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Review paper

Research on reference frames and reference networks in Poland in 2019–2022

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Abstract: The article presents the reviewed and summarised research activities of Polish research groups on reference frames and reference networks in a period of 2019–2022. It contains the results on the implementation of latest resolutions on reference systems of the International Union of Geodesy and Geophysics and the International Astronomical Union focusing on changes in the consecutive issues of the Astronomical Almanac of the Institute of Geodesy and Cartography, Warsaw. It further presents the status of the implementation of the European Terrestrial Reference System 1989 (ETRS89) in Poland, monitoring the terrestrial reference frame, including research on global terrestrial reference frames, GNSS data analysis within the EUREF Permanent Network, research on GNSS receiver antenna phase centres, research on impact of non-tidal loading effects on position solutions, and on station velocities. Then the activities concerning the realization of ITRS and ETRS89 in Poland are discussed, including operational work of GNSS IGS/EPN stations as well as operational work of the laser ranging station of the International Laser Ranging Service, with special emphasis on the Polish active GNSS network for the realization of ETRS89 and maintenance of the vertical control network. Extensive research activities are observed in the field of implementation of the International Terrestrial Gravity Reference Frame in Poland, maintenance and modernization of gravity control network in Poland but also in Sweden, establishment of gravity control network in Ireland based on absolute gravity survey as well as maintenance of the national magnetic control network in Poland which is traditionally performed on a regular basis.

Keywords: reference system, reference frame, vertical control, gravity control, magnetic control

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1. Introduction

The article presents the achievements of Polish research and government institutions in the years 2019–2022, concerning the issues related to the implementation of global and regional reference systems, integration of geodetic, gravimetric and magnetic measurements for the realization and maintenance of a unified reference frame and reference networks, mainly in Poland but also in some other countries. Results of research conducted by the teams affiliated in the following Polish institutions: AGH University of Science and Technology in Cracow (AGH), Polish Head Office of Geodesy and Cartography (GUGiK), Institute of Geodesy and Cartography in Warsaw (IGiK), Military University of Technology in Warsaw (MUT), Rzeszow University of Technology (RUT), Space Research Centre of the Polish Academy of Sciences (SRC PAS), Warsaw University of Technology (WUT), University of Warmia and Mazury in Olsztyn (UWM), Wroclaw University of Environmental and Life Sciences (UPWr), are presented.

Research on the implementation of resolutions of General Assemblies of the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) regarding celestial reference systems, time systems as well as transformations between celestial and terrestrial systems has been continued at the Centre of Geodesy and Geodynamics of IGiK. The latest resolutions of IAU and IUGG are consequently implemented in consecutive editions of the Astronomical Almanac (pol. *Rocznik Astronomiczny*). The Astronomical Almanac is developed and published by IGiK every year since 1946. Recent releases of the Astronomical Almanac of IGiK are shortly presented in Section 2.

Control networks in Poland: horizontal, vertical, gravimetric, and magnetic are integrated in a common reference system – the European Terrestrial Reference System 1989 (ETRS89) which is a standard reference system in Europe adopted in 1990 by EUREF – the Regional Reference Frame Sub-commission for Europe acting under the Commission 1 on Reference Frames of the International Association of Geodesy (IAG). Since 1992 the ETRS89 has been realized in Poland by means of the Global Navigation Satellite System (GNSS). The latest realization of ETRS89 in Poland (PL-ETRF2000), was developed in 2011 through the network of 103 GNSS permanent stations, i.e. the Active Geodetic Network – European Position Determination System (ASG-EUPOS), and was officially adopted in 2013 (Krynski et al., 2019a). More information on the realizations of ETRS89 in Poland is provided in Section 3, while the status of the ASG-EUPOS system is given in Section 6.

Polish GNSS and Satellite Laser Ranging (SLR) stations operate also within IAG services and support the international geodetic community in the realization of global and regional terrestrial reference frames. Several GNSS stations are part of the International GNSS Service (IGS) and EUREF Permanent Network (EPN). The satellite laser ranging station in Poland operates within the International Laser Ranging Service (ILRS). More details on the operational work of Polish stations are given in Section 5.

Polish institutions contribute also to the maintenance of the ETRS89 at the pan-European level. Two EPN analysis centres (ACs) at MUT and WUT regularly process GNSS data and estimate coordinates of stations belonging to their EPN sub-networks. Since 2014, WUT and MUT are also running the EPN Analysis Combination Centre (ACC). The ACC analyses and combines the GNSS solutions of 16 EPN analysis centres. The activities of the ACC and the Polish ACs in 2019–2022 are presented in Section 4.2.

For several years, Polish groups have been conducting research on various topics related to global and regional reference frames. Research on global terrestrial reference frames and the improvement of the determination of global geodetic parameters and future ITRFs was conducted at UPWr (Section 4.1). Research on issues related to receiver antenna phase center correction was conducted at UWM, MUT, and AGH. It concerned the development of a field calibration procedure, and the analysis of the influence of the use of different receiver antenna calibrations on station positions (Section 4.3). The impact of non-tidal loading effects (atmospheric, oceanic and hydrospheric) on the results of satellite navigation techniques was investigated in UPWr, and MUT (Section 4.4) and on the results of space gravity missions in IGiK (Section 7). The research on the determination of station velocities and their uncertainties was conducted at MUT (Section 4.5).

In 2014, the PL-EVRF2007-NH reference frame was adopted for the Polish fundamental vertical network. Since then, local authorities started implementing the PL-EVREF2007-NH for the detailed vertical network. In 2020, GUGiK initiated works for the new country-wide levelling campaign. The status of the PL-EVRF2007-NH implementation and the preparations for the new levelling campaign are presented in Section 7.

The reference surface for heights in the vertical system in Poland is a static quasigeoid derived from a gravity field considered to be invariant in time. For last 20 years temporal variations of gravity are monitored using data from Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On satellite missions. Global Geopotential Models (GGMs) obtained from those missions were used by the team of IGiK in the research on modelling and predicting temporal variations of gravity functionals, in particular geoid heights over Central Europe, in the context of the definition and realization of a modern vertical reference system. The results of those investigations are also summarized in Section 7.

The gravity control in Poland, based on the network of absolute gravity stations, was established in 2012–2013. The review and maintenance of that network in 2022 will be followed by surveying campaigns in next few years. An extensive activity of IGiK towards implementation of the International Terrestrial Gravity Reference System/Frame (ITGRS/ITGRF) in Poland was observed. In particular it concerns on preparing the Borowa Gora (BG) Observatory infrastructure to become a reference station of ITGRF.

The activities of IGiK related to gravity control were extended beyond Polish borders. They concerned the modernization of the gravity control network in Sweden as well as extended works on designing surveying the gravity control network in Ireland. More detail information on the subject is given in Section 8.

The magnetic control network in Poland was established in 1955 (Section 9). The network is regularly surveyed and maintained by IGiK. Presently the magnetic control network consists of 21 repeat stations. Two magnetic observatories of the global international network for monitoring geomagnetic field (INETRMAGNET) together with two permanent magnetic stations in Poland provide data that are used to control magnetic surveys.

The activities of Polish research groups related to terrestrial reference frames, geodynamics and gravity in Poland are integrated within the Research Network for Global Geodetic Observing System (GGOS-PL). In years 2017–2022, IGiK, MUT, and UPWr together with the Institute of Geophysics of the Polish Academy of Sciences and with several other institutions carried out a regional project EPOS-PL on the development of the Polish Earth science infrastructure. The project was integrated with the European Plate Observing System Programme (EPOS) (Krynski et al., 2019c). Within the project, centres of research infrastructure for geomagnetic and magnetotelluric data, GNSS data, gravimetric data, and integrated data for GGOS-PL have been developed, and all new data is regularly supplied to the relevant databases.

2. Implementation of IUGG and IAU resolutions on reference systems

The team of the Centre of Geodesy and Geodynamics of IGiK traditionally has implemented consecutive IAU and IUGG resolutions in computing programs or in developed new algorithms for calculating ephemeris for the Astronomical Almanac of IGiK (AA IGiK).

The full version of the AA IGiK, containing a complete set of tables, is available on web pages of IGiK[1] in pdf format. Starting from 2014, presentation of high precision astrometric and geodetic data in the AA IGiK was consequently modified considering the latest achievements in the field of reference systems. In 2015, an “on-line” calculator of apparent places of stars was developed and made available on web pages of IGiK[2]. It has been extended in 2017 by calculations of mean positions of stars and reduction terms for the computation of apparent places at arbitrary time (Krynski et al., 2019a). The Internet “on-line” AA IGiK based on direct calculations ensures significantly better accuracy than the traditional Astronomical Almanac of a reasonable volume. Simultaneously, the content of tables of the printed version of the AA IGiK has been reduced. The consecutive issues of the AA IGiK for the years 2020 (Krynski and Sekowski, 2019), 2021 (Krynski and Sekowski, 2020), 2022 (Krynski and Sekowski, 2021), 2023 (Krynski and Sekowski, 2022) (Fig. 1) are in agreement with recent resolutions of IAU and IUGG and contain all updates to their previous editions.

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[1] http://www.igik.edu.pl/pl/rocznik-astronomiczny/

[2] http://www.igik.edu.pl/pl/Rocznik-Astronomiczny-On-Line/

Fig. 1. The Astronomical Almanacs of IGiK issued in the years 2019–2022

3. Implementation of the ETRS89 in Poland

The ETRS89 is a geodetic reference system for Europe which was adopted by EUREF in 1990. The ETRS89 coincides with the International Terrestrial Reference System (ITRS) at epoch 1989.0, and is fixed to the stable part of the Eurasian Plate.

Presently, two ETRS89 realizations, namely PL-ETRF2000 and PL-ETRF89, are officially used in Poland (Krynski et al., 2019a). The PL-ETRF89 (in Poland named also EUREF-89) was developed on the basis of GPS observations collected during two surveying campaigns (in 1992, and in 1994–1995) and includes coordinates of 348 passive ground stations, while the PL-ETRF2000 was realized on the basis of GPS observations collected at Polish permanent GNSS stations (during 66 days in 2008 and 2010/2011) belonging to the ASG-EUPOS network (Section 9), which was established in 2008 and is maintained by GUGiK. The PL-ETRF2000 reference frame was adopted by GUGiK in 2013.

The PL-ETRF2000 reference frame is based on GPS data collected at the ASG-EUPOS stations up to March 2011. Since then, most stations included in this reference frame experienced a change of GNSS equipment (antenna, receiver), which caused coordinate changes on some stations (e.g., Liwosz and Ryczywolski, 2016). Also, several new stations were established after the PL-ETRF2000 was developed and 14 new stations are planned to be installed in 2023. Therefore, to take into account the changes on the ASG-EUPOS stations, and to include all new stations, an update of the ETRS89 realization in Poland is required; the preparation of the new realization of the ETRS89 is foreseen after the installation of new stations in 2023.

4. Monitoring the terrestrial reference frame

In this section research conducted by Polish institutions on various topics related to global and regional reference frames has been summarized.

4.1. Research on global terrestrial reference frames

The research on global terrestrial reference frames (TRF) and possible improvement of the de-termination of global geodetic parameters such as geocenter and pole coordinates, as well as future ITRFs was conducted by the group at the Wroclaw University of Environmental and Life Sciences. Zajdel et al. (2019a) analysed the impact of various factors on GNSS products, e.g., station coordinates, geocenter coordinates, Earth orientation parameters, and GNSS orbits obtained from a double-differenced multi-GNSS (GPS, GLONASS, Galileo) global processing. The authors found that when no-net-translation minimum constraints are not applied in the GNSS solution, the station position repeatability is degraded by 70% for the north, 55% for the east, and 25% for the up component, as compared to the solution in which those constraints were applied and the network origin coincided with the ITRF. The authors concluded that it is mandatory to apply the no-net-translation minimum constraints in global GNSS solutions.

Zajdel et al. (2019b) analysed the impact of various approaches of the TRF realization using minimum-constraints as well as the selection of reference stations on the estimated coordinates of SLR stations, TRF scale, Earths orientation parameters and geocenter coordinates. The authors found that when using a robust station selection for TRF realization, the repeatability of station positions may be improved by 8% for the north, 4% for the east, and 6% for the vertical component. On the other hand, the impact of the selection of stations used for the TRF realization on the scale of resulting SLR solutions was found negligible.

The possibility to use new SLR and GNSS observations for the determination of the global parameters was studied (Sosnica et al., 2019; Strugarek et al., 2019; Bury et al., 2021a; Zajdel et al., 2022). Sosnica et al. (2019) analysed the contribution of SLR observations performed to GNSS satellites for the realization of an SLR terrestrial reference frame and the determination of global parameters. It was concluded that those observations increase the number of coordinate solutions with respect to SLR-only solutions and improve the repeatability of station positions, and thus they should be considered for the future ITRF realizations. Strugarek et al. (2019) investigated the quality of global geodetic parameters and reference frame parameters obtained from SLR observations performed to active Sentinel-3A/3B satellites for which orbits were determined using GPS observations. The authors found that those observations may be used for determination of precise station coordinates and global parameters e.g., geocenter and pole co-ordinates. Also, after increasing the number of active SLR satellites and extending the observation period, those observations could be considered in further realizations of TRFs. In 2019, the BeiDou Satellite Navigation System (BDS) released the antenna phase center corrections for BeiDou satellites. Since then, the BDS constellation became a potential second GNSS contributor (in addition to Galileo) to the realization of the scale in future ITRF realizations. Zajdel et al. (2022) analysed the possibility to use BeiDou-3 observations to realize the scale of the terrestrial reference frame. It was found that the estimated scale depends on the frequencies of signals used for GNSS data processing. The common usage of GNSS and SLR-to-GNSS observations in the realization of TRF was analyzed (Bury et al., 2021b). In the approach applied the co-location between SLR and GNSS techniques takes place in space, on board of GNSS satellites. Such co-location in space could replace in future local ties between SLR and GNSS stations. The authors found that the best results in terms of TRF realization can be obtained when imposing NNT and NNR conditions on both GNSS and SLR core stations.

Development of multi-year GNSS solutions involves the correction of discontinuities in station position time series in order to reliably estimate station velocities. Najder (2020) used the FODITS program of the Bernese GNSS Software (Dach et al., 2015) to automatically detect the discontinuities in station positions of selected global IGS stations and compared the results with ITRF2014 and JTRF2014 (the Jet Propulsion Laboratory realization of the ITRS). Najder (2020) provided confidence intervals for automatic detection of the discontinuities, but also indicated some drawbacks of this approach in the identification of the discontinuities epochs and velocity changes.

4.2. GNSS analysis in the frame of the EUREF Permanent Network

The purpose of the EUREF Permanent Network (EPN) is to provide access to the ETRS89. Presently EPN consists of about 400 permanent GNSS stations located in Europe. Two Polish analysis centres (ACs) operating at the WUT and the MUT, regularly analyze GNSS observations and provide their solutions (station coordinates and tropospheric zenith delays) to EPN.

Since 2014, WUT and MUT are also responsible for operating the EPN Analysis Combination Centre (ACC). The tasks of the EPN ACC include the analysis and combination of GNSS coordinate solutions generated by 16 EPN analysis centres. Since 2016, EPN daily and weekly combined solutions have been developed at WUT (Liwosz, 2022a). The EPN daily combined solutions are the input for the EUREF reference frame solution (Legrand, 2022). The ACC website[3] containing plots of EPN station position time series and AC position residuals is maintained at MUT. In 2019–2022, the ACC tasks were continued.

The EPN combined solutions, as the EUREF reference frame product, are also provided by WUT to the EPOS (European Plate Observing System) GNSS products portal within the EPOS-GNSS thematic core service (Fernandes et al., 2022).

In 2019 the ACC investigated the impact of adding Galileo observations to AC solutions (in addition to GPS and GLONASS) on combined EPN station positions. For majority of stations the mean position differences between the two-system (GPS, GLONASS) and three-system (GPS, GLONASS, Galileo) solutions were up to 1 mm

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[3] http://www.epnacc.wat.edu.pl/epnacc/

for the east and north components, and up to 3 mm for the vertical component. It was also found that for stations with antennas for which type-mean calibrations were used, larger position differences were obtained, especially for the vertical component, than for stations with individually calibrated antennas (Liwosz and Araszkiewicz, 2019a). Since the beginning of GPS week 2044 (10 March 2019), 11 EPN ACs have started including Galileo observations (in addition to GPS and GLONASS) in their operational products.

In 2019 the ACC analyzed also the impact of adding globally distributed stations to the EPN regional network on the positions of EPN stations. The official EPN combined solution (regional) was compared to the combined solution in which additional global stations were included. The differences in station positions between both solutions resulted mostly from a different alignment of each solution (global, regional) to the reference frame. Time series of position differences were also compared to series of modelled non-tidal loadings (due to atmosphere and continental water) and good agreement was obtained (Liwosz and Araszkiewicz, 2019b).

On 27 November 2022 (start of GPS week 2238) the IGS switched from the IGb14 to the IGS20 reference frame and IGS repro3 standards for the generation of its operational products. The EPN ACC and ACs also started preparations for the switch to the IGS20 in EPN analysis. The details regarding the switch were discussed at the EPN Analysis Centres Workshop on 3 November 2022 (virtual meeting). Minutes and presentations from this meeting are available at the EPN CB webpage[4]. Changes in the EPN analysis after the switch to IGS20 will include, e.g. the use of the consistent three-system (GPS, GLONASS, Galileo) IGS AC final products, the adoption of the new EPN receiver antenna model (based on the IGS type-mean model with additional calibrations for antenna-radome pairs not included in the IGS model), the consideration of receiver antenna misalignments from true north, the use of the FES2014b ocean tide loading model, the use of the VMF3 for troposphere modelling, and the adoption of the new long filename IGS convention for the EPN products. The activities of the EPN ACC in 2019–2022 were regularly presented at the EUREF Symposia and EPN Analysis Centres Workshops (e.g., Liwosz and Araszkiewicz, 2019a; 2019b; 2022; Liwosz, 2022b).

4.3. Research on GNSS receiver antenna calibrations

The GNSS receiver antenna phase center issues are closely related to GNSS reference frames. The research on antenna calibrations in Poland concerned the development of a field calibration procedure, and the analysis of the influence of receiver antenna calibrations on station positions.

In 2019, the UWM and Astri Polska, started a European Space Agency (ESA) project dedicated to the development of the receiver antenna field absolute calibration procedure for a multi-frequency and multi-GNSS signals. The methodology and algorithms proposed are based on the principles developed at the University of Hannover, with implementing own innovations. The initial results were published (Krzan et al., 2020;

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[4] http://www.epncb.eu/_newseventslinks/workshops/EPNLACWS_2022/

Dawidowicz et al., 2021). The calibrations obtained from the independent UWM analysis for selected GNSS antennas showed good consistency (within 2 mm); slightly larger differences were observed for low zenith angles as well as at certain azimuth ranges in high zenith angles. The comparison of antenna models developed at the UWM with type-mean calibrations included in the IGS model showed that differences up to 3–4 mm could also be found for low elevation angles. The obtained results demonstrated a consistent performance for the Astri/UWM calibration procedure. However, some aspects, e.g. the modelling of phase center corrections at low elevations need to be further investigated.

Research team from the UWM investigated also offsets in the station position components caused by the receiver antenna changes at selected EPN stations (Dawidowicz et al., 2023), in particular, the correlation between the occurrence of the offset and phase center correction model calibration type (type-mean, individual robot, individual chamber) as well as multipath values changes after the antenna replacement. GNSS data from 12 EPN stations from 2017–2019 were analysed. The results proved that the antenna replacement is critical in the context of station coordinates stability and, in most cases, it causes visible shifts in the position time series. Depending on the solution type, multipath changes after the antenna replacement are responsible for 21%–42% of variations in the coordinates. In other cases, the imperfections in phase center correction models were the most probable reason for the observed position shifts.

The impact of various receiver antenna phase centre calibrations on the estimated positions of GNSS stations was investigated at the MUT. Araszkiewicz et al. (2019) analysed the differences between individual and type-mean antenna models, and evaluated the impact of applying those models on estimated station heights. The authors found that both models give very similar results in terms of stability of the determined height and its variability caused by changing the elevation mask. The impact of applying GPS receiver antenna corrections to Galileo observations on GNSS positions was also investigated (Araszkiewicz and Kiliszek, 2020). It was found that the use of GPS L2 corrections for the Galileo E5a signals may change the estimated height up to 8 mm; similar results were obtained for absolute and relative positioning methods.

Borowski et al. (2022) analyzed the reliability of selected receiver antenna phase center calibrations included in models published by the IGS. Height differences for close stations obtained from different GPS solutions (EPN, PPP, short baseline) were compared with the measurements of spirit levelling. The best consistency with the levelling results was obtained for a short-baseline L1-only GPS solution. For one of the tested antennas, a change of the antenna calibration from IGS08 to IGS14 model resulted in 8 mm difference in height.

4.4. Research on impact of non-tidal loading effects on position solutions

Non-tidal loading effects due to atmosphere, ocean and continental water cause deformation of the Earth's surface. Although these effects are visible in position determined using space geodetic techniques, they are not modelled in official operational analysis and are subject to research.

Klos et al. (2021) examined the sensitivity of GPS to the non-tidal loading effects for a set of Eurasian permanent GNSS stations. The authors found that correcting vertical GPS displacements by the atmospheric non-tidal loading effect leads to the reduction of the time series variances, and to the improvement in the uncertainty of the GPS vertical velocities by a factor of 2. They recommended application of the atmospheric non-loading at the observation level, while application of the hydrological loading to the resulting position time series.

Bury et al. (2019) analysed the impact of the atmospheric non-tidal loading on the determination of global geodetic parameters using SLR observations to GNSS satellites. The authors found that neglecting the atmospheric non-tidal loading effect causes the systematic shift of station positions (so-called Blue-Sky effect) up to 2.3 mm for inland stations; it also causes systematic effects in the estimates of geocenter coordinates and satellite orbits. They concluded that the atmospheric non-tidal loading should be applied by all space geodetic techniques to remove systematic effects from estimated global parameters and to improve consistency between techniques.

Kaczmarek (2019) analysed time series predicted from the non-tidal atmospheric, non-tidal ocean, and hydrological loading models and compared them to the global GNSS position time series of eight stations in Europe. The author computed correlation coefficients between the corresponding time series and found that the atmospheric non-tidal loading had the greatest influence on GNSS position time series at the considered area.

4.5. Research on vertical displacements

Detecting and monitoring vertical displacements are crucial for the realization and the maintenance of the vertical reference frame. Research in that field on both regional and global scale is conducted by numerous research groups all over the world.

The applicability of the co-kriging method for modelling vertical movements of the Earth's crust in Poland with the use of precise levelling data from the vertical control network and GNSS data from permanently operating stations was investigated by the team of UWM (Kowalczyk et al., 2020). The authors indicated the difference in terms of isotropy between levelling and GNSS data. Strong dependence of the evaluation of vertical movements on the data set applied was observed in the results obtained. Thus co-kriging was found to not be a suitable method for modelling vertical movements of the Earth's crust based on combination of levelling and GNSS data.

Possibility of the determination of the most relevant common points in hybrid networks, i.e. network of repeated levelling measurements combined with a network of permanent GNSS stations, using scale-free network theory with the distance criterion for modelling vertical movements of the Earth's crust was examined (Kowalczyk et al., 2021a). The computing tests per-formed using the UELN + EPN hybrid network provided successful results for identification the most significant pseudo-nodal points in large hybrid networks.

Kowalczyk et al. (2021b) analysed the accuracy of determining the vertical movements of the Earth's crust based on time series of four techniques: satellite altimetry, tide gauges, GNSS and radar interferometry. The authors found that the accuracies of vertical movements obtained from the radar interferometry were similar to those obtained from GNSS position time series. On the other hand, the vertical movements of the Earth's crust determined from GNSS data differed from the results obtained on the basis of data from other techniques.

4.6. Research on GNSS stations velocities

Station velocities derived from GNSS solutions can be used for the analysis and interpretation of geodynamic phenomena. Estimation of station velocities from the position time series requires careful modelling of seasonal signals, discontinuities in positions, non-linearity of velocity, noise processes to reliably estimate the values of velocities and their uncertainties. Bogusz et al. (2019) proposed a methodology for the position time series analysis, recommended to be used to obtain reliable GPS vertical station velocities, in particular for studying the post-glacial re-bound. The authors validated their methodology for 469 stations in Europe. They found that velocity uncertainties may be underestimated up to 8 times when assuming only white noise instead of power-law and white noise together during the position time series analysis. Klos et al. (2019a) proposed the Wiener filter to model the time-varying seasonal amplitudes in position time series. The model was applied to synthetic and real GPS position time series. The authors showed that the proposed method provides optimal modelling of seasonal signals, while the underlying noise properties of the time series are not altered.

Klos et al. (2019b) studied sea level changes at gauge stations focusing on vertical land motions (VLM). The authors proposed a new methodology for modelling of GPS-derived non-linear VLM. In addition to standard linear VLM model, the authors proposed to account also for co-seismic offsets, changes in the vertical velocities, and postseismic transient. The new methodology was applied for GPS station position time series (spanning years 1993–2015) in the earthquake affected Western North Pacific region. The authors found that introducing the new non-linear VLM model improves absolute tide gauge sea level estimates by 20% on average. It was also found that the new non-linear VLM model reduced the difference between altimetry and tide gauge derived absolute sea level trend estimates

4.7. Research on estimation of tectonic plates motion parameters

Tectonic plate motion models are needed for various geodetic and geodynamical applications. Such models can be computed on the basis of station velocities derived from space geodetic techniques, i.e.: GNSS, SLR, Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). Jagoda et al. (2020a) estimated plate motion parameters for six plates: Eurasian, North American, Pacific, Australian, African and Antarctic using ITRF2008 station velocities. The plate parameters were computed separately for SLR, VLBI and DORIS techniques using different number of stations until stability in determined plate parameters was observed. The results were compared with the APKIM2005 (Actual Plate Kinematic and Crustal Deformation Model) plate motion model and good agreement was obtained. The estimation of plate motion parameters of the six plates mentioned using only VLBI station velocities was studied in more detail in Jagoda and Rutkowska (2020a). Jagoda and Rutkowska (2020b) analysed the motion of Eurasian plate using GNSS station velocities from the ITRF2014 solution. The authors estimated Eurasian plate motion parameters using four different station sets. The final parameters were computed using all (120) GNSS stations analysed in this study. The results were compared with the APKIM2005 model and with another model based on GPS observations from years 1991.0-1996.3.

5. Stations in Poland involved in realization of ITRS and ETRS89

An overview of Polish GNSS and SLR stations that are part of the IAG services and that support the international geodetic community in the realization of terrestrial reference frames is provided in this Section. Several Polish GNSS stations operate within the International GNSS Service (IGS) and the EUREF Permanent Network (EPN). The only SLR station in Poland operates within the International Laser Ranging Service (ILRS).

5.1. Operational work of GNSS permanent IGS/EPN stations

Permanent IGS and EPN GNSS stations have been operating in Poland for the last 29 years. Presently 19 permanent GNSS stations (Fig. 2) operate in Poland within the EPN network and 6 of them operate also within the IGS network[5].

In 2022, the WUT installed two GNSS permanent stations (WUTH00NOR, PPSH00NOR) in the Stanislaw Siedlecki Polish Polar Station in Hornsund, located at the bay of Isbjørnhamna in the southern part of Svalbard. The stations operate in cooperation with the Institute of Geophysics of the Polish Academy of Sciences. The two new GNSS stations have been included in the EPN and the European Plate Observing System (EPOS). The station WUTH00NOR was also proposed to join the IGS and was accepted in March 2023.

Seven stations (BOGI, BOGO, BOR1, JOZ2, JOZE, LAMA, WROC) were included in the ITRF2020 – the latest realization of the ITRS (published in April 2022). Two Polish stations: BOR1 and JOZE, were used for the estimation of official transformation parameters between ITRF2020 and ITRF2014; they were also included in the latest IGS terrestrial reference frame – IGS20, which is based on the ITRF2020.

Data from the above mentioned stations are regularly uploaded to two Regional Data Centres located at the BKG (Federal Agency for Cartography and Geodesy, Germany) and at the BEV (Federal Office of Metrology and Surveying, Austria). Stations BOGI,

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[5] http://www.epncb.eu/_networkdata/stationlist.php/

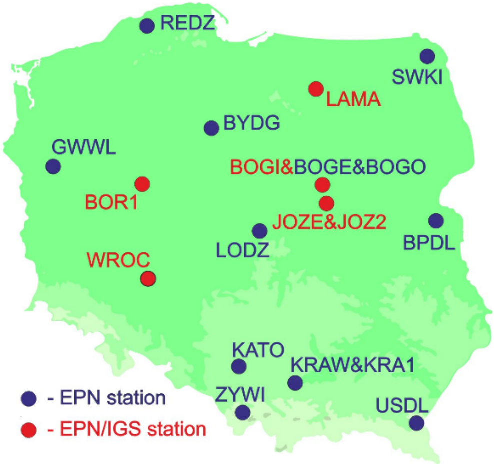

Fig. 2. EPN/IGS permanent GNSS stations in Poland (as of January 2023)
(Krynski and Rogowski, 2021)

BOR1, JOZ2 and WROC provided also data for the IGS Real-time GNSS Data project[6]. All stations belonging to the IGS are additionally included into the IGS Multi-GNSS Experiment (MGEX) pilot project[7].

Stations at Borowa Gora (BOGI), Borowiec (BOR1), Jozefoslaw (JOZ2), Cracow (KRAW, KRA1), Lamkowko (LAMA), and Wroclaw (WROC) provide also data for the EUREF-IP project[8]. Since 2005 the AGH University of Science and Technology has been operating the Ntrip Broadcaster[9].

5.2. Operational work of ILRS laser ranging station BORL

The Satellite Laser Ranging Station Borowiec (BORL) of the SRC PAS tracks satellites and space debris (cooperative and uncooperative targets) on regular basis: in 2019 – 82 objects, in 2020 – as many as 97 targets (Krynski and Rogowski, 2021), in 2021 – 99 objects (Liwosz and Dykowski, 2022), while in 2022 – 64 objects.

The station operates within the framework of the International Laser Ranging Service (ILRS) and EUROLAS Consortium as well as, since 2015, in the framework of the Space Debris Study Group run by the ILRS and internal contracts signed with the European Space Agency (ESA) and the European Consortium EUSST[10]. Tracking space debris and determining their position as well as their rotation/tumbling and orientation in space is of great importance from the perspective of future debris removal missions (e.g. ENVISAT).

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[6] http://igs-ip.net/home/

[7] http://igs.org/mgex/

[8] https://igs.bkg.bund.de/ntrip/

[9] http://home.agh.edu.pl/~kraw/ntrip.php/

[10] https://www.eusst.eu/

The number of space debris grows rapidly; more than 25 000 orbiting objects of diameter above 10 cm was counted in 2022 (Liwosz and Dykowski, 2022).

The current information about the position of the objects like rocket bodies is very crucial and critical, from the point of view of the Space Surveillance and Tracking services, i.e. re-entry, collision avoidance or anti-satellite-weapon. Data provided by the BORL station contribute to global research on the determination of space debris spin dynamics (ENVISAT, ERS-1, ERS-2, OICETS, Seasat-1, TOPEX/Poseidon, and others). The results obtained were sent to the Crustal Dynamics Data Information System (CDDIS), EUROLAS Data Center (EDC), EUSST databank, and Space Debris databank in Graz (Krynski and Rogowski, 2021). Table 1 presents a brief summary of SLR observations at BORL station in 2019–2022.

Table 1. SLR observation at BORL station in 2019–2022

Year	Satellites observed	Passes	Successful passes		RMS of a single shot (cm)
			normal points	single shots	
2019	44 SLR (30 LEO + 14 MEO)	1079	15 197	743734	1.20–3.81
	38 space debris objects	388	4 074	188499	2.04–221.72
2020	40 SLR (27 LEO + 13 MEO)	1352	18 644	918999	1.49–4.11
	57 space debris objects	698	7 396	300046	1.42–187.58
2021	53 SLR (37 LEO + 16 MEO)	1396	17 923	885119	2.05
	46 space debris objects	382	4 686	214575	22.19
2022	51 SLR (27 LEO + 24 MEO)	1356	16955	842882	1.13–3.87
	13 space debris objects	226	3643	136292	1.31–141.05

Twelve geodetic-geodynamic satellites: Ajisai, Etalon-1, Etalon-2, Geo-IK-2, GRACE-FO-1, GRACE-FO-2, LAGEOS-1, LAGEOS-2, LARES, LARETS, STARLETTE, and Stella, were tracked at BORL in the years 2019–2022. Summary of observational statistics of these satellites in the years 2019, 2020 (Krynski and Rogowski, 2021), 2021 (Liwosz and Dykowski, 2022) with indicating the largest number of passes, returns and normal points are given in Tables 2, 3, 4, and 5, respectively.

A novelty in 2022 is LARES-2 passive geodynamic satellite[11] launched on 13 July 2022. First successful observation of this satellite made by BORL station was performed on 3 August 2022. In total, 4 passes of this satellite with 938 returns, 30 normal points and mean RMS 1.59 cm were recorded by BORL station.

Tracking results of LAGEOS-1 and LAGEOS-2 satellites are used for evaluation of the BORL laser sensor quality. Report on the station performance is regularly delivered by ILRS. Both quality and effectiveness of the laser measurements at BORL are significantly improved as compared to the previous years of its operational activity. For example, in 2020 the average LAGEOS RMS was at the level 17–18 mm, and approximately 150

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[11] https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/lrs2_general.html

Table 2. SLR observations of geodetic satellites in 2019

Satellite name	Passes	Returns	Normal points	Avgerage RMS (cm)
Ajisai	62	84860	785	3.81
Etalon-1	3	453	14	3.76
Etalon-2	4	295	20	2.60
Geo-IK-2	3	4229	31	2.19
GRACE-FO-1	23	9880	564	3.08
GRACE-FO-2	11	5291	285	2.88
LAGEOS-1	**100**	**125946**	**923**	1.76
LAGEOS-2	43	43780	440	1.82
LARES	75	37186	821	1.55
LARETS	56	21245	405	2.16
STARLETTE	53	46889	573	2.31
Stella	13	7851	103	2.07
Total	443		4933	

Table 3. SLR observations of geodetic satellites in 2020

Satellite name	Passes	Returns	Normal points	Average RMS (cm)
Ajisai	**111**	**189595**	**1387**	3.41
Etalon-1	0	0	0	0
Etalon-2	3	364	14	3.61
Geo-IK-2	6	4705	38	2.22
GRACE-FO-1	21	10077	432	3.45
GRACE-FO-2	15	7731	350	3.19
LAGEOS-1	46	45220	423	1.73
LAGEOS-2	50	30870	388	1.78
LARES	104	36486	1004	1.51
LARETS	92	37412	713	1.98
STARLETTE	97	70903	931	2.02
Stella	7	5109	65	2.02
Total	552		5745	

average LAGEOS measurements in a normal point as well as approximately 1800 average LAGEOS full rate measurements per pass were observed.

Since many years the BORL station keeps its products quality on an equal and very good level. Based on the quality report for 2022 performed by four independent analysis centres (Hitotsubashi University, Joint Center for Earth System Technology/Goddard

Table 4. SLR observations of geodetic satellites in 2021

Satellite name	Passes	Returns	Normal points	Avgerage RMS (cm)
Ajisai	90	**131444**	**1240**	3.12
Etalon-1	2	100	7	2.90
Etalon-2	2	130	9	3.57
Geo-IK-2	23	10136	547	3.35
GRACE-FO-1	13	5720	312	3.76
GRACE-FO-2	5	6151	57	2.56
LAGEOS-1	**100**	95514	1047	1.77
LAGEOS-2	65	23544	590	1.76
LARES	70	23744	516	1.90
LARETS	87	36161	942	1.53
STARLETTE	74	62326	760	1.81
Stella	11	6746	85	1.87
Total	542		6112	

Table 5. SLR observations of geodetic satellites in 2022

Satellite name	Passes	Returns	Normal points	Avgerage RMS (cm)
Ajisai	84	**134618**	1314	3.32
Etalon-1	7	903	31	3.32
Etalon-2	0	0	0	0
Geo-IK-2	8	7516	70	2.09
GRACE-FO-1	12	5917	286	2.87
GRACE-FO-2	15	6858	396	3.55
LAGEOS-1	**122**	113752	**1344**	1.85
LAGEOS-2	51	23711	491	1.83
LARES	60	21909	458	1.93
LARETS	81	29145	868	1.54
STARLETTE	74	33032	592	1.82
Stella	11	7330	96	2.13
Total	519		5976	

Space Flight Center, Russian Mission Control Centre and Shanghai Astronomical Observatory), the average LAGEOS normal point RMS, a short-term stability, and a long-term stability of BORL station are 3.9 mm, 9.7 mm, and 4.9 mm, respectively.

A new software dedicated to reduction of laser measurements, adopted to the newest operating systems (Windows/Linux) and equipped with a very flexible graphic interface, was developed by the team of the Borowiec Observatory in the years 2020–2021. Its code is compatible with the specifications and requirements given by ILRS. The software allows for the determination of a number of parameters, i.e. residuals O–C, normal points, RMS of normal points, RMS of observation, time bias, range bias can be determined with that software. The final works are underway and are planned to be completed with a quarantine procedure launched by ILRS in 2023.

In 2019, orbits of 13 space debris objects (Russian and Chinese boosters from LEO regime) were calculated. The improvement of orbits of the tracked rockets by using laser ranging data from a single station was investigated. Calculations were performed with the advanced orbital programme GEODYN-II, using laser measurements from BORL. The ephemerides based on initial orbital elements (TLE) were compared with positions obtained from laser measurements (Fig. 3).

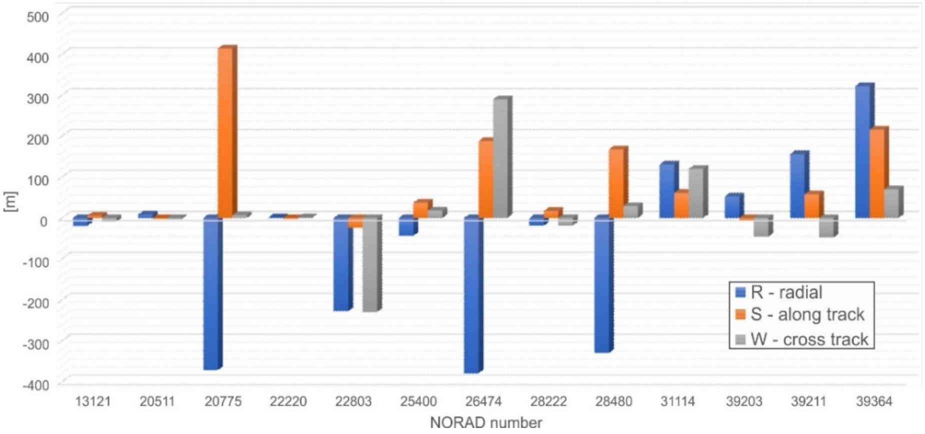

Fig. 3. Input TLE ephemerides vs. laser measurements in RSW frame

For all analysed targets the differences between the ephemerides based on TLE and observations performed at BORL (corrected elements/positions) are given in the radial, along-track, cross-track (RSW) frame. The results obtained showed that a single short observation (from a dozen to several dozen seconds) of analysed objects improves the variance-covariance matrix by as much as 20–40% (Lejba et al., 2020). In 2022 the positions and velocities of objects such as rocket bodies from the LEO regime and their covariance matrix based on full-rate laser measurements collected by the laser sensor BORL were determined. The purpose of those calculations was to show that a single short laser observation is sufficient to maintain a high-quality orbit of the LEO junk objects like rocket bodies. The results of those calculations are under preparation for publication.

The SST/Space Safety programme dominating amongst the activities of the team of BORL station in the years 2019–2022 constitutes one of the pillars of the Space Situational Awareness programme implemented by both ESA (Space Safety in the next years), and the EUSST Consortium (Konacki et al., 2019). It is dedicated to monitoring both active and inactive satellites, discarded debris orbiting the Earth. Responsibility for the research and development in SLR in the project, in which Poland is an official member of the EUSST Consortium, and the SRC PAS is one of the members of the Polish SST consortium, is entrusted to the team of the BORL station. A second independent optical-laser system, dedicated to the SST programme also operates at the BORL station (Krynski and Rogowski, 2019; Suchodolski, 2019).

The results of computation of coordinates of the BORL station based on LAGEOS measurements performed by the ILRS network in the years 2016–2019 which was one of the most important scientific achievements of the station team in 2020, confirm the high quality of data provided by the BORL station.

One of the most important scientific achievements in 2021 was the determination of the BORL station coordinates from laser observations of LARES as well as LAGEOS-1 and LAGEOS-2 satellites, to intercompare them and to assess their quality. The coordinates of 17 selected stations were computed the for weekly arcs from 29 February 2012 to 31 December 2015 with the use of the NASA GSFC GEODYN-II software. In the first stage, the coordinates were calculated only from the observations of the LARES satellite, in the second stage – only from LAGEOS-1 and LAGEOS-2 satellites, and in the third stage – of all three satellites LARES + LAGEOS-1 + LAGEOS-2. The results from the 1st stage (LARES only) indicate significant errors in stations' coordinates, mainly due to the low satellite orbit (1450 km) and large distances between stations (continental effect). The average 3DRMS of the positions of all stations was 23.5 mm with the uncertainty of ±6.5 mm. In the 2nd stage (LAGEOS only) the results were significantly better and amounted to 9.9 mm ±3.6 mm, respectively. The 3rd stage (LARES + LAGEOS) provided the best results; the mean RMS of 9.9 mm with the uncertainty of ±3.2 mm (Fig. 4). It has been concluded that the solution from three satellites (LARES + LAGEOS-1 + LAGEOS-2) gives slightly better results for determining the coordinates of SLR stations and should be taken into account in subsequent realizations of ITRF (Schillak et al., 2021).

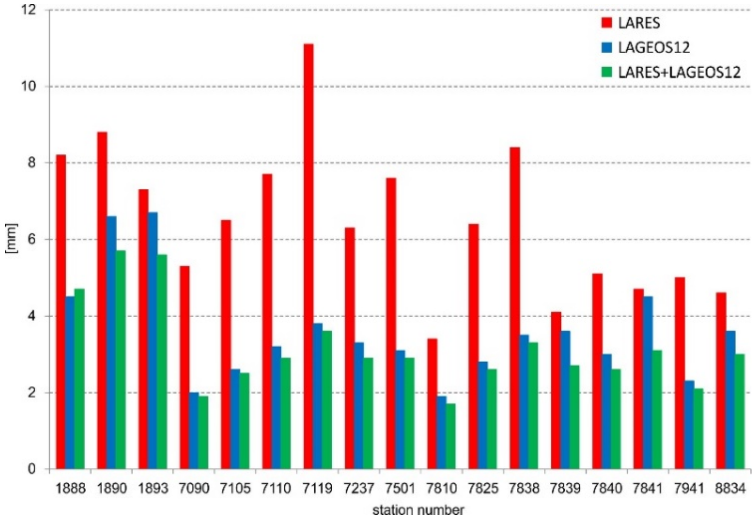

Fig. 4. The average 3D precision for each station for three solutions: LARES only (red), LAGEOS-1+LAGEOS-2 (blue), LARES+LAGEOS-1+LAGEOS-2 (green) (Schillak et al., 2021)

Coordinates of the BORL station determined as both geocentric and topocentric ones for the period July 1993 – December 2019 were analysed and the activity of SLR third generation system was summarized. The BORL station has been providing high-quality observations since the installation of the 3rd generation laser in July 1993. Since then, SLR observations of LAGEOS-1 and LAGEOS-2 satellites – the basic satellites for determining the coordinates of stations – were regularly performed. The station coordinates were determined from 168 monthly orbital arcs with 28 168 normal points using the GSFC NASA GEODYN-II orbital program. 3DRMS stability of the determined positions throughout the period investigated was estimated as 12.7 mm with the uncertainty of ±4.3 mm. A very high level of agreement of the results for both satellites LAGEOS-1 and LAGEOS-2 was observed; for the orbital RMS of fit, i.e. 21.3 mm and 21.0 mm, and for the range bias and its long-term stability –7.3 mm ±11.0 mm and –6.3 mm ±2.4 mm, respectively. Coordinates of BORL determined over the entire 26.5 year period exhibit high consistency with a slight improvement in quality with time (Fig. 5).

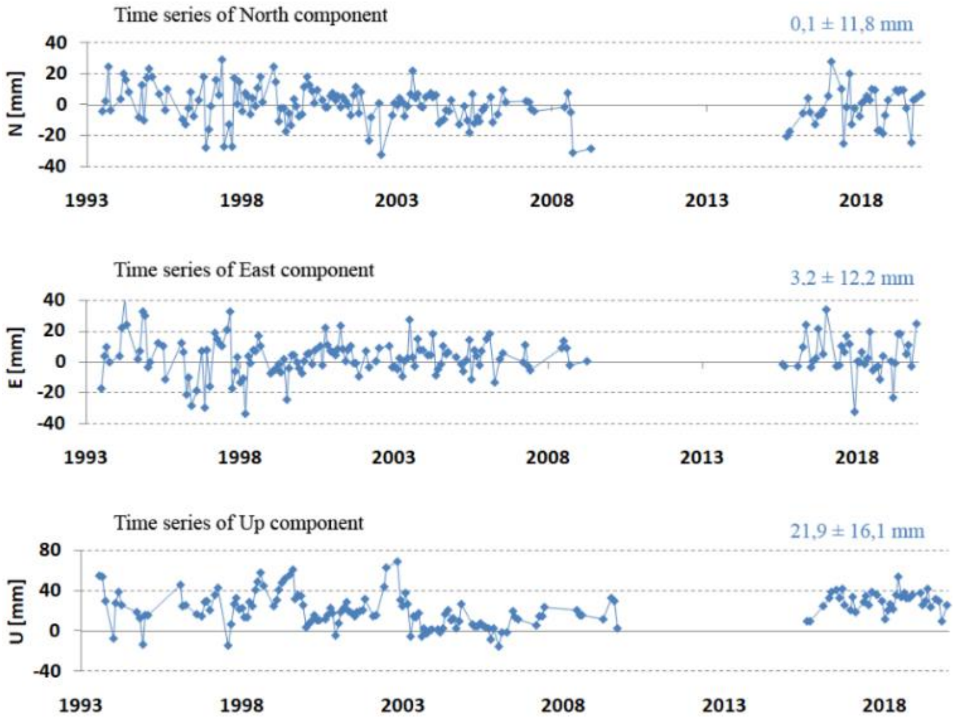

Fig. 5. De-trended for epoch 2010.0 topocentric coordinates N, E, U of BORL station in 1993–2019 (Schillak et al., 2022)

Only a 2 cm jump in the vertical component was detected at the turn of 2002/2003, caused by a change in the parameters of the constant-fraction discriminator in the “stop” channel. The velocity and direction of the station motion were also assessed. Due to the very long period of 26.5 years, the obtained results for the velocity of the BORL station determined are fully consistent with ITRF2014, 24.9 mm/year and 25.0 mm/year, respectively. The work can be a template for the other SLR stations for assessing the quality of the observations, making it easier to find and correct random and systematic errors (Schillak et al., 2022).

The laser measurements of space debris objects performed by BORL station in the years 2016–2020 have been the subject of a detail analysis. The BORL station is tracking now regularly 80–90 different space debris objects. The sum of all successful passes registered in the years 2016–2020 is 1936 with 23 436 normal points. The average RMS of objects equipped with SLR-dedicated retroreflectors ranges from 1.5 cm to 14 cm, and of objects without such retroreflectors – from 8 cm to 222 cm (Smaglo et al., 2022).

The analysis of the local Love and Shida numbers (h2 and l2 parameters) using SLR measurements to Stella, STARLETTE, LAGEOS-1 and LAGEOS-2 satellites, conducted at the Australian Yarragadee and Mount Stromlo SLR stations from 1 January 2014 to 1 January 2019 was performed (Jagoda et al., 2020b).

6. Active GNSS station networks for the realization of ETRS89 in Poland

ASG-EUPOS – a multifunctional precise satellite positioning system in Poland

The ASG-EUPOS is a GNSS permanent network in Poland which was established in 2008. Stations belonging to the ASG-EUPOS constitute the fundamental geodetic control network which is used for the official realization of the ETRS89 in Poland (Section 3). The ASG-EUPOS is also a multifunctional augmentation system for precise GNSS positioning. The ASG-EUPOS is maintained by GUGiK. Presently, the ASG-EUPOS network consists of 129 GNSS permanent GNSS reference stations of which 107 are located in Poland, and 22 – in neighbouring countries near the Polish border (Fig. 6). In December 2022 GUGiK has signed the agreement with the State Service of Ukraine for Geodesy, Cartography and Cadastre to include Ukrainian stations located near the Polish-Ukrainian border to the ASG-EUPOS system (GUGiK, 2023).

In 2021 the densification of the reference network has been undertaken to increase availability and accuracy of real time services. In 2022, 4 new reference stations were installed, and in 2023 the additional 14 new reference stations will be established.

In the years 2017–2019, the ASG-EUPOS system was upgraded and since then the provided services are based on 4 GNSS constellations: GPS, GLONASS, Galileo, and BeiDou. Presently, all reference stations operating within the ASG-EUPOS network are tracking all 4 GNSS constellations. However, since GNSS receivers installed on 43 stations do not track the BeiDou-3 satellites, it is planned to replace them in the years 2024–2025, so that all receivers in the ASG-EUPOS network could track all available signals from 4 GNSS constellations (GUGiK, 2023). Since 2021, the GNSS data from ASG-EUPOS stations are stored in RINEX 3 format.

In cooperation with MUT, GUGiK participates in the EPN Densification project[12] (Kenyeres et al., 2019). The purpose of that project is to realize a dense, homogeneous,

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[12] http://www.epncb.oma.be/_densification/

Fig. 6. Reference stations of the ASG-EUPOS system (as of February 2023, www.asgeupos.pl)

and high quality position and velocity product for Europe. Within the project, GUGiK regularly provides the GNSS solutions of the ASG-EUPOS network which are included in the successive releases of the densification product.

7. Maintenance of the vertical control network in Poland

In 2014 the PL-EVRF2007-NH was adopted as the official reference frame for the Polish fundamental vertical network. The implementation of the PL-EVRF2007-NH by local authorities for the detailed vertical network is still in progress. In accordance with Polish regulations, the EVRF2007 reference frame is to be implemented locally by the end of 2023. Currently (March 2023) over 80% of the local units have completed the implementation (GUGiK, 2023). Also the new quasigeoid model (PL-GEOID2021-NH) for the PL-EVRF2007-NH was developed by UPWr and published in 2022 on the GUGiK website.

Activities related to the new levelling campaign in Poland have been initiated by GUGiK in 2020. GNSS/levelling surveys were performed in 2021 for more than 100

UELN benchmarks. In 2022 GUGiK has completed the designing works of the levelling campaign for about 25% area of Poland. The designing works for the remaining part of Poland are planned to be done in 2023.

Data provided by geodetic space techniques, i.e. GNSS and gravity field dedicated satellite missions to, allow to monitor temporal variations of the reference surface for heights caused by temporal variations of the gravity field due to mass displacements in the Earth system. An extensive research on monitoring, assessing, and modelling mass variations in the Earth system was conducted at IGiK.

Temporal variations of orthometric/normal heights induced by hydrological mass variations over 24 large river basins over the world were assessed by the team of IGiK using GRACE-based GGMs (Godah et al., 2020a). They exhibit a distinctive seasonal pattern. Correlation between them and temporal variations of equivalent water thickness ΔEWT obtained from the WGHM hydrological model were observed in 88% of subareas of river basins investigated, exhibiting strong correlation in 48% of them. It was also shown that the amplitudes of orthometric/normal heights variations in large river basins investigated significantly differ from each other, e.g. 8 cm over the Amazon river basin, and 2 cm for the Orange river basin. In many cases hydrological mass changes patterns substantially differ among subareas of the same large river basin, what results in significant differences between the variations of orthometric/normal heights at those subareas. For example, at the Congo river basin they even exceed a triple amplitude of the average of variations of orthometric/normal heights over the entire river basin.

Inter-annual hydrology-induced crustal deformations in Europe were investigated by the team of MUT using RL06 GRACE-based GGMs and WGHM and GLDAS hydrological models (Lenczuk et al., 2020). The strength of the deformation signal from three data sources was found not uniform. The largest long-term non-linear variations in surface deformation time series from all three datasets were observed at the eastern part of Europe; the further from the Atlantic Ocean the larger. Correlation between precipitation and an uplift was discussed and the contribution of GRACE mission to hydrology-induced crustal deformations was highlighted.

Vertical deformations of the Earth's surface determined using GRACE-based GGMs and GNSS data were investigated in terms of EWT variations in Southeastern Poland (Godah et al., 2019; 2020b). The authors confirmed that GNSS data can provide information valuable for the determination of ΔEWT. They also showed that the combination of ΔEWT obtained from GNSS and GRACE data fits better to ΔEWT obtained from WGHM hydrological model than ΔEWT obtained from GRACE data only. Vertical deformations of the Earth's surface determined using GRACE-based GGMs compared with those from GNSS data show the local temporal mass variation signal which can be sensed by GNSS observations but not by GRACE data (Godah et al., 2020b).

The use of national GNSS CORS networks for the determination of temporal mass variations within the Earth system as well as for improving GRACE/GRACE-FO solutions was investigated. The case for Poland with the ASG-EUPOS CORS network was considered (Godah et al., 2020c). Temporal variations of EWT as well as vertical deformations of the Earth's surface were determined at the stations of the ASG-EUPOS network. ΔEWT solutions from GNSS data were combined with the corresponding ones from GRACE data. Strong correlations (correlation coefficients from 0.6 to 0.9) between detrended vertical deformations of the Earth's surface determined from GRACE/GRACE-FO data and the corresponding ones from GNSS data were observed at 93% of GNSS stations investigated. It was shown that the temporal mass variations determined from GNSS data from CORS network stations provide valuable information to complement those obtained from GRACE data.

The dynamics of physical heights and their use for the determination of accurate orthometric/normal heights were further extensively investigated. Temporal variations of orthometric/normal heights over Poland obtained using GRACE data reach up to 23 mm. It was shown that they can be modelled with 1 mm accuracy, and predicted with the accuracy of ca. 1–2 mm (Godah et al., 2021). Those variations in Central Europe were assessed at the level of 23 mm, and in Turkey – 25 mm (Szelachowska et al., 2022a). The authors showed that having geoid/quasigeoid obtained from local gravimetric geoid/quasigeoid model or dedicated gravity satellite missions with 1 cm accuracy, one could determine the height with GNSS levelling with the accuracy of a few centimetres using PPP solution, and the accuracy of a few millimetres using double-differencing.

As a continuation of a previous study a contribution of GRACE data to the determination of precise levelling corrected for their dynamics was investigated at the territory of Poland as a test area (Szelachowska et al., 2022b). The new approach of determining such heights was proposed. First, height variations were obtained using Release 6 GRACE-based GGMs and Love numbers from the preliminary reference Earth model. Then they were modelled and predicted using the Seasonal Decomposition Method. It was shown that the major part of the signal, i.e., ca. 66% of variations of orthometric/normal heights results from the variation of the ellipsoidal height, while its remaining part is due to the variation of geoid/quasigeoid height.

The research conducted indicate the importance of the knowledge of the dynamics of physical heights for the determination of reliable orthometric/normal heights, which are still considered static over the majority of the Earth land areas (Godah et al., 2020a; Szelachowska et al., 2022b). It is fundamental for precise levelling to fulfil the contemporary geodetic scientific and applications purposes (Godah et al., 2021; Szelachowska et al., 2022a). It was shown that monitoring variations of orthometric/normal heights can significantly mitigate artifacts and aliasing of repeated levelling measurements (Szelachowska et al., 2022b).

The determination of vertical land movements is important to investigate the factors affecting the sea level change on a sea coast. The sensitivity of satellite altimetry, tide gauge and GNSS observations to changes in vertical displacements was investigated in the area of the Adriatic Sea coast by the team of UWM in cooperation with Riga Technical University (Pajak et al., 2021). The results obtained show highly coherent regional patterns of sea level change on both Italian and Croatian costs simultaneously indicating land subsidence on both coasts of Croatia and Italy, and the rise of sea level. The authors suggested more pronounced geophysical processes in the area investigated in the last decades. Changes in mean sea level on the Polish coast of the Baltic sea derived from tide gauge data from the years 1811–2015 were investigated using several statistical methods (Kowalczyk, 2019). It was shown that the use of Fourier function with the moving average window of 19 years which corresponds to the 18.6 years nutation cycle provides best fitting linear trend. A gradual, slight increase in the mean sea level ranging from +0.8 mm/y to +2.4 mm/y was observed for tide gauge stations considered.

8. Maintenance and modernization of the International Terrestrial Gravity Reference Frame

Maintenance and modernization of national gravity control as well as implementation of developments in gravimetry within the IAG, are a continuous and ongoing subject of activities in Poland. The team of IGiK continued, the initiated in 2018, modernization of national gravity control of the Republic of Ireland and Northern Ireland, performing the absolute gravity survey with the use of the A10-020 gravimeter. The gravity system in Sweden (the RG2000) established in cooperation with Polish researchers was finalized and published. Gravity control in Poland went through a maintenance and review process in 2022 in order to evaluate its current condition. The development of the International Terrestrial Gravity Reference System/Frame (ITGRS/F) was implemented at the Borowa Gora Observatory of IGiK to make it fully suitable as a reference station of ITGRS. In addition to two absolute gravimeters: A10-020 (IGiK), and FG5-230 (WUT), operating in Poland, IGiK acquired in 2021 the Absolute Quantum Gravimeter (AQG sn B07) manufactured by iXblue, providing new capabilities for modernization and maintenance of gravity reference frames.

8.1. Maintenance and modernization of the gravity control network in Poland

Within the period of 2019–2022 no dedicated gravity survey was conducted on both fundamental stations (located indoors) and base stations (located outdoors) of the national gravity control in Poland. In 2022 the gravity control in Poland underwent a thorough review and maintenance ordered by GUGiK and performed by the team of WUT. As a result 6 fundamental stations and 8 base stations were found destroyed (and/or no longer available for survey) and their replacement locations have been selected. The establishment of replaced stations is planned by GUGiK for early 2023 while the re-measurement of the fundamental gravity stations for 2023, and base gravity stations for the years 2024–2025.

Independently, the team of IGiK performed repeated absolute gravity measurements at selected fundamental and base stations of the Polish gravity control as part of other activities, such as EPOS-PL project (4 base stations in the Upper Silesia region), EPOS-PL+ project (fundamental station at Borowiec Observatory of SRC PAS), and regular activities of IGiK (fundamental stations at the Central Gravimetric Calibration Baseline). These additional surveys will be helpful in long term evaluation of the stability of the gravity control in Poland. They are described in more detail in Krynski et al. (2023).

8.2. Implementation of the International Terrestrial Gravity Reference System/Frame in Poland

Resolution 4 on "Establishment of the Infrastructure for the International Gravity Reference Frame" of the IAG, adopted at the XXVII IUGG 2019 General Assembly[13], 2019, encourages national institutions to establish absolute gravity stations with regular gravity observations on them. In accordance to IGRS 2020 Conventions (Wziontek et al., 2021), the so called "reference stations" would serve as basic realization of ITGRF. At such stations, "gravity reference function" is strongly suggested to be established to maintain continuous gravity record with a superconducting gravimeter supplemented with periodic gravity measurements with absolute gravimeters (at least every 2 months, 6 times per year). Those absolute gravimeters are supposed to participate in international comparisons of absolute gravimeters in order to assure traceability to the internationally established gravity reference value.

Within the period of 2019–2022 IGiK focused on building up and preparing the Borowa Gora (BG) Observatory infrastructure to become a reference station of ITGRF. Since 2016 the iGrav-027 superconducting gravimeter was running continuously at BG Observatory. Simultaneously, regular monthly gravity measurements with the A10-020 gravimeter (operated since 2008) were performed along with several gravity comparison campaigns with the FG5-230 gravimeter (owned by WUT). Starting from late 2021, regular gravity measurements at BG Observatory have also be conducted with the AQG-B07 quantum gravimeter.

Within the last seven years, the A10-020 gravimeter participated in 3 significant absolute gravimeter comparisons: Belval in 2015, Wettzell in 2018 (Falk et al., 2020), and Onsala in 2022. Results from 2015 and 2018 absolute gravimeter comparison campaigns were used for combining of iGrav-027 and A10-020 results to establish the gravity reference function and evaluate the drift rate of the iGrav instrument (Dykowski et al., 2019c) (Fig. 7).

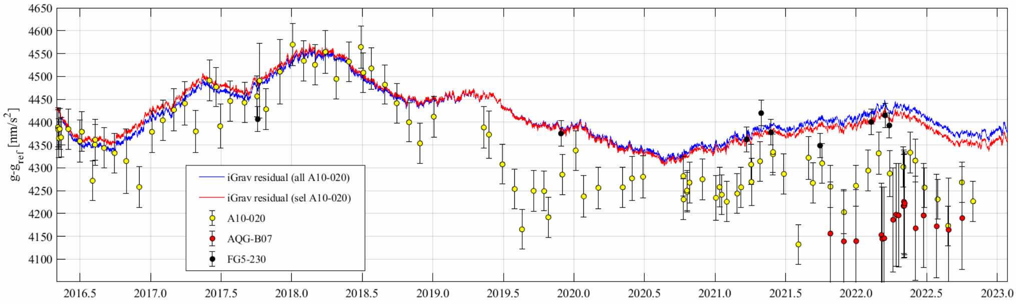

Fig. 7. Gravity reference function at BG Observatory with gravity surveyed with the A10-020, AQG-B07, and FG5-230 gravimeters; $g_{\mathrm{ref}} = 9812500000$ nm/s^2 (Dykowski et al., 2019c)

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[13] https://iag-aig.org/doc/GH2020/209_IAG{%}20Resolutions.pdf

Up to early 2019 results obtained with the A10-020 gravimeter agree with those from the iGrav-027, i.e. both are referenced to the international gravity reference level. Linear drift of the iGrav-027 in the period 2016–2019 was estimated for 2 variants: 1) with the use of all available surveys with the A10-020 gravimeter (var. A – +4.9 nm/s^2/year), and 2) selected (within single Total Uncertainty (T.U.) to iGrav-027 results) A10-020 gravity surveys (var. B – –1.1 nm/s^2/year). The gravity reference function realized by the iGrav-027 gravimeter (Fig. 7) is also presented in two versions of drift estimates: 1) reduced for var. A (Fig. 7 – blue curve), and 2) var. B (Fig. 7 – red curve). To constrain the gravity reference function at the BG Observatory from 2019 until 2022, another comparison campaign of absolute gravimeters is required. In June 2022 all three instruments, i.e. FG5-230 (owned by WUT), and A10-020 and AQG-B07 (owned by IGiK), participated in the NKG-CAG2022 comparison campaign organized by the Nordic Geodetic Commission in the Onsala Space Observatory in Sweden. Results from that comparison are not yet available at the time of this publication what makes impossible a complete evaluation of the gravity reference function.

Starting from mid-2019 (Fig. 7) offsets for none of the absolute gravimeters are included and only approximate estimates can be made as to the systematic effects of the instruments. At this level of analysis the approximate offsets within the period of 2019–2022 are within single tens of nm/s^2 for the FG5-230, –100 nm/s^2 for the A10-020 and –200 nm/s^2 for the AQG-B07. For the A10-020 gravimeter this is an expected level based on the instrument performance before 2019. For the AQG-B07 during 2022 both systematic effects as well as uncertainty budget were still under evaluation.

Maintaining a gravity reference function proved to be especially important in this period because of the Covid-19 pandemic, which effectively reduced the possibility to perform international absolute gravimeter comparisons. Evaluated offsets from the gravity reference function at BG Observatory were and will be used in all gravity activities carried out by IGiK, therefore disseminating the international gravity reference level.

8.3. Modernization of gravity control in Sweden

No new measurements were conducted by Polish teams in the years 2019–2022. Final results of the RG 2000 establishment and adjustment were completed and published in 2019 (Engfeldt et al., 2019).

8.4. Establishment of gravity control in the Republic of Ireland and Northern Ireland

The team of IGiK, in cooperation with the Ordnance Survey Ireland (Republic of Ireland) and Ordnance Survey of Northern Ireland (Northern Ireland) established the national gravity control on the Ireland island (both Republic of Ireland and Northern Ireland). The work was initiated in mid-2018 following a design approved by both OSI and OSNI. The main concept of the new gravity control in Ireland (Absolute Gravity Network – AGN) assumes that the gravity at all its stations, homogenously distributed over the island of Ireland (selected after extensive studies and field reconnaissance) are determined with the use of the A10-type absolute gravimeter (Dykowski et al., 2019a; 2019b). For all stations vertical gravity gradients were also determined with a set of two LaCoste&Romberg (LCR) gravimeters.

AGN Ireland consists of 57 stations of which more than 20 stations are co-located with permanent GNSS stations of the active GNSS network for the island of Ireland (Fig. 8). A number of 51 AGN Ireland stations, so-called Network Stations are located outdoors, typically on bedrock or church steps. Six AGN Ireland stations located indoors (confirmed solid concrete), forming the traverse running meridionally, were designed specifically to serve as a gravimetric calibration baseline. Additionally seven gravity stations were identified as stations of the previous most recent reference network established in late 1960s, recognised as World Relative Gravity Reference Network (WRGRN) stations (Krynski and Rogowski, 2019).

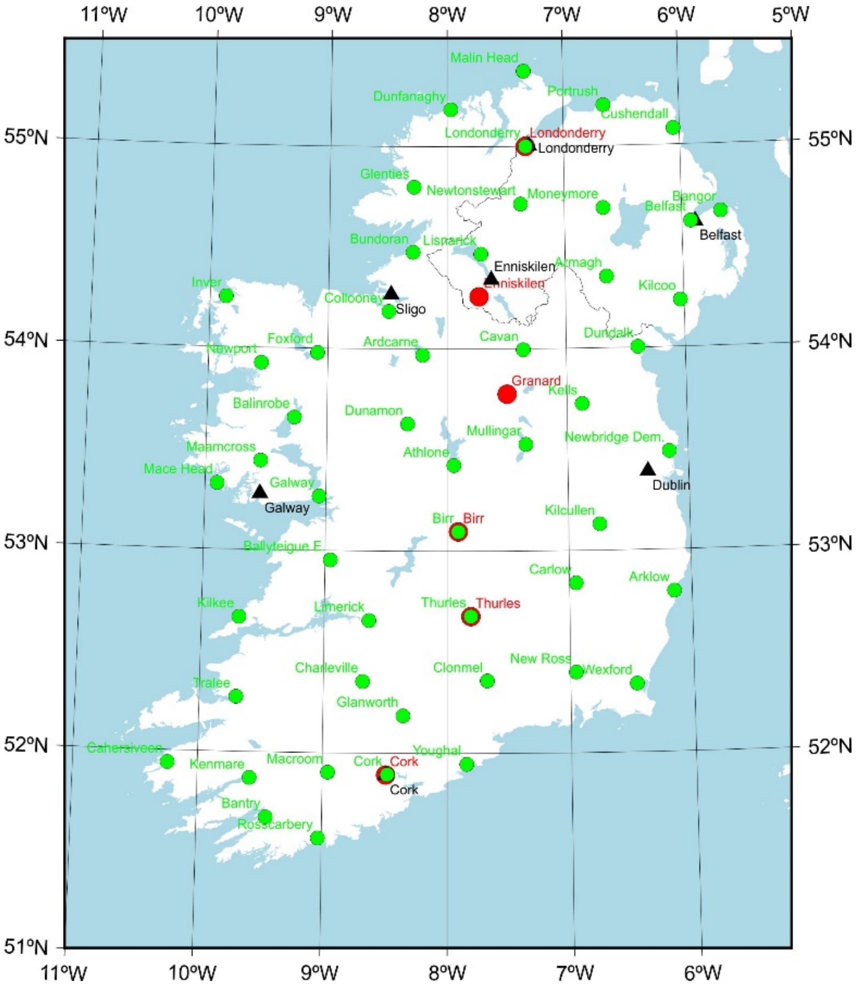

Fig. 8. The Absolute Gravity Network in Ireland: Network Stations (green circles), gravimetric calibration baseline stations (red circles), WRGRN stations (black triangles) (Krynski and Rogowski, 2019)

Gravity survey at the stations of a new gravity control in Ireland, disrupted by Covid-19 pandemic, was carried out in three campaigns: September 2018, August/September 2019, and June/August 2021. At the AGN stations gravity was surveyed with the A10-020 absolute gravimeter (Krynski et al., 2019a; 2019b), and the vertical gravity gradient was determined using two LCR gravimeters (G-1012 and G-1036) of IGiK, except 4 WRGRN stations which have been connected to Network Stations with relative gravity survey using also two LaCoste&Romberg gravimeters (G-1012 and G-1036) of IGiK.

For the evaluation of absolute gravity values within the project the following corrections were used with compliance of the recently established IGRS 2020 conventions (Wziontek et al., 2021): gravimetric Earth tides, polar motion, effect of atmospheric mass variations, ocean tidal loading, vertical gravity gradient reduction, self-attraction correction, diffraction correction (Dykowski et al., 2022).

As an important element of the project, the spring gravimeter LCR G-1084 of IGiK with dedicated self-programmed recording system based on a Raspberry Pi device was installed at the OSi headquarters in the Phoenix Park, Dublin, to evaluate the ocean tide model best fitting for the Irish region (following the recommendations of IGRS 2020 Conventions). Raw tidal data was recorded in the period September 2018 – February 2021. For tidal analysis with the ETERNA software (version: et34 x v80 gnusim, Schueller, 2015) ~500 days of best quality record was used. In total 29 different ocean tidal models (OTL models obtained from Chalmers Loading Provider M.S. Bos and H-G. Scherneck[14]) were tested in combination with the Tamura body tide model against the adjusted local tidal model. As a result of the study, standard deviations and max-min differences of the residual signal remaining from subtracting the combination of the Tamura tide model with each of the ocean tide models from the local model (result of tidal analysis) were defined as the parameter for selecting the best fit ocean tidal loading model (Fig. 9). Both

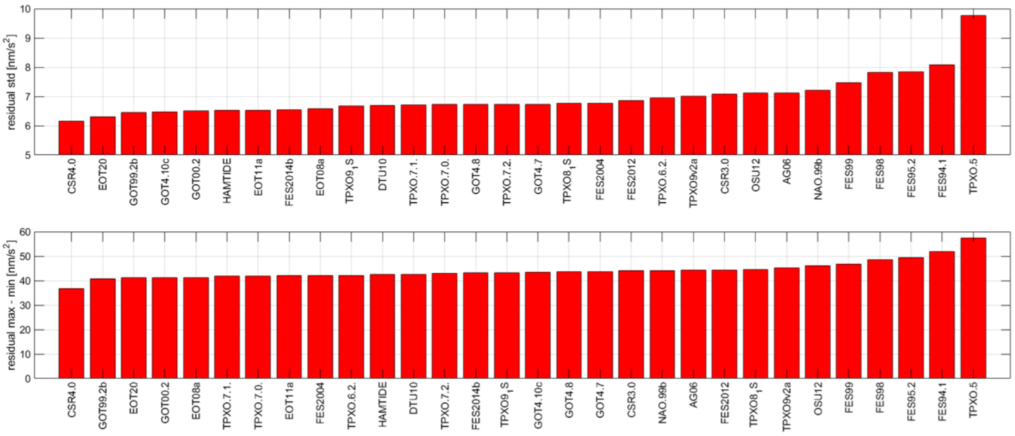

Fig. 9. The results of the analysis determining the most suitable tidal model for Ireland (Dykowski et al., 2021)

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[14] http://holt.oso.chalmers.se/loading/

estimated parameters indicate the CSR4.0 model as the best one for Ireland (Dykowski et al., 2021). This model was used in processing all gravimetric measurements made in Ireland.

Positions and heights of the AGN stations were determined during the course of the project by the teams of the Ordnance Survey Ireland and the Ordnance Survey of Northern Ireland. Results from the establishment of AGN Ireland will be tied to the ITGRF gravity reference level.

9. Maintenance of the magnetic control network in Poland

The magnetic control in Poland has been established in 1955 and regularly maintained since then providing data on variability of geomagnetic field over the territory of Poland which allow to determine its actual parameters. It consists of 21 repeat stations (Fig. 10) and is traditionally surveyed with full metrological consistency, and maintained by IGiK, following the rules of the Magnetic Network of Europe (MagNetE) of the International Association of Geomagnetism and Aeronomy of IUGG. The magnetic control is densified by magnetic points, in particular in the areas of strong magnetic anomalies.

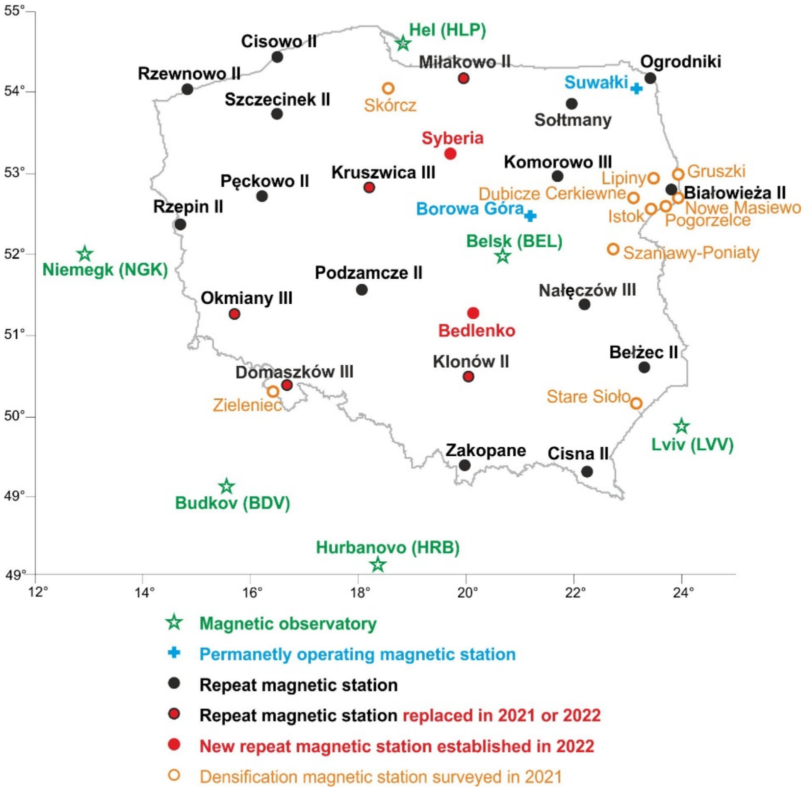

Fig. 10. Polish magnetic repeat station network 2022

Due to quick and irregular variability of the magnetic field of the Earth, three independent components of the intensity vector of the geomagnetic field, i.e. magnetic declination D, magnetic inclination I, and the module of the magnetic intensity vector F are measured roughly every 2–3 years at each repeat magnetic station, starting from 1970. During each survey the benchmarks of repeat stations and their eccentric stations are carefully checked; the actual horizontal gradient of the geomagnetic field at the stations are examined. When necessary, a new location of the benchmark is found and new monumentation of the repeat station is established, which is followed by the magnetic survey performed using a special procedure to ensure the continuity of observations.

Secular variations of the Earth's magnetic field in Poland are determined from repeated survey of the magnetic control as well as using data from the magnetic observatories which operate in the framework of the global international network INETRMAGNET: two Polish magnetic observatories run by the Institute of Geophysics of the Polish Academy of Sciences (IGF PAS): Central Geophysical Observatory in Belsk and Magnetic Observatory in Hel as well as four magnetic observatories of neighbouring countries: Niemegk (Germany), Budkov (Czech Republic), Hurbanovo (Slovakia), and Lviv (Ukraine) (Fig. 10) (Krynski and Rogowski, 2019; 2021; Liwosz and Dykowski, 2022). Additional data used to control magnetic surveys in Poland are provided by two permanently operating magnetic stations (Fig. 10): Borowa Gora of IGiK, and Suwalki of IGF PAS.

The X, Y, Z components of the magnetic intensity vector at the magnetic stations are calculated using magnetic declination D, magnetic inclination I and the module of the magnetic intensity vector F, determined at those stations, reduced to the mid-year period using data from magnetic observatories of the INTERMAGNET network. The results of magnetic data processing are regularly submitted to the magnetic database of IGiK and partially to the World Data Centre for Geomagnetism in Edinburgh, UK.

The Polish magnetic repeat station network is regularly maintained and improved following the European standards defined by MagNetE (Krynski and Rogowski, 2019; 2021). The list of the Polish magnetic repeat stations surveyed in the years 2019–2022 is given in Table 6. Some magnetic repeat stations were replaced with the new ones and monumented in new locations. In 2021, station Milakowo was replaced by Milakowo II, Klonow – by Klonow II, and Okmiany II – by Okmiany III. In 2022, a complementary design of the fundamental magnetic control addressed the need for new locations of two existing repeat stations: Kruszwica II, and Domaszkow II as well as for the establishment of two new magnetic repeat stations: Bedlenko and Syberia (Fig. 10). In the same year two replaced repeat stations: Kruszwica III, and Domaszkow III as well as two new repeat stations: Bedlenko and Syberia (Fig. 10) were monumented and magnetic declination D, magnetic inclination I as well as the module of the magnetic intensity vector F were measured at those stations.

In 2022 an inspection of 14 eccentric stations of the magnetic repeat stations (Fig. 11) was carried out accompanied with the examination of the horizontal gradient of the geomagnetic field in the close vicinity of the stations.

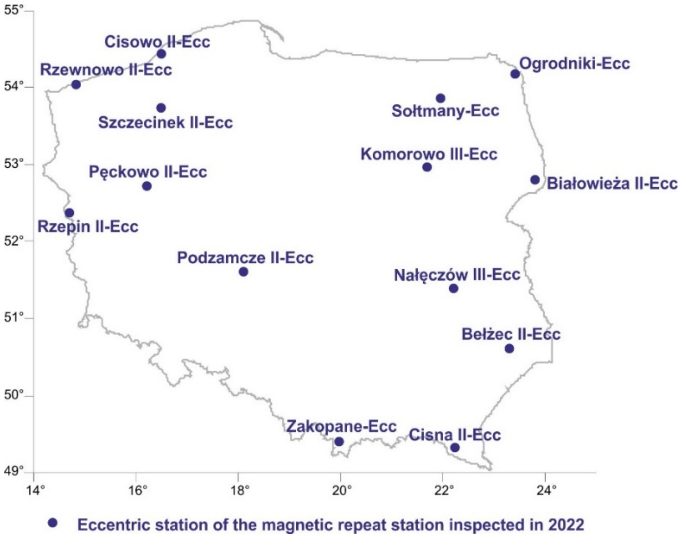

Fig. 11. Eccentric stations of the magnetic repeat stations inspected in 2022

Table 6. Polish magnetic repeat stations surveyed in the years 2019–2022

No	Station name	2019	2020	2021	2022
1	Cisowo II	–	×	×	–
2	Ogrodniki	×	–	×	–
3	Milakowo II	–	–	×	–
4	Rzewnowo II	–	×	×	–
5	Soltmany	–	–	×	–
6	Szczecinek II	–	×	×	–
7	Komorowo III	×	–	×	–
8	Bialowieza II	×	–	×	–
9	Kruszwica II/ Kruszwica III	–	–	×/–	–/×
10	Peckowo II	×	–	×	–
11	Rzepin II	×	–	×	–
12	Podzamcze II	–	–	×	–
13	Naleczow III	–	×	×	–
14	Okmiany II/Okmiany III	–	–	×/×	–
15	Belzec II	–	–	×	–
16	Klonow/Klonow II	×/–	–	×/×	–
17	Domaszkow II/Domaszkow III	–	–	×/–	–/×
18	Zakopane	×	–	×	–
19	Cisna II	–	–	×	–
20	Bedlenko	–	–	–	×
21	Syberia	–	–	–	×

10. Summary and conclusions

The article contains the summary of activities of Polish research and government institutions in the years 2019–2022 in the areas related to the implementation of regional and global reference frames, integration of geodetic, gravimetric and magnetic observations for the realization and maintenance of a unified reference frame and reference networks.

Traditionally the team of IGiK continued in the years 2019–2022 developing the Astronomical Almanac series. The almanacs were in agreement with resolutions of recent General Assemblies of IAU and IUGG. They contain all updates to their previous editions. The development of the on-line version of the Almanac made possible to reduce the printed version of the Almanac as compared with its full version – both available on IGiK web page.

The presently used ETRS89 realization in Poland – PL-ETRF2000, was adopted by GUGiK in 2013. It is based on GPS data collected up to March 2011 at the permanent stations of the ASG-EUPOS network. Since then, GNSS equipment (antenna, receiver) was changed on most ASG-EUPOS network stations which caused coordinate changes on some stations. There were also new stations established, and 14 additional stations are planned to be installed in 2023. To take into account all changes that occurred after the PL-ETRF2000 was developed a new realization of the ETRS89 in Poland is required.

The ASG-EUPOS system established in 2008 operates and is maintained by the GUGiK. Since 2019 the system provides services based on 4 GNSS constellations: GPS, GLONASS, Galileo, and BeiDou. In 2021 the reference network started to be densified to increase availability and accuracy of real time services. In 2022 four new stations were established and 14 additional are planned for 2023. Presently there are 107 permanent GNSS stations of the ASG-EUPOS network. ASG-EUPOS stations together with 22 stations operating in neighbouring countries are the official reference stations for precise positioning in Poland.

Nineteen Polish permanent GNSS stations continued their operational work within the international IAG services: EUREF and IGS (6 of 19 stations). In 2022 two new GNSS stations were installed by WUT at the Polish Polar Station in Hornsund, Norway; both of them were included in the EPN and one in the IGS. The only SLR station in Poland (BORL at Borowiec) continued laser ranging measurements to Earth's satellites and space debris; the number of measured space objects at the BORL station grows each year. These measurements are performed within the International SLR Service (ILRS), EUROLAS Consortium, as well as internal contracts signed with the ESA and the European Consortium EUSST.

The research on global terrestrial reference frames and the improvement of the determination of global geodetic parameters (e.g., geocenter and pole coordinates) as well as future ITRFs was conducted by the team of UPWr. For example, the possibility to use new GNSS observations to BeiDou-3 satellites and SLR observations to GNSS and Sentinel-3A/3B satellites and their impact on the estimation of global parameters was analyzed. Also, the common usage of GNSS and SLR-to-GNSS observations in the realization of terrestrial reference frame was investigated. In the proposed approach the co-location between SLR and GNSS techniques took place in space, on board of GNSS satellites. Such co-locations could replace the presently used local ties between stations.

Teams of WUT and MUT continued the activities of the EPN analysis centres and the EPN Analysis Combination Centre (ACC). The impact of adding Galileo observations on EPN combined solutions was analyzed. Also, the preliminary works on adding a number of globally distributed stations to the EPN network were done and its impact on solutions for station positions was analyzed. Recent activities of the ACC included the preparations for the switch to the IGS20 reference frame and new IGS standards in the EPN analysis.

In recent years, the research on receiver antenna calibrations was also conducted in Poland. In 2019, the UWM in cooperation with Astri Polska started a European Space Agency project on developing and implementing a field calibration procedure for a multi-frequency and multi-GNSS. The initial calibrations obtained from independent UWM analysis showed good consistency (at the 2 mm level). Similar consistency was obtained in comparison with the type-mean IGS model. However, it was indicated that some aspects, e.g. the modelling of phase center corrections for low elevations, needs to be further investigated.

The PL-EVRF2007-NH reference frame has been implemented by local authorities for the detailed vertical network in Poland for over 80% of the country. The preparations for the new levelling campaign in Poland started in 2020. In 2022 the designing works were completed for 25% of the Polish territory and the works are going to be continued in 2023.

Geoid height variations as well as vertical displacements of the Earth surface were extensively investigated using GRACE mission data in the context of the realization of a modern vertical reference system in different areas of the world, in particular in Central Europe, including Poland. It was shown that temporal variations of orthometric/normal heights over Poland obtained using GRACE data reach up to 23 mm, that they can be modelled with 1 mm accuracy, and predicted with the accuracy of ca. 1–2 mm. It was also shown that the major part of those variations results from the variation of the ellipsoidal height, while its remaining part is due to the variation of geoid/quasigeoid height.

Advanced research and activities towards the implementation of the International Terrestrial Gravity Reference System/Frame in Poland was conducted. The gravimetric infrastructure of the Borowa Gora (BG) Observatory has been supplemented with the AQG-B07 quantum gravimeter. Metrological activities concerning the gravimetric infrastructure of IGiK are regularly performed and the gravity reference function is regularly maintained. The Observatory has been prepared to become a reference station of ITGRF. The survey of the Absolute Gravity Network in Ireland has been completed. The measurements have been processed applying all state-of-the-art corrections. The long-term record of the spring gravimeter LCR G-1084 of IGiK equipped with the self-programmed recording system, installed at the OSi headquarters in the Phoenix Park, Dublin, was used to evaluate the ocean tide model best fitting for the Irish region.

Magnetic control network in Poland, due to strong variability of the geomagnetic field, needs to be regularly maintained. It is surveyed on regular basis (approximately every two years) which ensures that the parameters describing secular variations of magnetic field in Poland are up to date. In the years 2019–2022, 21 magnetic repeat stations and 10 densification stations were surveyed at least once, and 14 eccentric stations of magnetic repeat stations were maintained.

Author contributions

Conceptualization: J.K., T.L.; original draft preparation: J.K., T.L.

Data availability statement

No datasets were used in this research.

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