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Review paper

Research on reference frames and reference networks in Poland in 2015–2018

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Abstract: Research activities of Polish research groups in a period of 2015–2019 on reference frames and reference networks are reviewed and summarised in this paper. The summary contains the results concerning the implementation of latest resolutions on reference systems of the International Union of Geodesy and Geophysics and the International Union of Astronomy with special emphasis on the changes in 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, operational work of GNSS permanent IGS/EPN stations in Poland, operational work of the laser ranging station in Poland of the International Laser Ranging Service (ILRS), active GNSS station network for the realization of ETRS89 in Poland, validation of recent ETRS89 realization, expressed in ETRF2000 in Poland, and maintenance of the vertical control in Poland (PL-KRON86-NH). Extensive research activities are observed in the field of maintenance and modernization of gravity control not only in Poland, but also in Sweden and in Denmark, as well as establishment of gravity control in Ireland based on absolute gravity survey. The magnetic control in Poland was also regularly maintained. The bibliography of the related works is given in references.

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: Gdansk University of Technology(GUT), Polish Head Office of Geodesy and Cartography (GUGiK), Institute of Geodesy and Cartography in Warsaw (IGiK), Military Academy of Technology in Warsaw (MUT), Rzeszow University of Technology (RUT), Space Research Centre of the Polish Academy of Sciences (SRC), Warsaw University of Technology (WUT), Wroclaw University of Environmental and Life Sciences (WUELS), in the years 2015–2019, in the areas related to the implementation of global reference systems, integration of geodetic, gravimetric and magnetic measurements for the realization and maintenance of a unified reference frame and reference networks in Poland.

Research on the implementation of celestial reference systems, time systems, transformations between celestial and terrestrial systems has continued at the Centre of Geodesy and Geodynamics of IGiK. Since 1946, IGiK releases the Astronomical Almanac (Pol. *Rocznik Astronomiczny*). Each year, a new version of the Astronomical Almanac of IGiK is published, and the latest resolutions of General Assemblies of the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) are implemented. In the paper, the recent releases of the Astronomical Alamanac of IGiK are presented.

Geodetic, vertical, gravimetric and magnetic networks are integrated in Poland in the European Terrestrial Reference System (ETRS89). ETRS89 is a standard reference system in Europe which was adopted in 1990 by the Subcommission for the European Reference Frame (EUREF) of the International Association of Geodesy (IAG). The ETRS89 is realized in Poland by means of the Global Navigation Satellite System (GNSS) since 1992. The latest realization of ETRS89, expressed in ETRF2000 at epoch 2011.0, in Poland (PL-ETRF2000) was realized in 2011 through the network of 103 GNSS permanent stations – Active Geodetic Network – European Position Determination System (ASG-EUPOS) – and was officially adopted in 2013.

ASG-EUPOS system was established in 2008 and is operated and maintained by the GUGiK. From the year 2014 to 2018 the GNSS equipment on 76 ASG-EUPOS stations has been upgraded to allow multi-GNSS tracking. By September 2018, there were 49 stations observing GPS, GLONASS, Galileo and BeiDou satellites, 37 stations observing GPS, GLONASS and Galileo satellites, 15 stations observing GPS and GLONASS satellites, and 2 stations observing only GPS satellites. In 2015, a new reference frame was created for ASG-EUPOS, with the intention of replacing the former PL-ETRF2000.

Eighteen Polish GNSS stations operate also within IAG services: International GNSS Service (IGS), and EUREF Permanent Network (EPN). The only satellite laser ranging (SLR) station in Poland operates within the International Laser Ranging Service (ILRS). The GNSS and SLR stations in Poland support the international geodetic community in the realisation of terrestrial reference frames.

The research in Poland also concentrates on the analysis of solutions obtained using observations collected by space geodetic techniques: GNSS, SLR, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Very Long Baseline Interferometry (VLBI). The impact of adding GNSS constellation to the SLR-derived station coordinates and Earth orientation parameters was conducted by WUELS (Sosnica et al., 2018). The research on reliable station velocities obtained using GNSS and DORIS was conducted at MUT (Klos and Bogusz, 2017; Klos et al., 2018). At WUT, the impact of non-tidal loading effects due to atmosphere, ocean and continental water on Global Positioning System (GPS) solutions (station coordinates, velocities, position time series) in a regional network was studied (Liwosz, 2015a, 2015b).

The vertical system in Poland is conventionally based on a static geoid derived from constant, i.e. non varying in time gravity field. Since temporal variations of the gravity field caused by mass displacements in the Earth system result in variations of the reference surface for heights, the usage of the Gravity Recovery and Climate Experiment (GRACE)-based global geopotential models for modelling temporal variations of gravity functionals, including geoid heights over Poland and surrounding areas, was investigated in the context of the definition and realization of a modern vertical reference system.

The existing gravity control in Poland, established in 2012–2013 by GUGiK, consists of exclusively absolute gravity stations. The impact of time-variable effects (ocean loading, the non-tidal atmospheric loading and hydrology loading), that were not modelled for the establishment of the present gravity control, on absolute gravity determinations was investigated by IGiK for the needs of the gravity control. Also, works of IGiK on the modernization of gravity control networks in Sweden and Denmark, and on the establishment of the gravity control network in Ireland are presented in the paper. The magnetic control in Poland, regularly surveyed and maintained by IGiK, was established in 1955. It consists of 19 repeat stations. In addition, two magnetic observatories operating in the framework of the global international network for the monitoring of the Earth's magnetic field (INETRMAGNET), and two permanent magnetic stations provide data used for control of magnetic surveys in Poland.

The activities related to terrestrial reference frames, geodynamics and gravity in Poland were integrated within the Polish Research Network for Global Geodetic Observing System (acronym GGOS-PL). In 2017, IGiK, MUT, and WUELS together with the Institute of Geophysics of the Polish Academy of Sciences (IGF PAS) and with some other institutions started a common regional project EPOS-PL – the Polish Earth science infrastructure – integrated with the European Plate Observing System Programme (EPOS) (Bosy et al., 2017). Developing of centres of research infrastructure for geomagnetic and gravimetric data integrated with GNSS infrastructure is one of the main objectives of the project (Bosy et al., 2016; Sosnica et al., 2017).

2. Implementation of IUGG and IAU resolutions on reference systems

Research on the implementation of the new paradigm of celestial reference systems, time systems, transformations between celestial and terrestrial systems and consecutive resolutions of IAU and IUGG has been continued at the Centre of Geodesy and Geodynamics of IGiK. It was reflected in a subsequent updating or developing new algorithms and computing programs for calculating ephemeris for the Astronomical Almanac of IGiK which besides a printed version is available since 2002 on web pages of IGiK (http://www.igik.edu.pl/) in pdf format. Following editions of the Astronomical Almanac of IGiK are subsequently updated. Methods of presentation of high precision astrometric and geodetic data are consequently modified in IGiK in view of the latest achievements in the field of reference systems, starting from 2014. The content of the printed version of the Astronomical Almanac of IGiK for the year 2015 has been reduced as compared to previous years issues by removing tables of apparent places of stars in IRS system, positions of stars in ICRS as well as barycentric and heliocentric positions of the Earth. Instead, the "on line" calculator of apparent places of stars at arbitrary time on web pages of IGiK was developed. The introduced changes have their source, above all, in striving to ensure the greatest possible consistency between the accuracy of the data included in the Astronomical Almanac of IGiK and their achievable level, resulting from the accuracy of source data and computational models currently used. This applies mainly to the apparent positions of stars in IRS calculated using the tables of apparent places of stars in this system. The accuracy of interpolated values inside the data range given in the tables with the 7-day step adopted for most stars has remained at the level significantly lower than the values possible to achieve by direct calculations at a given moment. A natural solution of this problem was thus to resign from the current method of tabular presentation of a part of the data in the printed version of the Astronomical Almanac of IGiK and transfer them to the Internet Astronomical Almanac of IGiK, on-line (Krynski and Sekowski, 2014). The on-line calculator of the apparent position of the star was further developed in the Internet Astronomical Almanac of IGiK for the year 2016 (Krynski and Sekowski, 2015). In particular, in order to raise the educational value of the Astronomical Almanac of IGiK, the "on-line" calculations for a given date have been supplemented with information on the calculation steps. The printed version of the Astronomical Almanac of IGiK for the year 2017 was further reduced, namely tables of mean positions of stars referred to the FK5 catalogue, tables of reducing quantities, tables of apparent places of stars in the FK5 system were removed. Simultaneously the on-line calculator of the Internet Astronomical Almanac of IGiK was extended to additional calculations of the mean positions of stars and reducing quantities at arbitrary time (Krynski and Sekowski, 2016). The Astronomical Almanac of IGiK for the year 2018 contains all updates to its previous editions (Krynski and Sekowski, 2017).

Changes in astronomical constants according to the resolution of the IAU XXIX General Assembly in Honolulu in 2015, as well as adoption of the new realization of the International Celestial Reference Frame (ICRF3) and the ITRS as the preferred GTRS for scientific and technical applications by the IAU XXX General Assembly in Vienna in 2018 were noted in the Astronomical Almanac of IGiK for the year 2019 (Krynski and Sekowski, 2018).

3. Implementation of the ETRS89 in Poland

The ETRS89 was adopted in 1990 by EUREF (EUREF resolution 1). Its realization in Poland was performed in two steps. First, the EUREF-POL network consisting of 11 stations was established. The solution of the GPS campaign conducted in 1992 at the stations of the EUREF-POL network, recognized by the IAG Subcommission for EUREF (resolution No 1 of the EUREF Symposium in Warsaw, Poland, 8–11 June 1994) was the reference for its densification – POLREF network, consisting of 348 stations. In the second step, two consecutive GPS campaigns were conducted in 1994 and 1995 at the stations of the POLREF network. The first GPS-based nation-wide reference frame for Poland, which is now known as the PL-ETRF89 (also known as EUREF-89) was created on the basis of those three campaigns.

The ASG-EUPOS network, established in 2008 and then maintained by GUGiK, is nowadays the primary national geodetic network in Poland. The development of this permanent GNSS network has forced the introduction of new legal acts in which one of the essential element was the introduction of ETRF2000 as a conventional reference frame in Poland being the realisation of ETRS89 (resolution No 2 of the EUREF Symposium in Gävle, Sweden, 2–5 June 2010).

In 2013, GUGiK adopted for ASG-EUPOS the first official reference frame PL-ETRF2000 created at WUT (Liwosz and Rogowski, 2013). The PL-ETRF2000 was based on GPS observations from ASG-EUPOS stations during 66 daily sessions between 23 April 2008 and 1 April 2011. The selected days corresponded to GPS measurement campaigns which were conducted at epoch points included in the PL-ETRF89 reference frame in order to connect the PL-ETRF89 with the new reference frame for the ASG-EUPOS network. GPS observations were processed in the IGS05 framework (based on ITRF2005) using the Bernese GPS Software v.5.0 (Dach et al., 2007). The resulting daily solutions were then combined into the long-term solution (mean station coordinates at epoch 2011.0 and station velocities) which was aligned to the EUREF cumulative solution (the EUREF densification of ITRF2005). Finally, the station coordinates at epoch 2011.0 were transformed to ETRF2000 and adopted as the official reference frame for ASG-EUPOS (PL-ETRF2000). Presently, both PL-ETRF2000 and PL-ETRF89 are used as valid reference frames in Poland.

4. Monitoring the terrestrial reference frame

The impact of ITRF2014/IGS14 on the positions of the reference stations in Europe was investigated at the Faculty of Civil and Environmental Engineering of GUT (Figurski and Nykiel, 2017). It has been shown that ITRF2014 is highly consistent with ITRF2008 but the introduction of the new satellite and ground antennas phase centre calibrations in IGS14 cause differences in station positions at the level of several millimetres, change in the translation parameter, and the change in the network scale at the level of 0.7 ppb. It was indicated that the variable number of fixed reference stations in the GNSS local networks affects only the translation of the frame. The GNSS observations were computed using the Bernese v.5.2 software (Dach et al., 2015) double difference model, which assumes the use of constrained stations and fixed satellite ephemeris to estimate positions in ITRFyy. This becomes a problem, mainly due to the network error propagation, when the impact of different phase centre calibration on position is investigated.

A contribution of multi-GNSS constellations to the SLR-derived terrestrial reference frame and scientific products was analyzed at the Institute of Geodesy and Geoinformatics of WUELS (Sosnica et al., 2018). The authors processed SLR observations collected at 38 stations to two Laser Geodynamics Satellites (LAGEOS) and to 55 GNSS satellites equipped with laser retroreflectors (1 GPS, 31 GLONASS, 18 Galileo, 4 BeiDou and 1 QZSS), and estimated satellite orbits, SLR station coordinates, the geocenter coordinates, and the Earth orientation parameters (pole coordinates and the length-of-day (LOD)). In LAGEOS + GNSS solutions (based on SLR observations of LAGEOS and GNSS satellites) the GNSS orbits were treated in two different ways. In one solution the orbits were estimated ("LAGEOS+GNSS est"), while in the second one the GNSS orbits were fixed to the GNSS-based satellite positions provided by the Center for Orbit Determination in Europe (CODE) (solution "LAGEOS+GNSS fix").

The mean 3-D repeatability of all SLR station positions from the period 2014.0–2017.4 improved in LAGEOS + GNSS fix solution by 6.9%, 6.4%, and 15.7% for the north, east, and vertical component, respectively, as compared to the LAGEOS-only solution. The median 3-D error for all stations is 6.4 mm, 5.5 mm, and 3.9 mm in LAGEOS-only, LAGEOS+GNSS fix, and LAGEOS+GNSS est., respectively.

Using SLR observations of both LAGEOS and GNSS satellites also improved the consistency of SLR-derived Earth orientation parameters with respect to the IERS C04 series. In LAGEOS+GNSS fix solution, the reduction of LOD RMS from 122.5 µs/d to 43 µs/d, and of mean LOD offset from −81.6 µs/d to 0.5 µs/d, as compared to the LAGEOS-only solution was observed. The improvement in LOD estimates is due to the reduction of correlations between LAGEOS orbital parameters, the drift of the ascending node, and the LOD.

Velocities of geodetic stations were estimated at the Faculty of Civil Engineering and Geodesy of MUT. Bogusz et al. (2016) discussed the treatment of the GNSS position time series for the determination of the reliable station velocities. Time series of positions of geodetic stations consist of a deterministic part that includes a linear trend (velocity) and periodic terms, and a stochastic part. The parameters of the deterministic model can be estimated using Maximum Likelihood Estimation (MLE) method and assuming a stochastic model (noise) which best describes the residual position time series. Klos et al. (2015) analyzed time series of positions of Polish permanent GPS stations with a time span exceeding 5 years. It was shown that uncertainties of the intraplate velocities can become underestimated by up to 5 mm/year, if inappropriate stochastic model (white noise instead of combination of white noise and power-law noise) present in time series of positions is used during velocity estimation. For the European IGS stations included in ITRF2014, Klos and Bogusz (2017) computed the ratio of velocity errors obtained from MLE analysis using as a stochastic model a combination of white noise and power-law noise, to the corresponding velocity errors obtained in the official ITRF2014 solution (in which white noise was assumed). They showed that for 13% and 30% of analyzed stations that ratio exceeded 10 for horizontal and vertical components, respectively. The authors concluded that the use of the proper noise model is crucial when determining velocity. Bogusz and Klos (2016) proposed the use of extended deterministic model during velocity estimation from GPS-derived time series of positions which included all periodicities of Chandler, tropical and draconitic periods, instead of a commonly used model consisting of only annual and semi-annual periods. It was shown that the user of the proposed model may reduce velocity errors up to 56%.

Klos et al. (2018) analyzed in three separate groups time series of positions of 90 DORIS stations operating at 64 sites. The first group (years 1993–2003) concerned observations collected with the first generation of the on-board receivers. The second group (2003–2010) concerned observations collected by the second generation of DORIS receivers, while the third group (2010–2014) concerned data collected using the latest models of DORIS receivers. Station velocities were estimated using MLE method together with other parameters: mean position at a reference epoch, polynomial coefficients up to 4th degree, and phases and amplitudes of 11 signals in DORIS time series of positions. An appropriate noise model was used for each time series of positions (white noise, a combination of white noise and power-law noise, power-law noise or an autoregressive process of the 1st order). For the first group of data the median velocity errors for three groups of stations investigated are shown in Table 1.

Table 1. Median velocity errors (north, east, up components) estimated for three groups of DORIS stations investigated [mm/year]

Group of stations	North	East	Up
1993–2003	0.4	0.7	0.8
2003–2010	0.5	0.5	0.4
2010–2014	0.3	0.3	0.4

The uncertainties significantly decreased for almost all stations for latest observations compared to the previous ones. The authors concluded that it is possible to determine the velocity of station from the time series of DORIS-derived positions with a reliability of about 0.5 mm/year.

Research on the impact of non-tidal loading effects due to atmosphere, ocean, and continental water on regional GPS solutions was conducted at WUT (Liwosz, 2015). Ten years of GPS data acquired at 51 EPN stations were processed applying the non-tidal effects at the observation level. It was found that modelling the non-tidal loading effects can reduce the weighted RMS of the vertical component time series by 10%. The impact of modelling the non-tidal effects on estimated velocities was shown negligibly small. However, the formal errors of velocities could be improved by 7%, and by 23% when the annual and semi-annual signals present in position time series were also estimated during the velocity estimation. Modelling the atmospheric loading decreased the scatter of transformation parameters (3 translations, 3 rotations and scale) between daily solutions and the combined long-term solutions. Modelling the continental water removed annual signal from the time series of the scale parameter.

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

5.1. Operational work of GNSS permanent IGS/EPN stations

Recently 18 permanent GNSS EPN stations (Figure 1) operate in Poland of which 6 are included in IGS network (Krynski and Rogowski, 2018). Data from those stations are transferred via internet to data banks at Vienna, Austria, and at Frankfurt/Main, Germany, and together with data from other corresponding permanent GNSS stations in Europe are the basis of EUREF and IGS products applied for both research and practical use in geodesy, surveying, precise navigation, environmental projects, etc. Stations BOGI, BOR1, JOZ2 and WROC (Figure 1) participated also in IGS Real-time GNSS Data project while BOR1 and WROC stations are additionally included into the IGS Multi-GNSS Experiment (MGEX) pilot project (http://igs.org/mgex).

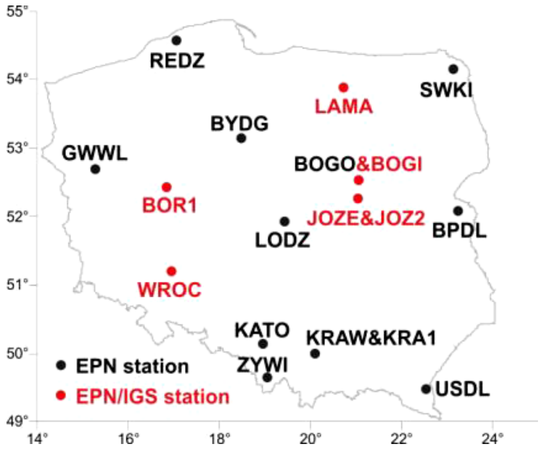

Fig. 1. Permanent GNSS EPN/IGS stations in Poland (2018)

Stations BOGI, BOR1, JOZ2, JOZ3, KRAW, KRA1, LAM5, and WROC take part in the EUREF-IP project (http://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_euref-ip.htm). Ntrip Broadcaster installed in March 2005 operates at the AGH University of Science and Technology (http://home.agh.edu.pl/~kraw/ntrip.php). Ntrip Caster broadcasts RTCM and raw GNSS data from KRAW0 and KRA10 sources take part in the EUREF-IP project and provide data to regional EUREF brodcasters at BKG, ASI and ROB.

5.2. Operational work of ILRS laser ranging station

After five years break in activity the satellite laser ranging (SLR) station BORL at Borowiec (7811) of SRC BORL resumed on 2 March 2015 laser measurements in the framework of the International Laser Ranging Service (ILRS) and EUROLAS Consortium. In its first operational stage BORL was in ILRS quarantine mode. First satisfactory results were obtained in 6 May 2015; 6 LAGEOS-1 passes remained to the fulfillment of the quarantine conditions (Krynski and Rogowski, 2015). Starting from 17 June 2015 all results of SLR observations from BORL were sent to the EUROLAS Data Center (EDC) and since 1 February 2016 they are available in SLR data banks (Krynski and Rogowski, 2016). The BORL station successfully completed quarantine procedure provided by ILRS Analysis Centers on 26 April 2016 and it became fully operational within

ILRS. All results of the station are sent to Crustal Dynamics Data Information System (CDDIS) and EDC; after 1 February 2016 they were released to the public (Lejba et al., 2016)[1]. High quality of the observations of LAGEOS-1 and LAGEOS-2 provided by BORL station reported in the quarantine bias report obtained from Joint Center for Earth System Technology/Goddard Space Flight Center (JCET/GSFC) was confirmed by NASA. The mean range bias for LAGEOS-1 and LAGEOS-2 was 11.0 mm, and 12.0 mm, respectively.

Starting from 2015, activities of BORL concerned also research and development in satellite laser ranging focused on the Space Surveillance Tracking (SST) programme of space debris laser observations dedicated to observing and detecting active and inactive satellites, discarded launch stages and fragmentation debris orbiting the Earth. In 2015 the BORL observed successfully defunct satellite Envisat in the framework of Space Debris Study Group (SDSG) of ILRS. Since 2016, BORL station regularly tracks space debris objects (Krynski and Rogowski, 2017; Lejba et. al, 2018). In mid 2017 Poland applied to the EU SST Consortium to participate in the Space Surveillance and Tracking Support Framework Decision. The SRC PAS is one of the members of the Polish SST Consortium (Konacki et al., 2017). The results debris objects tracking are regularly sent to SDSG data bank in Graz, Austria.

Brief summary concerning SLR observations at SLR BORL station in 2015-2018 is given in Table 2.

Table 2. SLR observation at SLR BORL station in 2015–2018

Year	Satellites observed	Passes	Successful passes		RMS of a single shot [cm]
			normal points	single shots	
2015	21 SLR (19 LEO + 2 MEO)	483	9 690	303 162	1.8–5.3
	1 debris object (ENVISAT)	27	285	10 769	4.1
2016	32 SLR (21 LEO + 11 MEO)	710	19 892	681 397	1.2–5.5
	11 debris objects	145	5 502	124 167	1.5–75.3
2017	24 SLR (20 LEO + 4 MEO)	587	16 611	564 367	1.3–6.5
	15 debris objects	251	11 869	230 901	5.2–81.6
2018 (incl. September)	39 SLR (27 LEO + 12 MEO)	1078	20 110	780 541	1.3–4.3
	10 debris objects	429	4 881	254 780	2.5–45.1

In 2016 eight SLR satellites (Ajisai, Etalon-2, LAGEOS-1, LAGEOS-2, Larets, LARES, STARLETTE and Stella) were tracked at BORL providing 442 135 single good shots and 4195 normal points over 385 passes. Several independent ILRS ACs from Germany, Japan, Russia, and USA produce combined range bias reports (based on LAGEOS-1 and LAGEOS-2 observations) on a regular basis. The average observational range bias for both satellites at BORL is at the level of single-several dozen millimetres.

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[1] http://www.cbk.poznan.pl/stacja_laserowa/lista_obserwacji_2016.php; and http://www.cbk.poznan.pl/stacja_laserowa/lista_obserwacji_2017.php.

In 2017 seven SLR satellites (Ajisai, LAGEOS-1, LAGEOS-2, Larets, LARES, STARLETTE and Stella) were tracked. The fifteen debris objects were observed in 2017 at the SLR station BORL. Based on tracking results of LAGEOS-1 and LAGEOS-2 satellites the quality of the BORL laser sensor is regularly evaluated. Significant improvement of quality and effectiveness of the measurements at the BORL is observed (Krynski and Rogowski, 2018).

To improve the theory of motion of such artificial satellites as, e.g. TOPEX/Poseidon or Envisat, and in consequence determination of orbits of uncooperative targets like rocket bodies from the LEO regime it is crucial to extensively investigate satellite and space debris rotation (tumbling) determination supported by measurements from SLR stations, including BORL 7811 station (Kucharski et al., 2017). Monitoring the position of targets like TOPEX/Poseidon and Envisat and their behaviour in space is essential from the point of view of future missions dedicated debris removal.

The TOPEX/Poseidon mission, and Envisat, belong to most successful missions of NASA and the Centre National d'Études Spatiales (CNES), and ESA, respectively. After losing control stabilization in 9 October 2005, TOPEX/Poseidon is spinning at about 10 s/rev and is in the accelerating mode. Since then the SLR observations of TOPEX/Poseidon are mainly used for investigation of satellite/space debris spin dynamics (Kucharski et al., 2017). Since 2012 the spacecraft which is particularly huge ($26 \times 10 \times 5$ m) and massive (over 8 tons) was orbiting in an uncontrolled way.

Second independent laser system, fully dedicated for SST programme of ESA and EC is under development at SRC Borowiec (Krynski and Rogowski, 2018; Lejba et al., 2018). The new system is situated on an azimuth-elevation mount with two telescopes: a 65 cm Cassegrain transmitting/receiving telescope equipped with servo drives that provide tracking accuracy below 1 arcsec, and a 20 cm Maksutov guiding telescope equipped with new two fast dedicated optical CMOS cameras. The multiplatform steering/tracking software supporting space debris prediction, real-time laser observations, system calibration, ADSB monitoring, data post-processing and other functions controls the whole system which will continuously operate. The new telescope mount is currently in tracking mode.

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

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

The ASG-EUPOS is a multifunctional augmentation system for precise GNSS positioning in Poland. It was established in 2008 and is maintained by GUGiK. Presently, the ASG-EUPOS network consists of 127 permanent GNSS reference stations of which 103 stations operate in Poland and 24 stations – in neighbouring countries near the Polish border (Figure 2) In the period of 2015-2018 two new stations in Poland were established, i.e. DZWE and HOLO, OPNT station replaced OPST, and the Lithuanian station VSTT was included into the ASG-EUPOS network.

Fig. 2. Reference stations of the ASG-EUPOS system (30 September 2018)

Modernization of the equipment installed on ASG-EUPOS stations started at the end of 2014 by GUGiK to allow for the multi-GNSS tracking capability reached already almost 80% of stations and is still in progress.

6.2. Validation of ETRS89 realization in Poland

In 2015, a new realization of ETRS89 in Poland for the ASG-EUPOS GNSS network was created to substitute the existing since 2013 PL-ETRF2000 after replacing the GNSS equipment on 29 ASG-EUPOS stations and extending the network by 6 new permanent GNSS stations. The new solution determined by the team of WUT and GUGiK (Liwosz and Ryczywolski, 2016) was based on continuous observations of GPS and GLONASS satellites at ASG-EUPOS stations, collected in daily sessions between 17 April 2011 and 31 December 2014 (3.7 years, 1355 daily sessions). GNSS data were processed according to the guidelines for the EPN Analysis Centres[2], and for the EUREF densification campaigns[3], using the latest version (5.2) of the Bernese GNSS Software, and in the latest reference framework IGb08/igs08.atx. The final solution (station coordinates and velocities) was expressed in ETRF2000 at epoch 2013.14. For the comparison with PL-ETRF2000, the new solution was expressed also at epoch 2011.0.

The new solution showed very good agreement with the PL-ETRF2000: position differences for most stations are below 5 mm, and 10 mm, in horizontal and vertical components, respectively. For 30 stations, however, discontinuities in position time series were observed, mostly due to GNSS equipment changes (for one station the origin of

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[2] http://www.epncb.eu/_documentation/guidelines/guidelines_analysis_centres.pdf.

[3] http://www.epncb.eu/_documentation/guidelines/Guidelines_for_EUREF_Densifications.pdf.

the discontinuity was unknown) which occurred after the introduction of PL-ETRF2000. Discontinuities were detected visually by inspecting position time series plots for individual stations. However, for EPN stations, the official EPN discontinuities were used. Discontinuities caused position changes reaching 9.1 mm and 26.9 mm in the horizontal and in the vertical components, respectively. In the new solution, in which six new stations which were installed after the introduction of the PL-ETRF2000 were included, the position discontinuities were taken into account. The new solution was planned to update the PL-ETRF2000, but eventually was not adopted.

The new solution was presented to the EUREF Technical Working Group (TWG) as the "EUREF Poland 2015" realization of the ETRS89 in Poland. It was accepted by the EUREF Symposium in Leipzig in 2015 as a class A solution (resolution No 2).

The PL-ETRF2000 and "EUREF Poland 2015" reference frames were also validated by Araszkiewicz et al. (2018). Both reference frames were compared with a weekly GPS solution computed for GPS week 1992 (11–17 March 2018). The results of comparison of the weekly solution with the "EUREF Poland 2015" solution showed very small differences for majority of ASG-EUPOS stations; increased residuals in the vertical component (1–5 cm) were noted for a few stations where GNSS equipment was changed. The comparison with PL-ETRF2000 showed larger coordinate differences. For most stations the differences the vertical component were between 2 and 5 cm. However, solutions in this comparison could not be expressed at the same epoch, because station velocities were not published in the PL-ETRF2000 solution.

7. Maintenance of the vertical control in Poland

Temporal variations of the gravity field caused by mass displacements in the Earth system result in variations of the reference surface for heights. They can be monitored with the use of data provided by satellite mission GRACE, dedicated to gravity field modelling. Re-definition of the vertical system conventionally used in geodesy which is based on a static geoid derived from constant, i.e. non varying in time gravity field, should be taken into consideration.

Suitability of GRACE-based geopotential models (GGMs) for modelling temporal variations of gravity functionals, including geoid heights, over Poland and surrounding areas were investigated. Temporal variations of terrestrial water storage (TWS) obtained from the 5th release GRACE-based GGMs provided by different computational centres were compared with the corresponding ones derived from hydrological models with the use of the principal component analysis (PCA) (Godah et al., 2015). The results obtained indicate the ability of the PCA method to extract a meaningful mass change signal related to the water mass variations, and in consequence – geoid height variations.

The impact of variations of geoid heights as well as vertical displacements of the Earth surface on the realization of a modern vertical reference system was investigated. A case study performed showed that within last 15 years geoid heights variations over the area of Poland reached the level of 1.1 cm (Godah et al., 2017a, 2017b). The precise geoid model for this area cannot any longer be a static one without considering temporal variations of geoid heights. The research conducted concerned also a possibility of prediction of geoid height variations using GRACE mission data over the area of Poland. Temporal geoid height variations can be predicted for a few months at 1 mm accuracy level. However, unusual change in seasonal and long term/trend components of temporal geoid height variations may cause large (2.3 mm in the investigated case) discrepancy between predicted and observed temporal geoid height variations (Godah et al., 2017a). GRACE mission products were also used to determine temporal vertical displacements induced from temporal water variations at Borowa Gora Observatory. The results of a case study for the area of Poland show that the combination of temporal geoid height variations and temporal vertical displacements of the physical surface of the Earth result in significant temporal variations of the vertical reference system (Godah et al., 2017b).

Similar research was performed for Central Europe (Godah et al., 2017c). It was shown that physical height changes as a combination of temporal variations of height anomalies and vertical displacements reach up to 22.8 mm over the selected study area. They can be modelled with the accuracy of 1.4 mm using the seasonal decomposition method. The models developed using the PCA/EOF method fit quite well (89.5%–96.5% in terms of correlations) to the corresponding values determined from GRACE mission. An essential role played by physical height changes estimated using GRACE mission data for the modernization of the vertical reference system over the area investigated was shown.

7.1. Conversion from the PL-KRON86-NH reference frame to PL-EVRF2007

The need of conversion from the PL-KRON86-NH reference system (the normal height system with a geoid passing through a zero of tide gauge in Kronstadt) to the European Vertical Reference Frame 2007 (PL-EVRF2007) is the result of the implementation of the resolution 5 of the EUREF Symposium in Tromso in 2000. PL-EVRF2007 is a kinematic height system referenced to the Amsterdam reference level. The system will be in force in Poland no longer than until the end of 2019 in accordance with the Regulation of the Council of Ministers of 15 October 2012 (Regulation, 2012). GUGiK has developed and made available appropriate numerical models enabling suitable conversion between these systems. The model of height differences between PL-EVRF2007-NH and PL-KRON86-NH was developed and publish by GUGiK[4]. The numerical model of the quasigeoid PL-geoid-2011 is also available[5].

A detailed description of both aforementioned models is provided on the GUGiK website. The above data models were created on the basis of the regular reference grid of $0.01^\circ \times 0.01^\circ$ for the area φ (49.00° N – 55.00° N) and λ (14.00° E – 24.20° E), however, the data values of individual models are available on the nodes within the borders of Poland including the buffer of about 5 km from the border on the territories of neighbouring countries[6].

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[4] http://www.gugik.gov.pl/__data/assets/text_file/0016/1843/gugik-evrf2007.txt.

[5] http://www.gugik.gov.pl/__data/assets/text_file/0017/1844/gugik-geoid2011.txt.

[6] http://www.gugik.gov.pl/_data/assets/pdf_file/0014/1841/Opis-modeli-danych.pdf.

Research on the transformation between Polish vertical reference frames has been conducted in the Department of Geodesy and Geotechnics, Faculty of Civil and Environmental Engineering and Architecture, RUT (Kadaj and Swieton, 2016). Universal software TRANSPOL v.2.06 for the transformation was published as an open product. An essential functional element of the program is the quasigeoid model PL-geoid-2011, which has been developed by fitting the quasigeoid model derived from EGM2008 to 570 satellite/levelling points.

8. Maintenance and modernization of the gravity control

Maintenance and modernization of national gravity control were subjects of extensive activities in Poland. The team of IGiK took part in the modernization of national gravity control Sweden, Denmark, Republic of Ireland and Northern Ireland, performing the absolute gravity survey at the points of 1st order gravity networks with the use of the A10-020 gravimeter. The establishment and modernization of national gravity control in several European countries by the IGiK team with the use of the A10-020 absolute gravimeter was extensively summarized and a number of practical recommendations were given (Dykowski et al., 2018).

8.1. Maintenance and modernization of the gravity control in Poland

The existing gravity control in Poland established in 2012–2013 by the GUGiK consists of exclusively absolute gravity stations (Figure 3): fundamental stations (blue triangles) located in buildings, and surveyed with the FG5-type gravimeters with the uncertainty

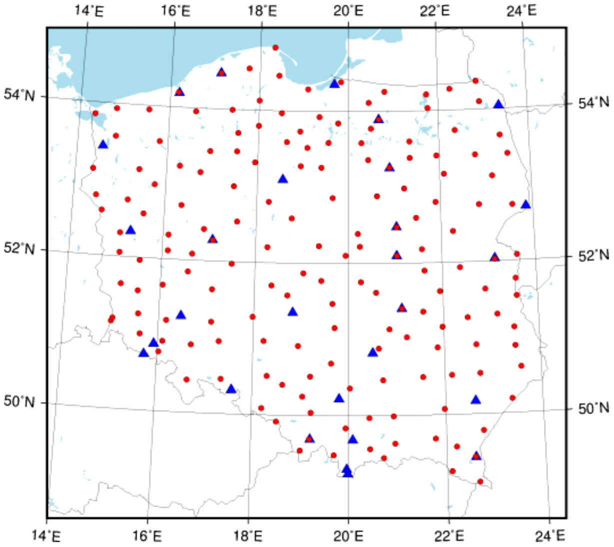

Fig. 3. Stations of the new gravity control in Poland (2016)

level of 0.004 mGal, and base stations (red dots) – field stations – surveyed with portable A10-type gravimeters with the uncertainty level of 0.010 mGal. Fundamental stations of the gravity control (28 stations; one in 15 000 km^2) were surveyed by the team of the WUT with the FG5-230 gravimeter while base stations (168 stations, one in 1850 km^2) – by the team of IGiK, with the A10-020 gravimeter (Bosy and Krynski, 2015). The integral part of the gravity control in Poland are gravimetric calibration baselines, including two vertical baselines – one in Tatra Mountains and the other in Sudety Mountains.

Quality of the new gravity control in Poland, represented by base stations (PBOG14), was assessed. Gravity of the Polish Gravity Control Network POGK98, established in 1993–1998, was compared at 77 control stations with the respective ones recently determined on the base stations (Figure 4). Estimated differences range from −37.6 µGal to 54.3 µGal while the average value equals 12.3 µGal with the standard deviation of 18.1 µGal. The histogram of the differences is presented in Figure 5. Due to known issues regarding the realization of POGK98 estimated differences should not be interpreted directly as gravity change (Dykowski et al., 2015).

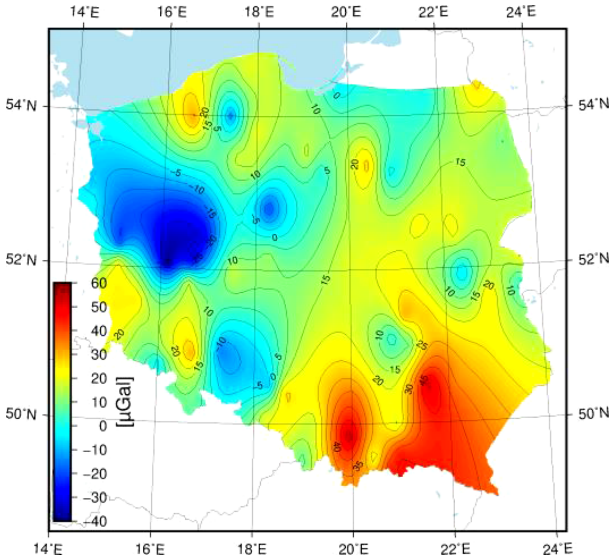

Fig. 4. Differences between PBOG14 and POGK98; black dots mark the POGK98 stations used for the comparison

Absolute gravity determinations are neither affected by common relative measurement errors nor by effects of network adjustment. For the establishment of gravity control they require, however, a number of corrections, i.e. tidal and ocean loading corrections, atmospheric corrections and hydrological corrections. It should be noted that those corrections were not considered when establishing the recent gravity control in Poland. Currently available services and software allow to determine corrections for atmospheric (based on digital weather models, e.g. ECMWF), hydrological (based on hydrological models, e.g. GLDAS/Noah), gravitational and loading effects of high accuracy and high

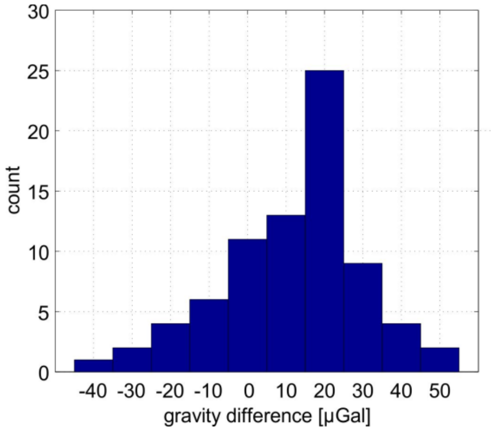

Fig. 5. Histogram of the differences between PBOG14 and POGK98

temporal resolution. Those corrections are recently mostly applied when processing high precision observations with superconducting gravimeters in the International Geodynamics and Earth Tide Service (IGETS). The research conducted shows that for the area of Poland the atmospheric correction based on weather models can differ even by ±2 μGal from the standard atmospheric correction. The hydrological model exhibits the annual variability of ±8 μGal. In addition, the standard tidal correction may substantially differ from the one obtained from the local tidal model (based on tidal records), e.g. up to ±1.5 μGal at the Borowa Gora Observatory. Atmospheric and hydrological effects together with uncertainty of tidal model easily exceeds the total uncertainty of the A10-020 free-fall gravimeter. Taking into consideration those effects is thus vital for current and future absolute gravity determinations for the needs of the gravity control (Dykowski and Krynski, 2015).

Quasi-regular monthly gravity surveys conducted on the stations of the gravimetric test network at the Borowa Gora Observatory, following the same observation strategy as used on PBOG14 stations, were applied to assess the quality of the A10-020 gravimeter during the course of the establishment of the new gravity control in Poland. The standard deviation of those determinations equal to 5.8 μGal was used as a component of the total uncertainty value for PBOG stations. Additionally, the hydrological correction (monthly solutions) obtained from GLDAS model (blue dots) were compared with absolute gravity data at Borowa Gora Observatory. Estimated correlation of 0.58 indicates sensitivity of the A10-020 gravimeter to large scale hydrological variations. It was shown that GLDAS hydrological model correction should necessarily be considered for detailed analysis of the results in the PBOG14 (Dykowski et al., 2015).

Multiple additional activities were performed to maintain the gravity control in Poland, in particular to ensure and provide a reliable gravity reference level. They concerned quasi-regular gravity measurements with the A10-020 gravimeter on the test network at the Borowa Gora Observatory, calibrations of the components of the A10-020 gravimeter, participation with the A10-020 gravimeter in the international (ECAG2015), and regional (EURAMET2018) comparison campaigns of absolute gravimeters as well as in local comparisons with the FG5-230 (Krynski and Rogowski, 2015, 2016, 2017, 2018), and scale factor calibrations of LCR gravimeters. A strong annual residual signal with a peak to peak variation of 200 nm/s^2, associated mainly with hydrology is observed in gravity measurements evaluated with a standard set of corrections. The use of selected models of corrections for absolute gravity measurements was discussed taking into consideration data from global hydrological models and from local hydrological sensors. With those models gravity variations observed with the A10-020 gravimeter were evaluated. Gravity changes due to hydrology were evaluated for the area of Poland and methodology of data elaboration was recommended (Dykowski and Krynski, 2017).

8.2. Modernization of gravity control in Sweden

The team of IGiK with the A10-020 gravimeter took part in re-measuring the First Order Gravity Network in Sweden within the project of establishing the new gravity reference frame RG 2000 for Sweden. The epoch of RG 2000 is 2000.0, which corresponds well with the epochs of the national height system, RH 2000 and the national 3D system, SWEREF 99. In five field campaigns conducted in 2011, 2012, 2013, and 2015, gravity was determined with the A10-020 gravimeter at 98 sites densifying the gravity reference frame for Sweden primarily based on the FG5 observations. Results of the RG 2000 adjustment were presented (Engfeldt et al., 2018). It has been concluded that future gravity reference frames should be based on absolute gravity measurements with absolute instruments periodically verified for their consistency with international gravity reference level. The data acquired with the A10-020 at the sites of RG 2000 are available in the International Absolute Gravity Database (AGrav) of IAG.

8.3. Modernization of gravity control in Denmark

The IGiK team took part in the project concerning modernization of gravity control in Denmark. In September 2018 eight gravity stations were re-surveyed with the A10-020 by the team of IGiK.

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

The team of IGiK was involved in the establishment of the national gravity control in Ireland (Republic of Ireland and Northern Ireland). The project of the new gravity control in Ireland consisting of the design structure, localization of the stations, accuracy requirements and observation strategy was developed by IGiK in 2017. It is based on the concept that the gravity at all its stations will be determined based on absolute gravity measurements, namely with the use of the A10-type absolute gravimeter. Gravity stations homogenously distributed over the island were chosen after extensive studies and field reconnaissance, and monumented when necessary The project of the national gravity control in Ireland (Absolute Gravity Network – AGN) has been accepted by the Ordnance Survey Ireland (Republic of Ireland) and Land and Property Services (Northern Ireland) in the autumn 2017. According to the current design AGN consists of 62 stations (Figure 6). Above 20 stations are co-located with the stations of permanent active GNSS network for the island of Ireland. In total there are 50 so-called network stations (located outdoors). In order make possible to transform gravity from the existing IGSN71 system to the newly established gravity system seven gravity stations that defined IGSN for Ireland were incorporated to the AGN project. The traverse consisting of 6 stations of AGN running from north to south of the island forms the gravimetric calibration baseline (stations located indoors).

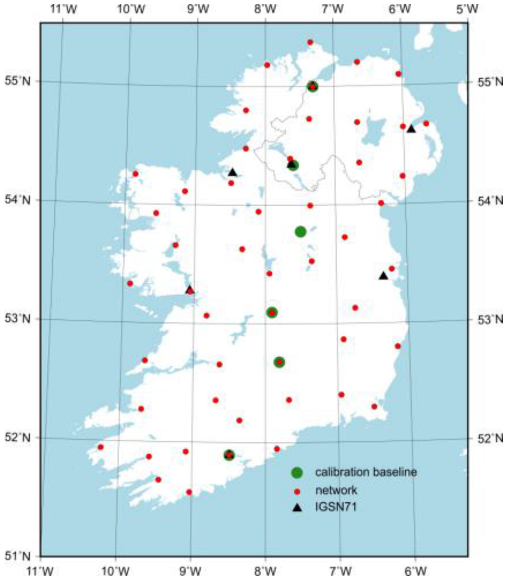

Fig. 6. Design of the Absolute Gravity Network in Ireland

The realization of the project concerning the establishment of a new gravity control in Ireland started in mid 2018. First campaign of gravity survey with the A10-020 absolute gravimeter of IGiK was conducted in September 2018, and included 26 stations.

9. Maintenance of the magnetic control in Poland

The magnetic control in Poland consists of 19 repeat stations (Figure 7) which are surveyed and maintained by IGiK. At each repeat station three independent components of the intensive vector of the geomagnetic field were measured, at first every 2÷4 years following the rules of the Magnetic Network of Europe (MagNetE) of the International Association of Geomagnetism and Aeronomy (IAGA) of the International Union of Geodesy and Geophysics (IUGG). Starting from 1970, the survey is performed roughly every 2 years. During each survey magnetic stations marks are controlled. When necessary, the benchmarks are displaced to the other site. At the new location of the station a special procedure is applied to ensure the continuity of observations.

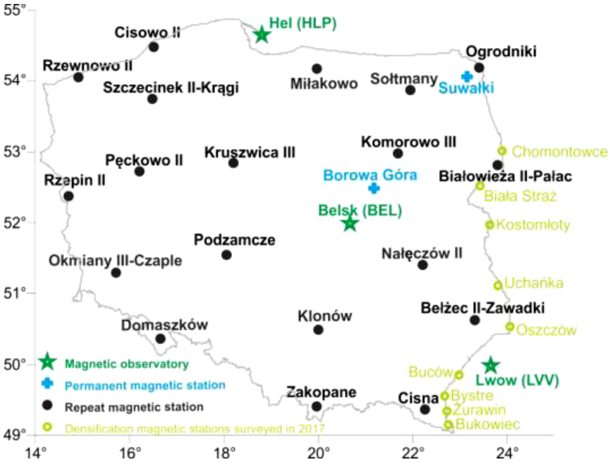

Fig. 7. Polish magnetic repeat station network 2018

Data from the observatories operating in the framework of the global international network of magnetic observatories monitoring the Earth's magnetic field INETRMAGNET, i.e. two Polish magnetic observatories run by IGF PAS: Central Geophysical Observatory in Belsk and Magnetic Observatory in Hel as well as from magnetic observatories of neighbouring countries (Figure 7) are also used for the determination of secular variations of the geomagnetic field in Poland (Welker et al., 2015).

Two permanently operating magnetic stations (Figure 7): Borowa Gora of IGiK, and Suwalki of IGF PAS provide additional data used to control magnetic surveys in Poland (Welker and Reda, 2016).

Magnetic declination D, magnetic inclination I and the module of the magnetic intensity vector F, acquired at the magnetic repeat stations, reduced using data from magnetic observatories of the INTERMAGNET network are applied to calculate X, Y, Z components of the magnetic intensity vector at those stations. The results of magnetic data processing are submitted to the magnetic database of IGiK and to the World Data Centre for Geomagnetism in Edinburgh, UK, on a regular basis.

The Polish magnetic repeat station network is improved continuously (Krynski and Rogowski, 2016, 2017, 2018) following the European standards determined by MagNetE. Polish magnetic repeat stations surveyed in the years 2015–2018 are listed in Table 3. In 2017, in addition, at 9 densification magnetic stations (Figure 7) three independent components of the magnetic intensity vector were surveyed (Krynski and Rogowski, 2018). The coordinates of the magnetic repeat stations were determined in the PL-ETRF2000 reference frame, and normal heights in the PL-KRON86 frame.

A need for repeating geomagnetic measurements on the Baltic Sea was indicated (Welker, 2015b; Krynski and Rogowski, 2016). The progress in the development of

Table 3. Polish magnetic repeat stations surveyed in the years 2015–2018

No	Station name	2015	2016	2017	2018
1	Cisowo II			×	×
2	Ogrodniki	×		×	
3	Milakowo				
4	Rzewnowo II	×		×	×
5	Soltmany	×		×	
6	Szczecinek II	×		×	
7	Komorowo III			×	
8	Bialowieza II			×	
9	Kruszwica III	×		×	×
10	Peckowo II		×	×	
11	Rzepin II		×	×	
12	Podzamcze			×	×
13	Naleczow II	×	×	×	
14	Okmiany III		×	×	
15	Belzec II		×	×	
16	Klonow			×	
17	Domaszkow			×	×
18	Zakopane			×	
19	Cisna			×	

measuring instruments, both navigational and geophysical, seems to force the need and gives a possibility of acquiring more detailed geophysical data aiding the navigational systems. The geomagnetic field – both onshore and offshore – is complicated in terms of its distribution, and variable in time. Precise knowledge of the secular variations of the geomagnetic field in the area of interest is thus essential. Establishing (re-establishing) a marine network of repeat magnetic points (repeat stations) on the Baltic Sea and regular magnetic measurements of the three independent components of the Earth's magnetic field is required. Such seaborne magnetic survey requires a very specific equipment that ensures not only high stability, but also information about sensors' orientation with respect to magnetic north and to the level. A new project of the network of magnetic repeat stations at the Baltic Sea with a solution for the instruments suitable for quasi-absolute seaborne magnetic measurements was presented (Welker et al., 2017).

10. Summary and conclusions

The paper presents the activities of Polish research and government institutions in the years 2015–2018 in the areas related to the implementation of global reference frames, integration of geodetic, gravimetric and magnetic observations for the realization and maintenance of a unified reference frame and reference networks in Poland.

In the years 2015–2018, IGiK continued developing the Astronomical Almanac series. The almanacs released for years 2015–2018 were in agreement with recent resolutions of the IAU and IUGG General Assemblies. Since the year 2015, the printed version of the almanac was reduced by removing tables of apparent places of stars in IRS system, positions of stars in ICRS as well as barycentric and heliocentric positions of the Earth, and the on-line version was developed instead. In the new version of the Astronomical Almanac, for the year 2019, the resolutions from the IAU XXIX (Honolulu, 2015) and XXX (Vienna, 2018) General Assemblies were implemented, which include, e.g., changes in astronomical constants or the adoption of the ICRF3.

In 2015, noting the GNSS equipment changes on 29 ASG-EUPOS stations and the installation of 6 new stations, the new GNSS solution was developed to update the existing ETRS89 realization in Poland (PL-ETRF2000) which showed very good agreement with the PL-ETRF2000. For most stations position differences did not exceed 5 mm in the horizontal, and 10 mm in vertical components. However, discontinuities were observed in time series of positions for 30 stations, mostly due to GNSS equipment changes, which occurred after the introduction of PL-ETRF2000. Position changes due to the discontinuities reached 9.1 mm in the horizontal components, and 26.9 mm in the vertical component. The change of the GNSS equipment on approximately 80% of ASG-EUPOS stations in years 2014–2018 causes the need for updating the existing realization of ETRS89 (PL-ETRF2000) with the new solution in the near future.

Eighteen Polish permanent GNSS stations continued collecting observations within the international IAG services: EUREF and IGS (6 of 18 stations). Also, in 2015, the only SLR station in Poland (BORL at Borowiec) resumed laser measurements within the International SLR Service (ILRS) after the 5-year break. In April 2016, after successful completing a quarantine mode, the BORL SLR station became again a fully operational ILRS station.

Geoid height variations and vertical displacements of the Earth surface were investigated using GRACE mission data in the context of the realization of a modern vertical reference system. A case study for Poland was conducted. The geoid height over the area of Poland vary at least within 1.1 cm which has to be considered when defining the geoid model of 1 cm accuracy for this area.

The impact of non-tidal atmospheric loading, hydrological loading as well as tidal and non-tidal ocean loading on the absolute gravity determinations was investigated. The atmospheric correction based on weather models can differ from standard atmospheric correction even by ±2 μGal for the area of Poland. The hydrological model exhibits the annual variability of ±8 μGal. Atmospheric and hydrological effects together with tidal model uncertainty easily exceed total uncertainties of gravimeters used for the gravity determination in Poland. It makes those effects vital for current and future absolute gravity determinations for the needs of the gravity control.

Magnetic control in Poland is continuously maintained. Due to strong variability of the Earth' magnetic field, magnetic control in Poland is re-surveyed (approximately every two years) on regular basis which ensures availability of actual parameters describing secular variations of that field. In years 2015–2018, 19 magnetic repeat stations and 9 densification stations were surveyed at least once. The need for repeating the magnetic measurements on the Baltic Sea was also indicated.

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