. The products of different computing centres were mutually compared in terms of signal strengths in the provided solutions. The superiority of DDK3 filter over the isotropic Gaussian filter was proved.

Monthly GGMs developed up to d/o 90 as a combination of SLR and high-low satellite-to-satellite tracking data from LEO satellites and SLR satellites including data from CHAMP, GRACE, and GOCE satellite missions were analysed. Monthly GGMs obtained from SLR observations to geodetic satellites were mutually compared with those obtained from GPS and K-band range-rate data of the GRACE mission, and from GPS observations of the three Swarm satellites showing the SLR and Swarm combined gravity field solutions match GRACE ones significantly better than those based on SLR-only.

GGMs developed in years 2019–2022 were carefully evaluated with the use of GNSS/levelling data at ASG-EUPOS network stations in Poland as well as with the use of absolute gravity data at the stations of the Polish gravity control. The contribution of gravity dedicated satellite missions products to the Earth's gravity field modelling over the area of Sudan, Ethiopia and Uganda, was assessed. GGMs from satellite missions considerably improve the modelling of the Earth's gravity field over East Africa, e.g. by as much as 40% and 50% in the area of Ethiopia and Uganda, respectively.

Research on geoid modelling and issues related to this process were continued. The use of the Geophysical Gravity data Inversion (GGI) method for modelling the disturbing potential and quasigeoid surface over the area of Poland as well as Colorado was investigated. The role of the reference crust's density applied as well as the interpolation methods implemented for local geoid/quasigeoid modelling was discussed. Determination of differences between geoid/quasigeoid heights and Bouguer anomalies with the use of the global topographic mass density model developed by the University of New Brunswick (UNB_TopoDens) over the area of the Western Carpathians was investigated.

The $5' \times 5'$ grid of mean free-air gravity anomalies was developed to be included in the EGM2020. The $1' \times 1'$ grid of mean Faye gravity anomalies was generated for developing new gravimetric quasigeoid model for Poland of 1.5 cm accuracy. A number of existing geoid/quasigeoid models for Poland were intercompared. In 2022 a new official quasigeoid model for Poland PL-geoid2011 has been adopted. Also a new quasigeoid model for the Baltic Sea area as well as a local geoid model for the area of Krakow were developed. The Polish team participated in the research on geoid modelling for the area of Ethiopia.

The research on the estimation of sea level with the use of SAR, GNSS, tide gauge, and geoid heights data was conducted within the ESA's project indicated the need of further investigation concerning active electronic corner reflectors performance, calibration of instruments and SAR positioning.

Author contributions

Conceptualization: J.K., P.D., W.G., M.S.; original draft preparation: J.K., P.D., W.G., M.S.

Data availability statement

No datasets were used in this research.

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