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# Preface

Wide range of activities carried on by the International Union of Geodesy and Geophysics (IUGG) and its Associations, in both organizational and research fields, is reported at IUGG General Assemblies regularly organized every 4 years. On the other hand, results of research from individual countries – IUGG members – are traditionally presented either to IUGG or to the Associations for the current IUGG General Assembly.

National Committee for the International Union of Geodesy and Geophysics, affiliated by the presidium of the Polish Academy of Sciences (PAS), is the adhering organization representing Poland to IUGG and its Associations. As such, the National Committee for IUGG coordinates the flow of information in both directions between IUGG and the respective Polish scientific community. For a number of decades the reports on activities on geodesy in Poland in the quadrenium were presented to the International Association of Geodesy (IAG) by the Committee on Geodesy of the Polish Academy of Sciences on the request of the Polish National Committee for IUGG.

In 2003 IAG established the Global Geodetic Observing System (GGOS). The GGOS is the component of IAG dedicated to providing the geodetic infrastructure necessary for monitoring the Earth system and for global change research. Polish research institutions providing geodetic observations in the framework of the IAG services (including GGOS) have signed in 2011 an agreement on the establishment of research network GGOS-PL integrating research activity of seven Polish observatories.

The Committee on Geodesy of PAS appointed three editors of the recent Polish National Report on Geodesy Prof. Jaroslaw Bosy, Prof. Jan Krynski and Prof. Pawel Wielgosz entrusting them simultaneously coordination of works on the report. This report has been prepared for submission to the IAG at its General Assembly in Montreal, Canada, during the 27th IUGG General Assembly, 8–18 July 2019. It consists a summary of research activity in geodesy performed in a period of 2015–2019 in Poland, mostly within the GGOS-PL components.

The Polish National Report on Geodesy 2015-2019 is in the form of the six peer-reviewed review papers (chapters):

1. Reference Frames and Reference Networks (Jan Krynski, Jerzy B. Rogowski and Tomasz Liwosz);
2. Gravity Field Modelling and Gravimetry (Jan Krynski, Przemyslaw Dykowski and Tomasz Olszak);
3. Earth Rotation and Geodynamics (Aleksander Brzezinski, Janusz Bogusz and Jolanta Nastula);
4. Positioning and Applications (Pawel Wielgosz, Tomasz Hadas, Anna Klos and Jacek Paziewski);

5. Global Geodetic Observing Systems (Krzysztof Sosnica and Jaroslaw Bosy);
6. General Theory and Methodology (Andrzej Borkowski, Wieslaw Kosek and Marcin Ligas);

which were developed in cooperation with the researchers from the following universities and research institutes:

– AGH University of Science and Technology in Krakow;
– Gdansk University of Technology;
– Institute of Geodesy and Cartography in Warsaw;
– Military University of Technology in Warsaw;
– Space Research Centre of the Polish Academy of Sciences in Warsaw;
– University of Agriculture in Krakow;
– University of Warmia and Mazury in Olsztyn;
– Warsaw University of Technology;
– Wroclaw University of Environmental and Life Sciences.

The report is published in the Geodesy and Cartography, the official journal of the Committee on Geodesy of the Polish Academy of Sciences. The editors thank the authors of all articles (chapters), reviewers and all those who contributed to develop the final form of the report.

*Jaroslaw Bosy, Jan Krynski* and *Pawel Wielgosz*
Editors of the Report

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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

## 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 4$^{th}$ 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 1$^{st}$ 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).

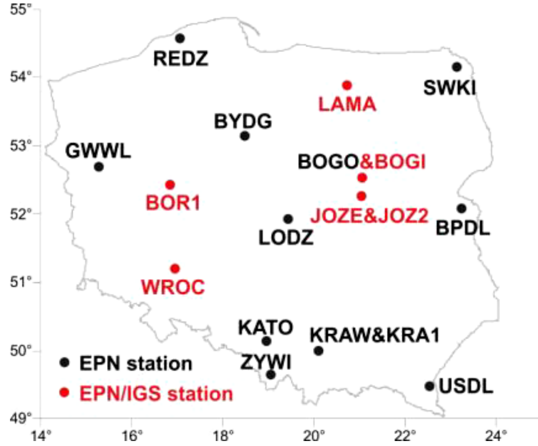


Fig. 1. Permanent GNSS EPN/IGS stations in Poland (2018)

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.

[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

[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 5$^{th}$ 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 $\varphi$ ($49.00^\circ$ N – $55.00^\circ$ N) and $\lambda$ ($14.00^\circ$ E – $24.20^\circ$ 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].

[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

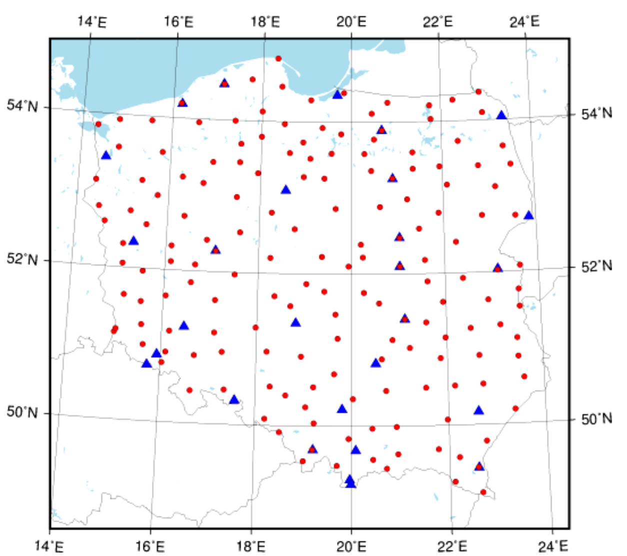


Fig. 3. Stations of the new gravity control in Poland (2016)

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).

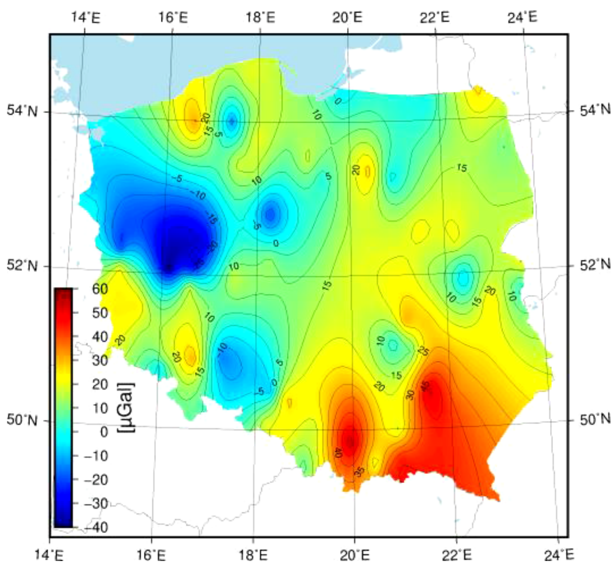


Fig. 4. Differences between PBOG14 and POGK98; black dots mark the POGK98 stations used for the comparison

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

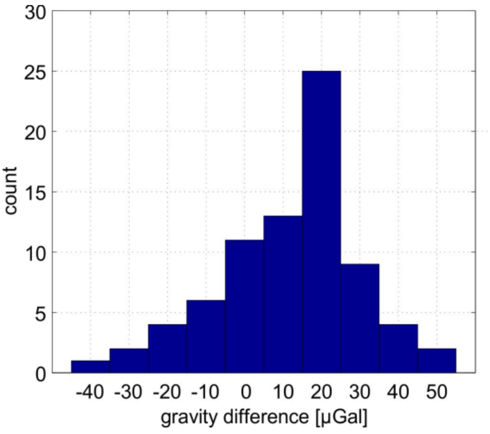


Fig. 5. Histogram of the differences between PBOG14 and POGK98

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 $\pm 2$ μGal from the standard atmospheric correction. The hydrological model exhibits the annual variability of $\pm 8$ 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 $\pm 1.5$ 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).

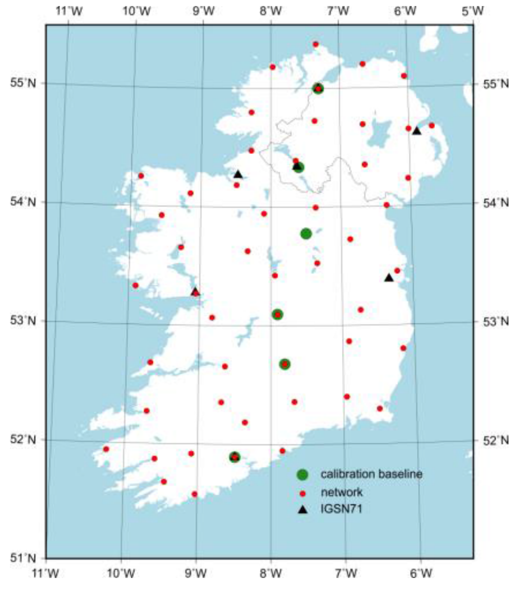


Fig. 6. Design of the Absolute Gravity Network in Ireland

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 $\pm 2$ μGal for the area of Poland. The hydrological model exhibits the annual variability of $\pm 8$ 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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***Review paper***

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

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

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

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## 1. Introduction

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

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

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

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

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

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

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

### *2.1. Evaluation of GOCE-based GGMs*

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

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

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

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

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

### 2.2. Geoid modelling

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

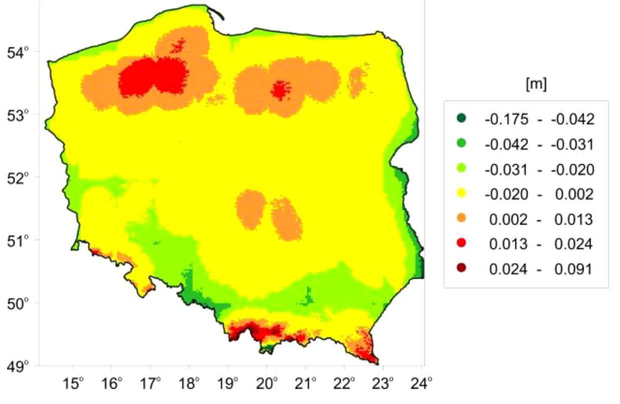


Fig. 1. Comparison of the GDQM-PL13 model with the GDQ08 model (Szelachowska and Krynski, 2014)

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

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

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

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

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

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

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

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

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

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

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

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

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

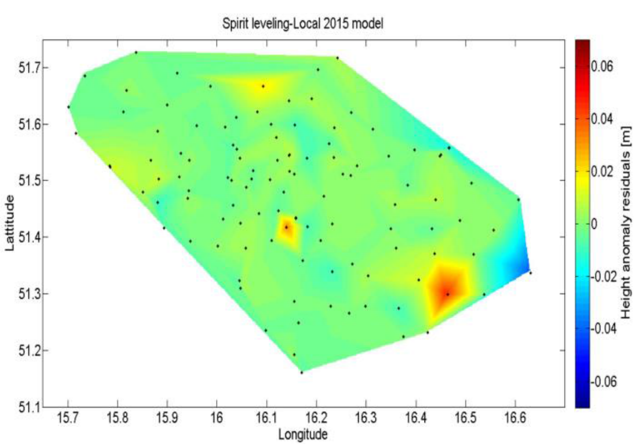


Fig. 2. Height anomaly residuals of the LGOM 2015 model (Stepniak et al., 2017)

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

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

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

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

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

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

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

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

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

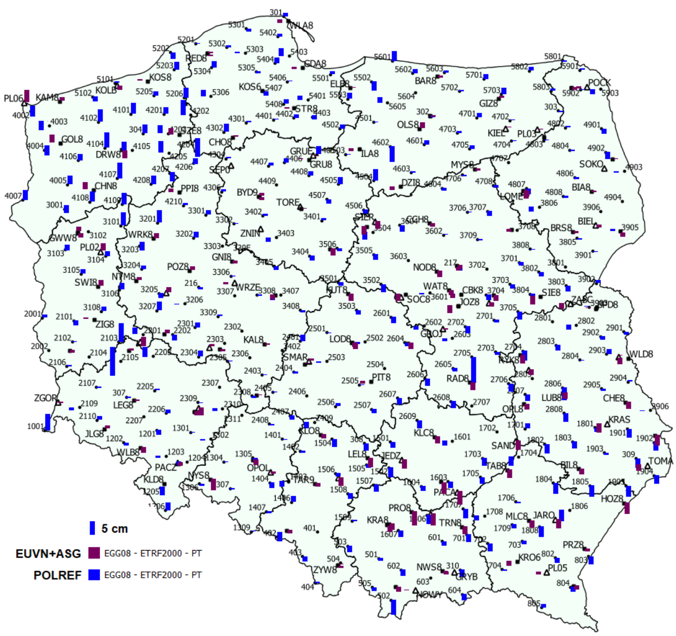


Fig. 3. Differences between height anomalies obtained from satellite/levelling data and the respective ones computed from EGG2008 gravimetric quasigeoid model (ellipsoidal heights in the zero tidal system)

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

## 3. Absolute gravity surveys

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

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

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

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

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

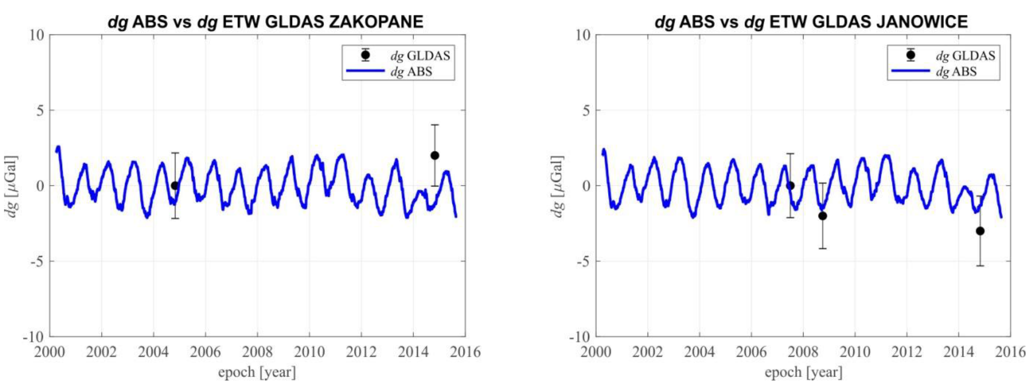


Fig. 4. Absolute gravity changes at Zakopane and Janowce stations with the gravity effect caused by the global hydrology changes derived from the GLDAS_NOAH10_M model

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

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

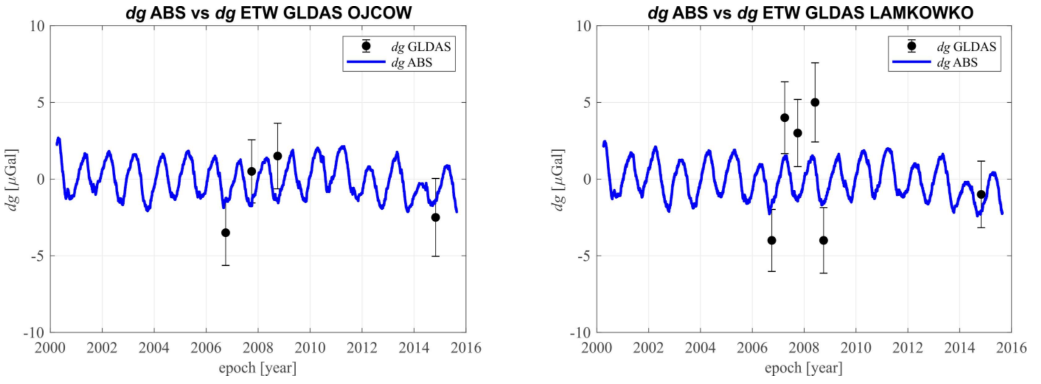


Fig. 5. Absolute gravity changes at Ojcow and Lamkowko stations with the gravity effect caused by the global hydrology changes derived from the GLDAS_NOAH10_M model

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

### *3.2. Absolute gravity surveys for gravity control maintenance in Europe*

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

#### *3.2.1. Sweden*

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

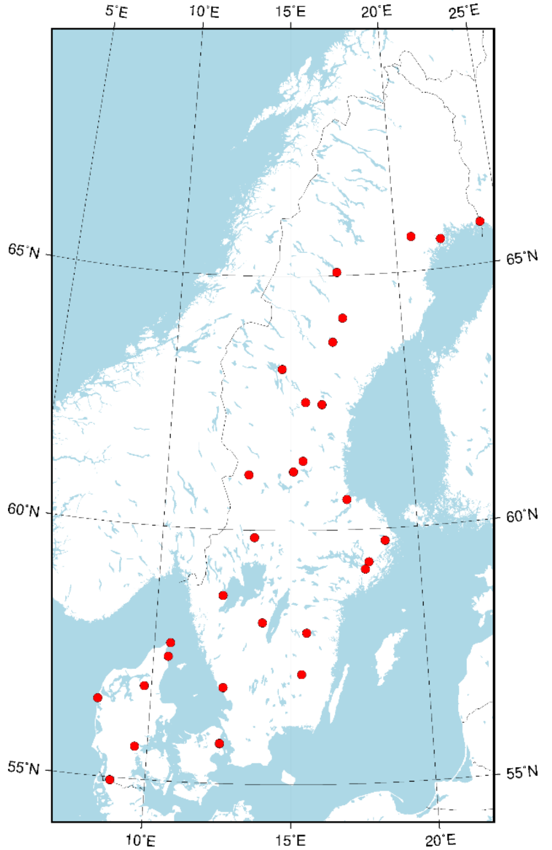


Fig. 6. Stations where absolute gravity was surveyed with the A10-020 in Sweden (2015) and Denmark (2018)

### 3.2.2. Denmark

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

### 3.2.3. Republic of Ireland and Northern Ireland

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

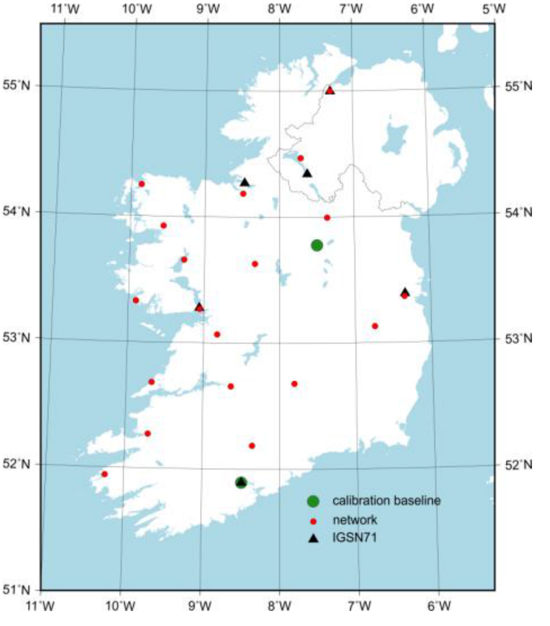


Fig. 7. Gravity stations surveyed in 2018 in the Republic of Ireland and Northern Ireland in the framework of the AGN Ireland Project

### 3.3. Absolute gravity surveys for geodynamic research

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

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

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

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

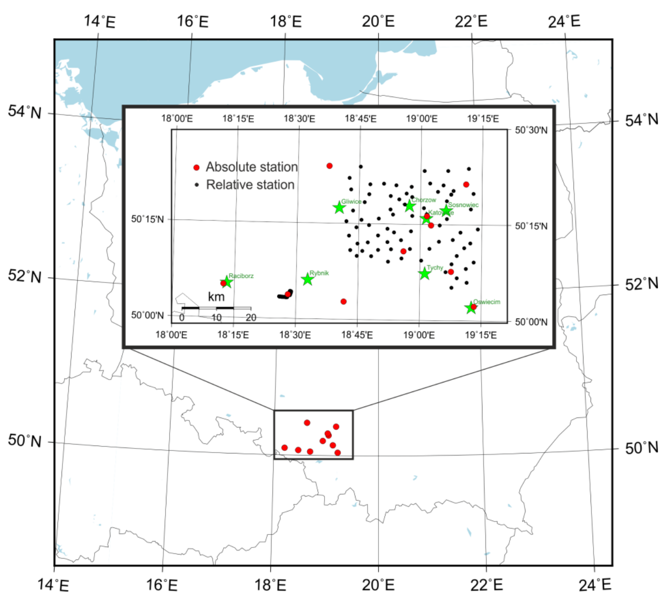


Fig. 8. Gravity stations surveyed within EPOS-PL project at MUSE polygons

### 3.4. Metrological aspects in absolute gravimetry

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

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

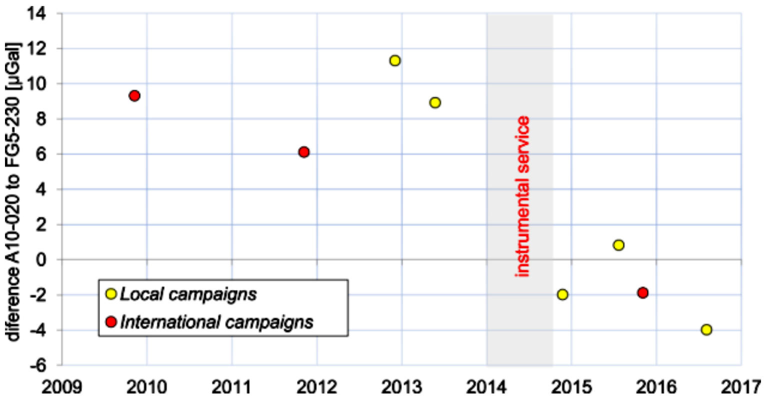


Fig. 9. Results of local comparisons of the A10-020 and FG5-230 absolute gravimeters

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

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

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

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

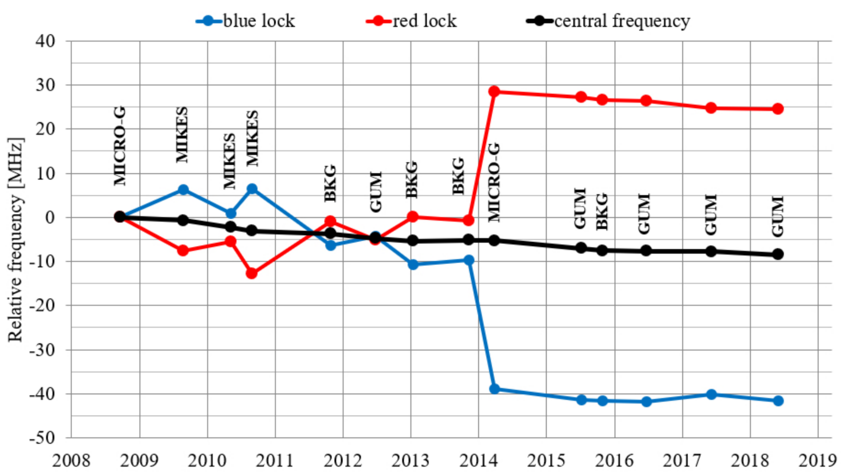

Fig. 10. Results of calibrations of the laser of the A10-020 gravimeter 2009–2018

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

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

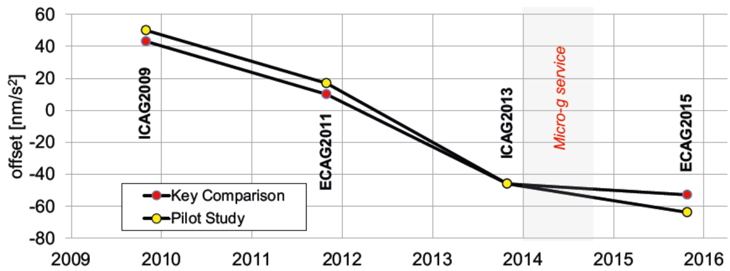


Fig. 11. Offsets of the A10-020 gravimeter during the International Comparison of Absolute Gravimeters Campaigns

### *3.5. Metrological aspects in relative gravimetry*

#### *3.5.1. Polish Gravimetric calibration baseline maintenance*

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

#### *3.5.2. Scale factor determination for continuous gravimetric records*

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

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

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

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

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

## 4. Investigations of non-tidal gravity changes

### *4.1. Monitoring of long term gravity variations in gravimetric laboratories*

#### *4.1.1. Monitoring program in Borowa Gora*

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

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

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

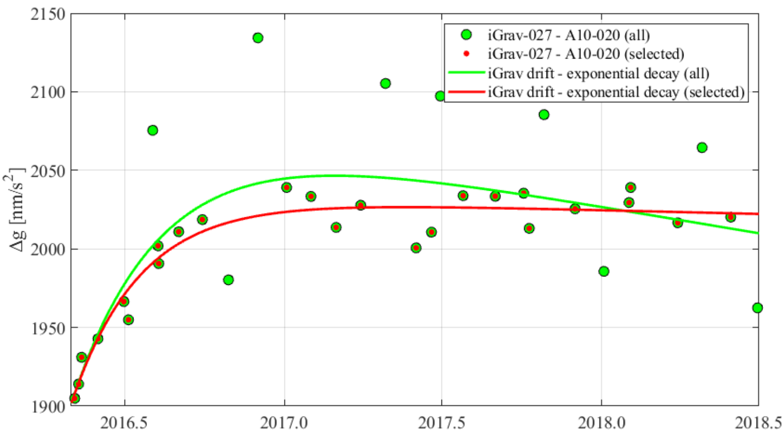


Fig. 12. iGrav-027 drift evaluation over the first 26 months of operation

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

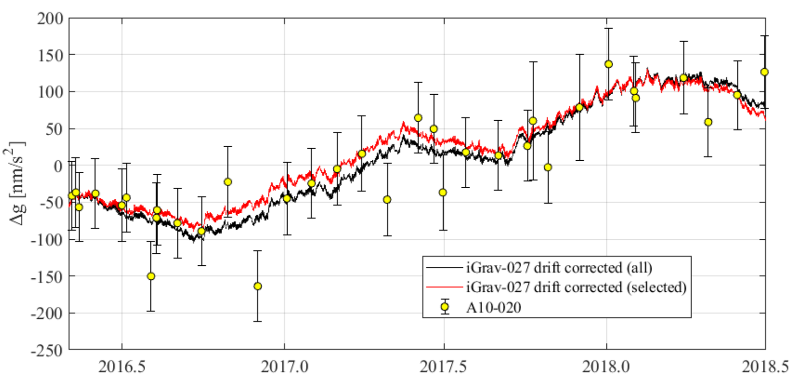


Fig. 13. Combined A10-020 and iGrav-027 records (after drift removal)

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

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

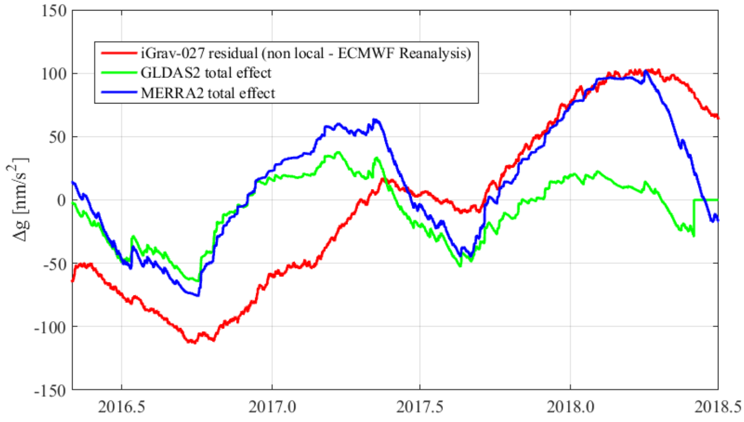


Fig. 14. iGrav-027 residual (red) compared with hydrological loading effect from GLDAS2 (green) and MERRA2 (blue)

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

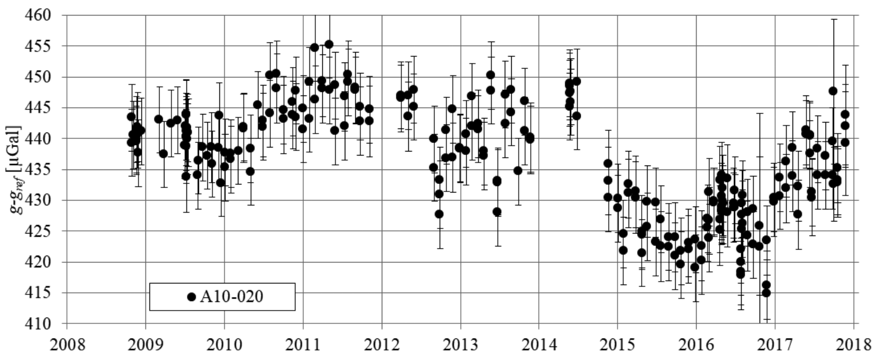


Fig. 15. Time series of A10-020 gravity determinations at BG-G2 station; $g_{ref} = 981\,250\,000$ µGal

### *4.1.2. Monitoring program in Jozefoslaw*

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

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

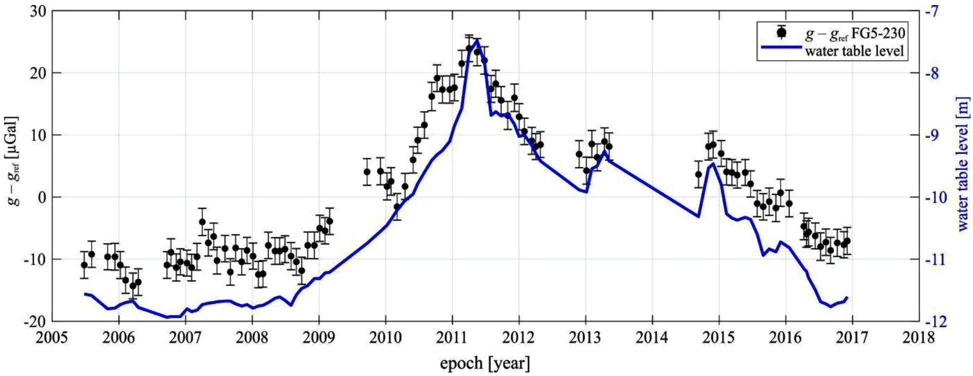


Fig. 16. Time series of absolute gravity and water table level (piezometer) measurements in the Jozefoslaw Astrogeodetic Observatory; $g_{\mathrm{ref}} = 981\,213\,780$ μGal

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

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

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

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

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

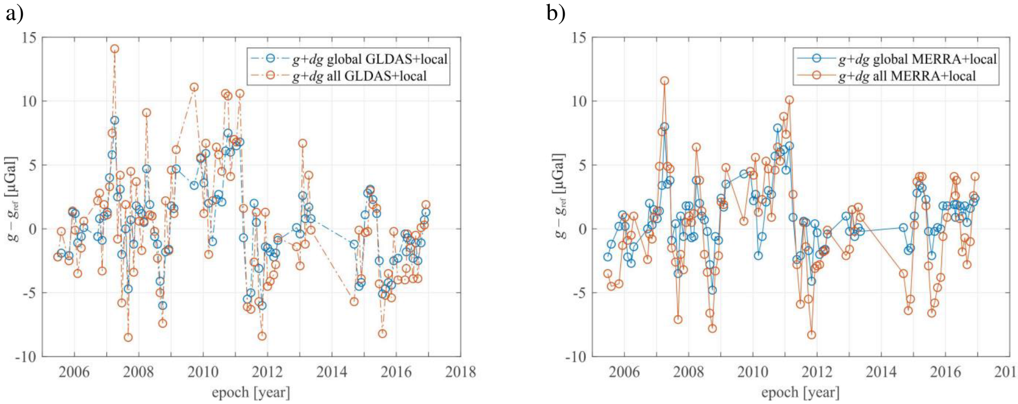


Fig. 17. Gravity series corrected for the effect of hydrology using global GLDAS (a) and MERRA (b) models and local water table changes; $g_{\mathrm{ref}} = 981\,213\,780$ μGal

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

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

<table>
<tr><th rowspan="2">Statistics</th><th rowspan="2">$g$ not corrected</th><th colspan="2">GLDAS model</th><th colspan="2">MERRA model</th></tr>
<tr><th>$g+dg_G+dg_{\mathrm{local}}$</th><th>$g+dg_A+dg_{\mathrm{local}}$</th><th>$g+dg_G+dg_{\mathrm{local}}$</th><th>$g+dg_A+dg_{\mathrm{local}}$</th></tr>
<tr><td>Mean ($g - g_{\mathrm{ref}}$)</td><td>788.8</td><td>780.3</td><td>780.3</td><td>780.9</td><td>780.3</td></tr>
<tr><td>Std</td><td>10.2</td><td>3.2</td><td>4.6</td><td>2.4</td><td>4.1</td></tr>
<tr><td>Max-Min</td><td>37.5</td><td>14.5</td><td>22.5</td><td>12.7</td><td>19.8</td></tr>
</table>

### *4.2. Temporal variations of the gravity field from GRACE data*

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

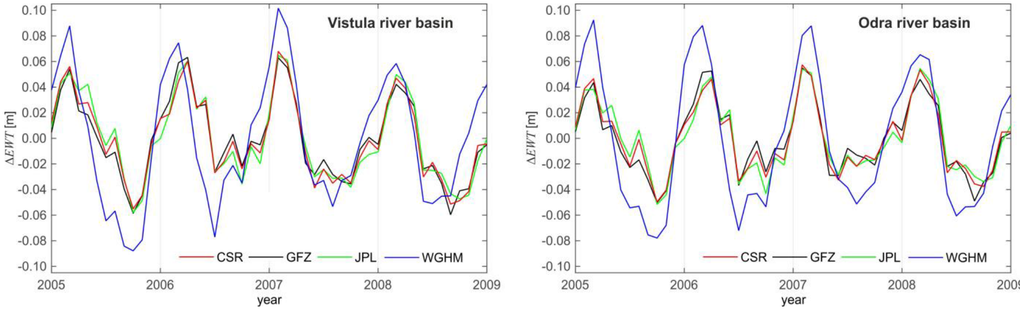


Fig. 18. Time series of equivalent water thickness variations $\Delta EWT$(WGHM) and $\Delta EWT$(GRACE) for the Vistula river basin and the Odra river basin; the DDK1 filter was applied to obtain $\Delta EWT$(GRACE) (Godah et al., 2015c)

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

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

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

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

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

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

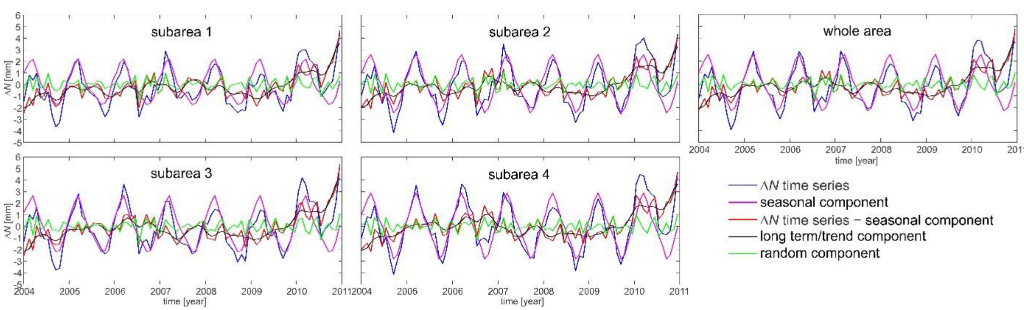


Fig. 19. Temporal geoid height variations and their components obtained with the use of SD method

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

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

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

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

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

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

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

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

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

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

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

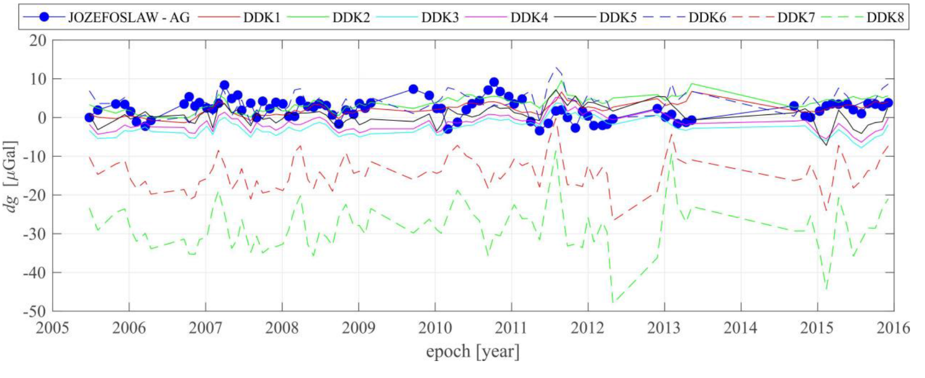


Fig. 20. Differences between variations of absolute gravity determined with the FG5-230 at Jozefoslaw and gravity variations from GRACE-based GGMs provided by CSR

## 5. Contribution of gravimetric records to seismic studies

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

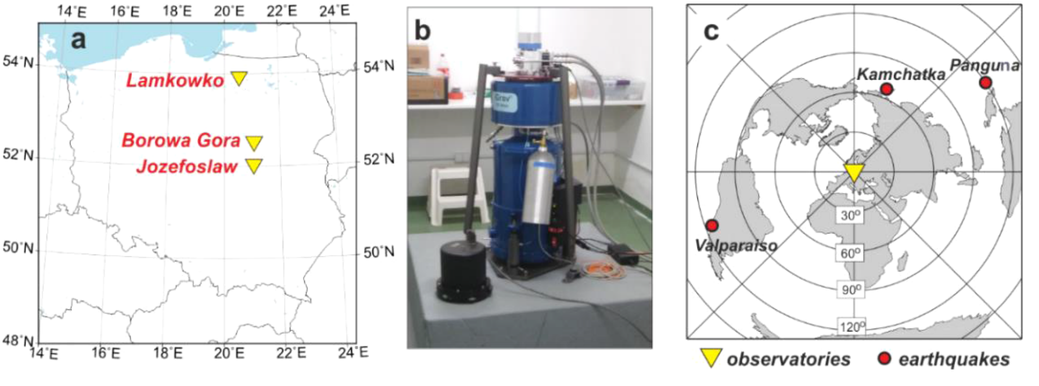


Fig. 21. (a) Location of observatories (yellow triangle); (b) the iGrav-027 superconducting gravimeter (blue instrument) at BG and the REF-TEK Observer 151B-120 seismometer (black instrument) during the operation time; (c) location of epicenters of analyzed earthquakes

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

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

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

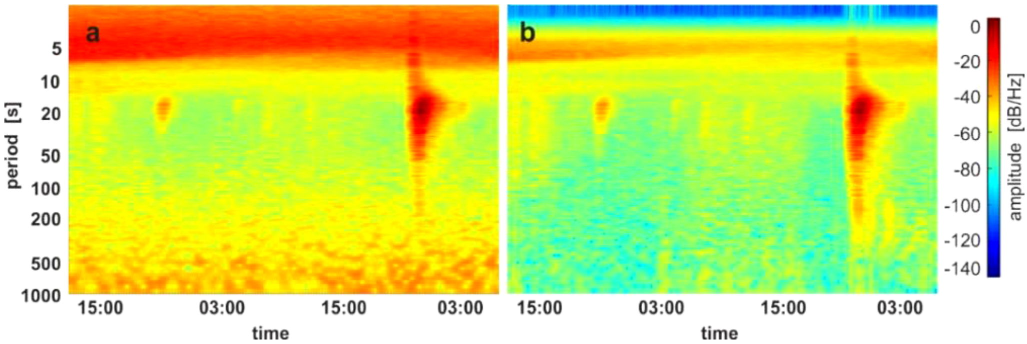


Fig. 22. Spectrograms of the M6.9 Valparaiso earthquake: (a) seismic station B941 (BG); (b) superconducting gravimeter iGrav-027 (BG); Each record was normalized with the maximum amplitude range of the event

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

## 6. Summary and conclusions

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

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

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

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

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

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

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*Review paper*

# Research on Earth rotation and geodynamics in Poland in 2015–2018

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**Abstract:** This paper summarizes the activity of the chosen Polish geodetic research teams in 2015–2018 in the fields of Earth: rotation, dynamics as well as magnetic field. It has been prepared for the needs of the presentation on the 27$^{\text{th}}$ International Union of Geodesy and Geodynamics General Assembly, Montreal, Canada. The part concerning Earth rotation is mostly focused on the use of modelling of diurnal and subdiurnal components of Earth rotation by including low frequency components of polar motion and UT1 in the analysis, study of free oscillations in Earth rotation derived from both space-geodetic observations of polar motion and the time variation of the second degree gravitational field coefficients derived from Satellite Laser Ranging (SLR) and Gravity Recovery and Climate Experiment (GRACE) observations, new methods of monitoring of Earth rotation, as well as studies on applications of the Ring Laser Gyroscope (RLG) for direct and continuous measurements of changes in Earth rotation and investigations of the hydrological excitation of polar motion. Much attention was devoted to the GRACE-derived gravity for explaining the influence of surface mass redistributions on polar motion. Monitoring of the geodynamical phenomena is divided into study on local and regional dynamics using permanent observations, investigation on tidal phenomena, as well as research on hydrological processes and sea level variation parts. Finally, the recent research conducted by Polish scientists on the Earth's magnetic field is described.

**Keywords:** Earth rotation, geodynamics, Earth magnetic field, GNSS

## 1. Introduction

In the research concerning Earth rotation and geodynamics carried out by Polish scientists in a period of 2015–2018 many research institutions were involved, listed in Acknowledgments part. The investigations on Earth rotation in Poland have been performed mostly by the scientists of the Space Research Centre of the Polish Academy of Sciences (SRC PAS). The main concern of the work was the use of the Gravity Recovery and Climate Experiment (GRACE) data for modeling time variations of Earth orientation parameters (EOP) due to surface mass redistributions. The research on Earth rotation variations due to the influence of geophysical fluids has been extended by including other geodynamic phenomena, such as sea level change and hydrological processes on different scales, from local and regional to global ones.

Thanks to Earth's artificial satellites the new possibilities of providing the Vertical Land Motion arise. The changes of the permanent Global Navigation Satellite Systems (GNSS) stations' positions along with precise levelling data allow to monitor the present dynamic of the Earth's surface. They may also be supported by other satellite (Satellite Laser Ranging – SLR and Doppler Orbitography and Radiopositioning Integrated by Satellite – DORIS) techniques. On the other hand, tidal observations support the geodynamic research to a very significant extent. Since 2016 first Polish observatory was equipped with superconducting gravimeter, being able to observe temporal changes of Earth's field of gravity with unprecedented reliability.

## 2. Earth rotation

In a period of 2015–2018 Polish researchers working on Earth rotation participated in the scientific programs of the international organizations, like the IAG (International Association of Geodesy), IAU (International Astronomical Union), IERS (International Earth Rotation and Reference Systems Service). In particular they contributed to the activity of the IAU/IAG Joint Working Group on Theory of Earth Rotation and Validation; see the report by Brzezinski (2015) for details. Short summaries of the most important publications concerning Earth rotation will be given below.

### *2.1. Modeling diurnal and subdiurnal components of Earth rotation*

The high frequency signals in polar motion, with periods from a fraction of day to daily, are small – at the submilliarcsecond level, nevertheless important for understanding the dynamics of Earth rotation. There is also a need for high quality models of diurnal and semidiurnal effects in polar motion and UT1 for reduction of GNSS data. Brzezinski et al. (2015) applied the complex demodulation (CD) technique, originally developed for extracting the subdiurnal signals in Earth orientation parameters (EOP), for analysis of the retrograde diurnal component of polar motion (PM) and the low frequency component of dUT1. By comparison to the results based on the celestial pole offsets and dUT1 series from the combined solutions provided by the IVS (International VLBI Service) and IERS they could demonstrate consistency of the CD parametrization with the standard approach. This research was extended by Wielgosz et al. (2016) who included in the analysis the low frequency components of PM and UT1 estimated by CD version of the VieVS (Vienna VLBI Software). They could conclude that the CD parametrization applied for analysis of VLBI observations does not change those EOP components which are included in standard adjustment, while enabling simultaneous estimation of diurnal and semidiurnal components from standard VLBI (Very Long Baseline Interferometry) measurements. The authors suggested also implementation of the CD algorithm for data analysis of other space geodetic techniques, like GNSS and SLR, which can help to retrieve of subdiurnal signals from past data.

### *2.2. Studying the free oscillations in Earth rotation*

The most important free oscillation in Earth rotation is the Chandler wobble (CW), the largest component of polar motion, discovered at the end of XIXth century and monitored on regular basis since that time. Several aspects of the Chandler wobble have been studied by the researchers from the SRC PAS since 1990-ties, including determination of the resonance parameters and explanation of the excitation mechanism of CW. Recently, Nastula and Gross (2015) estimated the period T and quality factor Q of CW after imposing the minimum condition on power of the difference between the observed and modeled excitations in the vicinity of the resonance frequency. The observed excitation was derived from both space-geodetic observations of polar motion and the time variation of the second degree gravitational field coefficients derived from SLR and GRACE observations. The modeled excitations were computed from the output parameters of the global circulation models of the surficial fluids, the atmosphere, the oceans and the hydrology. The preferred values of CW resonance parameters were T = 430.9 solar days and Q = 127, with the 95% confidence intervals (430.2, 431.6) and (56, 255), respectively.

The second rotational mode of the Earth is the Free Core Nutation (FCN) which affects both Earth rotation and body tide. The FCN parameters are usually estimated from VLBI estimation of nutation or from the tidal gravity observations by the superconducting gravimeters. Rajner and Brzezinski (2017) reported an attempt to determine the FCN parameters from gravity record collected with the use of a spring LaCoste & Romberg Earth Tide gravimeter, located at Jozefoslaw observatory near Warsaw. They estimated the FCN period T = 430 sidereal days, which is in good agreement with the VLBI nutation results, and the quality factor Q = 1300 which is roughly consistent with other determinations from gravimetry but significantly smaller than the VLBI nutation estimate.

### *2.3. Research on the methods of monitoring Earth rotation*

VLBI plays an important role in monitoring changes in Earth rotation. There is one VLBI station in Poland, in Piwnice near Torun, but it does not participate in geodetic programs. There are plans to adapt the old VLBI antenna in Piwnice to the VLBI2010 standards and to join with this instrument the VGOS (VLBI Global Observing System) network. In a frame of preparation, several research works have been performed. One is the study reported by Wielgosz et al. (2016). They considered the problem of the simultaneous estimation the Earth Orientation Parameters (EOP) and station coordinates by the networks of VLBI stations. Several tests have been performed using the VLBI analysis software VieVS. The main problem considered was the method of weighting the results from the stations having bigger post-fit residuals. Several weighting strategies have been considered and evaluated using different statistical indicators.

Polish researchers have been also involved in the studies on applications of the Ring Laser Gyroscope (RLG) for direct and continuous measurements of changes in Earth rotation. This technique has been considered since about two decades as a complement of the space geodetic techniques for monitoring Earth rotation. So far there is only one instrument, the G-ring at the Wettzell Observatory in Germany, which has sufficient sensitivity for this purpose, but according to our knowledge other instruments are under construction. Tercjak et al. (2015) investigated the application of RLG for estimation of nutation rates. They considered one instrument with parameters of G-ring, but also simulated results from several RLG's and their combination with actual VLBI data. The conclusion of this study was basically negative, showing that for improvement of the VLBI estimates at least 3 RLG are needed having relative level accuracy by at least 2 orders of magnitude higher than the G-ring. In the next study, Tercjak and Brzezinski (2017) performed detailed analysis how the known diurnal and subdiurnal signals in polar motion and UT1 are reflected in the observations of G-ring. They considered the available models of so-called diurnal polar motion, diurnal and semidiurnal ocean tide effects in polar motion and UT1 and librations, prograde diurnal in polar motion and semidiurnal in UT1. As a next step, the effects of changing the geographic location of a horizontally mounted instrument, or changing its orientation with respect to the crust, have been considered.

### *2.4. Investigations of the hydrological excitation of polar motion*

Polar motion is almost entirely excited by the global geophysical processes taking place in the external fluid layers of the Earth, the atmosphere, the oceans and the land hydrosphere commonly designated as hydrology. The excitation of polar motion is usually studied by comparing the so-called geodetic excitation function derived by applying the deconvolution procedure to the polar motion series determined by the space geodetic techniques, to the geophysical excitation series which are derived from geophysical models. Significant progress in polar motion excitation studies could be achieved in recent years due to the availability of the time variable coefficients of the Earth's gravity field, determined by the satellite experiment GRACE as well as by the Satellite Laser Ranging (SLR) observations. The reason is that the mass term of polar motion excitation components $(\chi_1, \chi_2)$ is proportional to time variable gravity coefficients $(C_{2,1}, S_{2,1})$. The mass term of polar motion excitation, derived from GRACE and SLR data, usually called the gravimetric excitation function, can be used to improve the excitation balance of polar motion, particularly at seasonal frequencies, but also to constrain the global hydrology models. The investigations of the hydrological excitation of polar motion using the excitation data from hydrological models and GRACE/SLR gravity data have been performed by researchers from the SRC PAS in cooperation with the scientists from JPL (Jet Propulsion Laboratory) and AER (Atmospheric and Environmental Research) in USA. Nastula et al. (2015) made an analysis of the Hydrology Angular Momentum (HAM) functions derived from 11 solutions based on GRACE/SLR data, including comparison to the geodetic excitation (Geodetic Angular Momentum – GAM) based on the IERS C04 series after removal of the Atmospheric Angular Momentum (AAM) series based on the NCEP/NCAR reanalysis model and the Oceanic Angular Momentum (OAM) series based on the ECCO-JPL ocean model (so-called geodetic residuals G-A-O). Different HAM series have been compared to the G-A-O residual that was a base of assessment of the quality of gravimetric solutions. In the next stage of research, Nastula et al. (2016) performed analysis of the HAM functions derived from the GRACE RL05 solutions provided by three GRACE processing centers, the Center for Space Research (CSR), the Jet Propulsion Laboratory and the GeoforschungsZentrum (GFZ). Comparison with the G-A-O residuals revealed significant differences between the three RL05 solutions which were attributed by the authors to different treatment of gravity signals over ocean areas. The best agreement with the observed (geodetic) excitation was found for the CSR solution. The impact of continental hydrology on polar motion had been investigated in a comprehensive study by Winska et al. (2016). The HAM functions were estimated from the GRACE RL04 and RL05 data and from different models of global hydrology like the Climate Prediction Center (CPC), Global Land Data Assimilation System (GLDAS), National Oceanic and Atmospheric Administration (NOAA), and Land Surface Discharge Model (LSDM). The authors considered not only the global values of HAM but also the regional hydrological excitations of polar motion. They found that the maximum values of the excitation functions derived from hydrological models and GRACE data have similar geographical patterns but the amplitudes are different. Final conclusion from the comparison of geodetic residuals and global hydrological excitation functions of polar motion was that none of the considered HAM functions has enough energy to significantly improve the agreement between the observed geodetic and geophysical excitations. In the associated paper by Winska (2016), the hydrological excitations of polar motion determined from different variables of FGOALS-g2 climate model from CMIP5 project have been compared to geodetic residuals G-A-O at decadal, inter-annual and multi-annual time scales. This analysis was completed by the consideration of GLDAS global hydrological excitation functions and GRACE gravimetric excitations. In the following work Winska et al. (2017) considered hydrological excitation of polar motion using different variables from the GLDAS models. The main purpose of the research was to check the individual contributions from different hydrological processes such as evapotranspiration, runoff, snowmelt and soil moisture, to polar motion excitations at seasonal and subseasonal periods. In addition, they used time variable gravity field solution from the GRACE experiment to estimate the hydrological mass component of polar motion excitation. A comparative analysis had been done for different regional and global estimates of the HAM functions. Finally, the hydrological excitations were compared with the geodetic residuals G-A-O to check how well the polar motion excitation budget can be closed. Sliwinska et al. (2018) investigated hydrological excitation of polar motion using the global and regional estimates of Terrestrial Water Storage computed on the base of Coupled Model Intercomparison Project Phase 5 climate models, GLDAS land hydrology models and observations from the GRACE satellite mission. The hydrological excitation functions estimated from models were compared to those based on GRACE data and to the geodetic residuals G-A-O. The comparison demonstrated that the GLDAS models of seasonal and non-seasonal TWS change are closer to GRACE data than the climatic models, however, no one of the considered models is fully consistent with GRACE results or with geodetic residuals. From analysis of different TWS components to the HAM function it could be concluded about the dominant role of soil moisture.

## 3. Geodynamic phenomena

In 2013 the International Association of Geodesy celebrated its 150$^{th}$ anniversary at the Scientific Assembly held in Potsdam. At this occasion the special issue of the IAG Symposia Series has been issued. Among the others, Kolaczek and Nastula (2016) presented very interesting overview on developments of geodynamical studies related to the Earth rotation in the XX century. They pointed the important scientific milestones and gave the information about developments and organizational achievements in the considered field.

### *3.1. Study on local and regional dynamics using permanent observations*

The research related to the local and regional dynamics of the Earth were presented in two review papers (Brzezinski et al., 2016a and Brzezinski et al., 2016b). They described in details engagements of two institutions (namely, Department of Planetary Geodesy, Space Research Centre, Polish Academy of Sciences and Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology). Moreover, Pasik et al. (2016) presented current state of the art of polar research carried out by the employees and students of the Faculty of Geodesy and Cartography, Warsaw University of Technology. Remaining in polar research, Rajner (2018) presented a comprehensive study of the present-day uplift rates of GNSS with geophysical predictions at the chosen stations in Spitsbergen obtained height changes related to ice mass loss in Svalbard of 6 Gt/yr.

For many years equipment which has permanently been working at the Geodynamic Laboratory of the Space Research Center in Ksiaz has been given very valuable data concerning the dynamics of the Sudeten area. Kaczorowski et al. (2015) presented a novel concept explored in the Laboratory by means of new techniques: short-range laser scanning, precise electronic tachometric and interferometric measurements, precise geometric levelling as well as gap gauges to complement currently working instruments. All those activities are aimed at providing a complete information of the dynamic processes in the Ksiaz Massif: deformation of tectonic origin, tilts of the bed rock, vertical movements and displacements on faults.

Several case studies concerning local geodynamics have been conducted. Among the others, Szafarczyk and Gawalkiewicz (2016) performed a tensor analysis of ground deformation in a landslide area. With the use of geodetic methods they measured and analyzed the deformation on a landslide of a natural slope in Milowka and landslide of the open cast mine Belchatow obtaining the values of the extreme deformations in the GPS-based rosettes. Szafarczyk and Gawalkiewicz (2018) researched the industrial chimney in the Bochnia Salt Mine. They analyzed changes in the deviation of the chimney's axis from the vertical with the use of bisector methods surrounding the tangential and laser scanning with total station. Szczerbowski and Piatkowska (2015) performed research involving the linking of the results of Interferometric Synthetic Aperture Radar (In-SAR) with those of levelling measurements, arising certain opportunities for interpretation by means of the determination of the vertical displacements: between levelling measurement campaigns and areas or spots uncovered by levelling. Their case study denoted Inowroclaw Salt Dome. Szczerbowski et al. (2016) found the horizontal displacements and deformation of shafts in Bochnia to be corresponding to similar effects observed in the Wieliczka Salt Mine with a northward tendency despite the differences between the geological and mining environments. Wajs and Milczarek (2018) presented the observations of surface subsidence in the open pit mining area by Synthetic Aperture Radar (SAR) active remote sensing technique. They found that the post-proceed satellite Line of Sight (LOS) displacement indicates vertical changes of the surface within the dumping and excavation area. Szczerbowski and Jura (2015) presented the results from the GPS/GNSS permanent stations of Legnica-Glogow Copper District (LGCD). Referring to the Polish Active Geodetic Network (ASG-EUPOS) they observed the subsidence basin being shaped after mining tremors with the center located near the area of epicenter. They found a vertical displacements of c.a. 10 mm at maximum. Milczarek et al. (2017) presented the results of surface displacements calculated with the Persistent Scattered Satellite Interferometry (PSInSAR) technique for the area of the former Walbrzych Hard Coal Basin (WHCB) in SW Poland. According to the analysis of the ENVISAT-acquired radar images for the 458 track and for the 2002–2009 period they presented continuous surface displacements for the entire former mining site. Blachowski et al. (2018) extended the area of interest to the selected zones from Czech Republic and Poland presenting the comparative analysis of secondary deformations in two former mining areas in the first period after cessation of underground hard coal mining. Blachowski and Herkt (2018) enhanced the Walbrzych Hard Coal Mines Geographic Information System (GIS) for deformation research purposes. As the result, the interactive maps with precise information on location and characteristics of underground mining were developed. The system was also supplied by the query tools streamline preprocessing operations necessary for geospatial analyses. Blachowski (2016) investigated the mining induced land subsidence with the use of weighted spatial regression method.

The study concerned the former Walbrzych coal mine area and very long 1886–2009 observational period. The modelling has been performed in GIS with Geographically Weighted Regression (GWR) method that allows for spatial variability of subsidence factors. The four of the considered parameters (namely, thickness, inclination and depth of coal levels and surface slope) turned out to be significant.

Two different areas of interest of Polish researchers covered two most dynamic orogens: Sudeten and Tatra Mountains. Walo et al. (2016) studied the Pieniny Klippen Belt (PKB), which is situated in Southern Poland, being one of the main fault zones on the boundary of the Outer and Inner Carpathians. The history of the geodetic measurements in this region reach early 60's last century. They determined the horizontal displacement in the PKB area based on GNSS as well as gravity (absolute) measurements. Szczerbowski (2016) searched for disturbances in daily GPS solutions possibly sourced at tectonic stress. He used the ASG-EUPOS coordinates, drawing conclusions that spatio-temporal evolution of horizontal displacements of ASG-EUPOS stations in the Sudety Mts. and in adjacent areas are determined by expressions of underlying geological structures. Kaczmarek et al. (2016) summarized the epoch satellite GPS/GNSS and gravimetric measurements from last 25 years in the regional research network GEOSUD, SILESIA, SUDETY and the local geodynamic polygons ("Snieznik", "Stolowe Mts."). The data from crack-gauges on several tectonic faults were also included. As the results they provided maps of vertical movements, with special attention being put on the levelling lines which intersect Sudeten main tectonic faults.

The models of crustal movements play essential role not only in recognition of the dynamic processed in the Earth's interior, but also for constructing the kinematic reference frames for geodesy, which should follow the Earth's dynamics. Kraszewska et al. (2016) used the Satellite Laser Ranging (SLR) coordinates for analysis of the accuracy of estimated parameters, which define the tectonic plate motions finding a remarkable concurrence agreement between their solutions and the APKIM 2005 model. The similar research has been conducted for global Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) network (Kraszewska et al., 2018). Klos and Bogusz (2017) analyzed the International GNSS Service (IGS) "repro2" contribution to the ITRF2014. They employed the GPS position time series of 115 European stations between 1995 and 2015 with the minimum length of 10 years and estimated their velocities with associated uncertainties. The determination of those uncertainties was followed by noise analysis to take power-law dependencies in the position time series into consideration. Special attention was paid to the Vertical Land Movement (VLM). Kowalczyk (2015) used data from Polish Active Geodetic Network for the construction of a model of relative vertical crustal movements in the Polish territory. In this research he focused on the changes of vertical velocity between the chosen ASG-EUPOS stations. As a result, several models of relative vertical movements were evaluated and compared each other. Kowalczyk and Bogusz (2017) gave an idea of determining the height changes with a use of Vertical Switching Edge Detection (VSED) algorithm. On the basis of the Least Squares Estimation (LSE), the VSED method detects the discontinuities in time series and determines the values of jumps at the same time. They used the time series from Precise Point

Positioning (PPP) solution obtained in the Nevada Geodetic Laboratory (NGL) using satellite data gathered at more than 50 permanent stations located in Latvia, Lithuania and northeastern Poland. The obtained vertical velocities gave an overview of a possibility of the proposed method to be used and the ongoing vertical movements. Kowalczyk and Kuczynska-Siehien (2018) examined the relationship between vertical movements of the Earth's crust and variation in geoid heights. They used data from the Gravity Recovery and Climate Experiment (GRACE), precise levelling, tidal gauge observations and GNSS stations providing the model of the vertical crustal movements of the Sudeten area together with geoid height variation. They concluded, that variations in geoid heights do not exceed one-tenth of the vertical movements of the Earth's crust in the considered area, what coincides with other determinations. The similar study was performed for northeastern Poland (Kowalczyk and Kuczynska-Siehien, 2017). Kowalczyk (2017) tested the correlation between the vertical crustal movements and temperature changes on the example of selected vectors between permanent GNSS stations. As an example he took two permanent ASG-EUPOS stations corelating the time series of height and temperature concluding that the influence of thermal expansion of materials holding the GNSS antenna on the estimated vertical crustal movements between the stations are of 0.1 mm/yr magnitude. Finally, Bednarczyk et al. (2018) solved the problem of identification of fiducial point in the subsequent levelling campaigns (precise and GNSS) by providing coherent database containing attributes of both types of data and automatization of the joint point identification process. They presented the results of such identification process, depending on the amount of data, on the example of the area of Poland.

Several numerical analysis on the geodetic time series aimed at reliable determination of the velocity (horizontal or vertical) were performed. Bogusz et al. (2016) proposed the methodology of reliable determination of the velocities of permanent GNSS stations. They showed, that proper treatment of either deterministic or stochastic part of the position time series will lead to the most reliable velocities along with their uncertainties. Rapinski and Kowalczyk (2016) proposed a new method for detection of discontinuities in the height component of GNSS time series. They proposed the Switching Edge Detection (SED) algorithm based on the detection of the epochs in which step occurs and estimation of either vertical movement parameters or magnitude of steps by preparing the model and Least Squares Estimation of the parameters. The performance of this approach was shown using the ASG-EUPOS time series. Kowalczyk and Rapinski (2018) continued the verification of a GNSS time series discontinuity detection approach to support the estimation of vertical crustal movements. Using several triangles formed from the GNSS permanent stations on the area of Poland and their loop misclosures they confirmed the efficiency of the provided method. Finally, Kowalczyk and Rapinski (2017) applied the Vertical Switching Edge Detection algorithm to all permanent GPS station included in the ASG-EUPOS network. They found, that in the process of identification based on the loops misclosure criterion, there were 35 time series that fulfilled the previously assumed criteria. Then, they performed the network adjustment of height time series showing, that the accuracy of VLM of 0.5 mm/yr can be obtained from the processing of GNSS navigation data.

The time series analysis aimed at reliable determination of either velocity or its uncertainty is an inseparable part of kinematic modelling of the Earth's dynamics. The incorrect interpretation of coordinate time series may provide the misinterpretation of the geophysical processes in the Earth's interior. Bogusz (2015) dealt with non-linear long term trend revealing that many of GNSS stations experience the non-linear movement. He used the final approximation of wavelet decomposition to mathematically describe the long term trend of Precise Point Positioning solutions provided by the Jet Propulsion Laboratory (JPL) using the GIPSY-OASIS software. He stated, that GPS-derived velocity inversions using wavelet approximation could be successfully compared to the elastic deformation that was predicted e.g. with finite elements modelling aimed at approximating the geometry of the subduction, spreading or transition zones. Bogusz and Klos (2016) analyzed another part of the functional model of the GNSS position time series by means of seasonal changes. They proposed that the deterministic part should include all periodicities from 1$^{st}$ to 9$^{th}$ harmonics of residual tropical, Chandler, and draconitic periods and compared this approach with frequently used assumptions of the tropical annual and semi-annual-only curves. They found that this approach to the subtraction of seasonals caused the Akaike Information Criterion (AIC) values to decrease in the median value of 30%. Finally, they noticed that there are some of the GPS stations that improved their velocity uncertainty even of 56%. Several research concerned the considering of the amplitudes of oscillations as being time-variable. Bogusz et al. (2015a) proposed to use non-parametric methods. They stacked 3D position times series from JPL into data sets according to year (from January to December) and applied wavelet decomposition using Meyer's symmetric wavelet to prove that amplitudes of the annual curve change in time. Following this idea Gruszczynska et al. (2016) and Gruszczynska et al. (2018) proposed the Singular Spectrum Analysis (SSA) as well as its multivariate variant (MSSA) to be optimal method for description of this variability, but with non-significant influence to the stochastic part as previously applied methods (e.g. wavelet decomposition, Chebyshev polynomials, or Kalman filtering – numerical experiments presented in details in the paper by Klos et al. (2018a)). Klos et al. (2018b) found that the effects of insufficiently modeled seasonal signals will propagate into the stochastic model and falsify the results of the noise analysis, in addition to velocity estimates and their uncertainties. They provided the General Dilution of Precision (GDP) as the ratio of velocity uncertainties determined from two different deterministic models while accounting for stochastic noise at the same time. Klos et al. (2018c) proposed a two-stage method of subtraction of environmental (atmosphere, non-tidal part of ocean changes and continental hydrosphere) loadings. They proved, that previous attempts failed by changing the stochastic part significantly along with uncertainties of the permanent station velocity. Application of the Improved Singular Spectrum Analysis (ISSA) solved this problem, which was demonstrated on the height changes of 376 permanent IGS stations, derived as the official contribution to International Terrestrial Reference Frame (ITRF2014). Kaczmarek and Kontny (2018) proposed to estimate the seasonal signals in GNSS position time series and environmental loading models with iterative Least-Squares Estimation (iLSE) approach. They used the Center for Orbit Determination in

Europe (CODE) "Repro2013" coordinates revealing the high (0.5-0.8) correlation between Up component of GNSS-derived position and deformations from loading models.

Subtraction of the deterministic part from original position time series leads to obtain the residual part, being almost purely stochastic. However, this ideal case occurs rare, so the residuals still contain some useful information to be extracted. Bogusz et al. (2015b) used a 5-year span time series (2008-2012) of daily solutions in the ITRF2008 from Bernese 5.0 processed at the Military University of Technology EPN Local Analysis Centre (MUT LAC) to evaluate using L1 and L2 norms the so-called Common-Mode Error (CME). It is defined as the superposition of the technique-dependent and environmental systematic errors in GPS-derived position time series. Consequently, Gruszczynski et al. (2016) proposed to use orthogonal transformation to subtract CME. They studied the Principal Component Analysis (PCA) with the existence of a non-uniform spatial response in the network to the CME being assumed. They found improvement (by means of better credibility) of accuracy of the determined velocity being accompanied by the spatio-temporal filtering of position time series. Gruszczynski et al. (2018) introduced for the first time in geodesy the probabilistic Principal Component Analysis (pPCA). It is a method which allow the spatio-temporal filtering aimed at estimation and subtraction of CME, but with no interpolation of the missing values. The efficiency of the proposed algorithm was firstly tested on the simulated incomplete time series, then CME was estimated for a set of 25 permanent stations located in Central Europe. They found, that more than 36% of the total variance represented by time series residuals can be explained by the 1st Principal Component (PC). Since the other PCs variances turned out to be less than 8%, they concluded that that common signals stored in the 1st PC are significant in GNSS residuals. Finally, Kaczmarek and Kontny (2018) modelled the position time series with the use of Least-Squares Estimation (LSE) and the inverse continuous wavelet transform (CWT).

### *3.2. Investigations of tidal phenomena*

It's been a tradition of the International Association of Geodesy to take patronage over the so-called "Tidal Symposium". The 18th Geodynamics and Earth Tides Symposium 2016 "Intelligent Earth system sensing, scientific enquiry and discovery" was held in Trieste, Italy with more than 110 attendants from all over the World. It was organized by the scientists worked under the umbrella of IAG Sub-Commission 3.1 "Earth tides and geodynamics", being currently chaired by Prof. Janusz Bogusz. The classical Earth Tide Symposia were held since 1957, the 18th was the first with the word "Geodynamics" being attached. The 2016 Symposium addressed a wide range of scientific problems in geodynamical research and chose the interactions of geophysical fluids with Earth tidal phenomena and observations as a specific focus (Braitenberg et al., 2018).

The gravimetric infrastructure of the Borowa Gora Geodetic-Geophysical Observatory of the Institute of Geodesy and Cartography, equipped so far with four LaCoste&Romberg model G gravimeters (three of them with modern feedback systems) and the A10-020 field absolute gravimeter was enhanced in 2016 with a new iGrav-

027 superconducting gravimeter. It was delivered to the Observatory at the beginning of February 2016 and became fully operational in late April 2016. Sekowski et al. (2016) presented major aspects of installation, preliminary results of initial data analysis as well as a comparison with A10 measurements. The reliable results of tidal data processing are expected soon.

After several years of break Borowiec laser station is back again to satellites tracking with new possibilities and new perspectives. At the beginning of 2016 station completed the quarantine procedure of the International Laser Ranging Service (ILRS). First results from BORL station confirmed a high quality of observations (Lejba et al., 2016).

Concerning the determination of the tidal parameters from permanent observations Jagoda et al. (2017a) estimated $h_2$ and $l_2$ (Love and Shida numbers of second degree) parameters based on the analysis of the Satellite Laser Ranging data from the period January 2013 to January 2015. The solution has been computed using the LAGEOS-1 and LAGEOS-2 data with two different approaches: separately and jointly for the two satellites. The obtained values of tidal parameters are equal to: $h_2 = 0.6140 \pm 0.0005$ and $l_2 = 0.0876 \pm 0.0002$. Consequently, Jagoda et al. (2017b) determined the values of $k_2$ and $k_3$ Love numbers using the same LAGEOS satellites and the period from January 2014 to January 2016. Moreover, in the paper the potential sources of the differences in the values of the determined parameters are discussed. In the paper by Jagoda et al. (2018) the considerations about obtained differences in the $k_2$ and $k_3$ values were continued.

### *3.3. Research on hydrological processes*

In Sec. 2 we reported on the investigations concerning the impact of hydrological processes on polar motion using data from global hydrology models and GRACE-based satellite gravimetry data. However, also the regional effects due to the hydrological processes have been studied in a period of 2015–2018 by Polish researchers, mostly from the University of Warmia and Mazury (UWM). Birylo et al. (2015a) attempted to evaluate local hydrosphere conditions using the data from satellite gravimetry mission GRACE and GOCO gravity model, with the purpose of prediction the flood and drought events in Poland. They concluded that a combination of gravimetric and meteorological models yields more reliable modeling of water flow than the contributing individual models. Birylo et al. (2015b) further extended this research by including geological data into the combination model of water flow. They developed a combined geopotential model, expressed by the equivalent water thickness – EWT, from GRACE data, meteorological WGHM model and geological data over the area of Poland. This model served in turn as a base for a map of water risk for Poland. Rzepecka et al. (2016a) applied the global land data assimilation system GLDAS for determination of groundwater changes in Poland. They evaluated two GLDAS parameters which are essential for the context, namely the snow water equivalent (SWE) and the soil moisture (SM), using four GLDAS sub-models, and then compared their estimates at two locations in Poland. They found that the differences between the parameters estimated from the sub-models are quite large, comparable to the size of the parameters themselves. This research was extended by Rzepecka et al. (2016b) by including the GRACE-derived EWT and direct measurement of ground water level (GWL) variations in the estimation. Preliminary comparison between the GWL determined using GRACE data augmented with GLDAS output parameters and direct measurements led the authors to the conclusion that the method applied yield promising results and will be validated in future studies. In the next stage of research, Rzepecka et al. (2017) performed extensive analysis of groundwater level variations, water balance and all the associated hydrological parameters, like precipitation, evapotranspiration, surface run-off and subsurface run-off. This analysis was done for the area of Sudety Mountains in the South-Western Poland, and for the period between 2002 and 2015. The GWL variations were estimated by the use of TWS values determined from the GRACE observations and GLDAS model with a spatial resolution one by one degree and temporal resolution of one month. The authors found in the Sudety area a high average stability of total water storage over the period considered with simultaneous decrease of groundwater level at a rate of about 1 cm/year. Birylo at al. (2018a) developed an algorithm for water budget prediction using the Autoregressive Integrated Moving Average (ARIMA) models. A comparison between a 12-month prediction and actual budget data provided a satisfactory assessment of the prediction method. The same statistical approach was applied by Birylo and Pajak (2018) for analysis of geoid variation in the region of Three Gorges Dam on the Yangtze River in China, computed as difference between the static gravity field model EGM2008 and the time variable gravity observed by GRACE. The main purpose of the paper was determination of the trend in data and short-term prediction based on ARIMA modeling. Birylo et al. (2018b) computed the water budget for the whole territory of Poland from the GLDAS model by considering all the relevant parameters including precipitation, surface run-off and evapotranspiration. Detailed tests were performed for the two areas adjacent to Lamkowko and Wroclaw stations and for the period 2009–2015. The estimated water budget was presented in a graphic form and interpreted.

The influence of hydrology on GNSS observations has been investigated by researchers from the Warsaw University of Technology (WUT). Zygmunt et al. (2016) performed analysis of vertical displacement of 23 IGS stations divided into three groups: inland stations, near shoreline and islands. The observed vertical displacements have been compared to the modeled deformation computed from the surface loading caused by continental water. A satisfactory agreement between the modeled and observed deformations could be found only for the inland stations. In case of other two groups of stations the modeled values were much lower and weakly correlated with the observed values. Rajner and Liwosz (2017) investigated seasonal signals in position time series for selected eight GNSS sites in Poland. They used for the analysis the weekly GNSS time series taken from homogeneously reprocessed global network solution and from regional solutions performed by WUT. The modeled deformations were computed from the GRACE-derived Total Water Equivalent (TWE) and from the output of Water GAP Hydrology Model (WGHM). Comparison of the observed and modeled deformations confirmed that the major part of observed seasonal variations for GNSS vertical components can be attributed to the hydrosphere loading. The horizontal displacements were found about three times smaller than the vertical ones, and the conclusions their origin were ambiguous.

### *3.4. Research on sea-level variations*

Polish researchers continued during the term 2015–2018 investigations on modeling sea level variations in both the global scale (mostly the members of the group of the University of Wroclaw) and the regional scale limited to Baltic Sea (researchers from UWM). In the first case the research was a continuation of earlier studies leading to implementation at the University of Wroclaw of the near-real time system and service "Prognocean" for sea level prediction. Recently, a new science-oriented version of this service, called "Prognocean Plus", based on the high performance supercomputing structure had been developed at the Wroclaw Centre for Networking and Supercomputing of Wroclaw University of Technology. Swierczynska et al. (2016) compared predictive skills of these two sea level forecasting systems and the third one called MyOcean which is a part of the European Copernicus Marine Environment Monitoring Service. The predictions from each of three systems have been compared with Sea Level Anomaly (SLA) data using various statistical indicators. The conclusion was that the data-based approaches used by Prognocean and Prognocean Plus show better performance in forecasting sea level variability than the physically-based model of MyOcean. On the other hand, MyOcean resolves irregular SLA changes better because its prognoses highly correlate with data. Niedzielski (2017) presented review on modeling and prediction of various features of marine environment. He focused on several empirical time series methods (like data transformations, polynomial-harmonic models, autoregressive processes, prediction equations) and some physical approaches (general circulation models and coupled air-sea models). He also discussed common statistical measures used to evaluate models and the resulting predictions. The reasons of imperfections in forecasting the sea level anomaly variations were investigated by Kosek et al. (2016). After performing detailed analysis of seasonal and subseasonal signals in the weekly SLA maps they could conclude that the main cause of the increase of the SLA prediction errors is the phase variation of the annual oscillation, which exhibits a random character to certain extent. Finally we should mention two works of the Wroclaw University team on estimation of the ocean reference depth, its present-day value (Jurecka et al., 2016) and the depth-age relationship over the geological time scale (Niedzielski et al., 2016).

A series of papers concerning sea level changes observed over the Baltic Sea basin has been published by researchers from UWM. Pajak (2017) performed analysis of 5-years long series of sea level anomaly data derived from the satellite observations for three points of the Baltic Sea, two inshore points and one open sea point. The work focused on seasonal variations using different statistical indicators. Further results concerning the estimation of sea level rise over the Baltic Sea from satellite altimetry data was reported by Pajak and Birylo (2016). An extensive analysis of seasonal Baltic Sea level changes was performed by Pajak and Birylo (2017) using the combination of satellite altimetry data, time variable gravity observations from GRACE mission, and terrestrial water storage estimates from GLDAS hydrology model. The estimation had been done for three offshore locations in Poland. Pajak and Kowalczyk (2018) reported detailed analysis of the dynamics of sea level and of the associated physical phenomena over the 5-year period 2010–2014 and for five Baltic Sea stations, Swinoujscie and Wladyslawowo in Poland, Helsinki in Finland and two open sea stations. They used in analysis the data of water temperature, salinity, sea level anomaly from satellite altimetry and equivalent water height from GRACE observations.

## 4. Earth magnetic field

Systematic (continuous or repeated) magnetic measurements are the key element to understand and properly predict the changes in the Earth's magnetic field. The elements to be measured are: absolute geomagnetic field magnitude ($F$), magnetic inclination ($I$) and magnetic declination ($D$). Welker (2015) presented the history of magnetic measurements in the Baltic Sea from the very beginning (the mid-1800s) to the present. The discovered anomalies in a geomagnetic field in the form of charts were stored in the Atlas of the Baltic Magnetic Charts. Welker and Reda (2016) presented the metrology of magnetic measurements with recent apparatuses. They described the checking and testing of the instruments for geomagnetic measurements performed in a geomagnetic observatory which holds trusted apparatus that participated in the relevant international comparison campaigns organized by the International Association of Geomagnetism and Aeronomy (IAGA). The Earth's magnetic field distribution – both onshore and offshore – is complicated and variable in time, so it is essential to know the secular variation on the area of interest. That is why, Welker et al. (2017) proposed a new project of the Baltic network of repeat stations and gave a solution for the instruments usable for quasi-absolute magnetic measurements.

## 5. Summary

In this review article an outline of researches concerning Earth rotation and geodynamics carried out by scientists from Polish scientific institutions from 2015 to 2018 is given. Most of the research works on Earth rotation focused on the use of time variable gravity data from GRACE satellite mission for constraining the hydrological excitation function HAM and improving the excitation balance of the observed polar motion. That includes research on seasonal components of polar motion but also the 14-month free Chandler wobble. Also the regional effects due to the hydrological processed have been investigated using the output parameters from global hydrology models and GRACE-derived time variable gravity data. Polish researchers continued also during the term 2015–2018 investigations on modelling sea level variations in both the global scale and the regional scale limited to the Baltic Sea.

In 2016 the Borowa Gora Geodetic-Geophysical Observatory was equipped with superconducting gravimeter as the first of the Polish research station. After a couple of years of inactivity the laser station at the Borowiec Astrogeodynamic Observatory started to track the satellites. These were two unquestionable successes related to the geodetic equipment. Plans related to the retrofitting of the Observatory in Ksiaz are advanced. Several measurements and analyses concerning local geodynamics in the Southern Poland were done, especially on the geodynamic network of the Sudety and Tatra Mts. Furthermore, several Vertical Land Motion models of the area of Poland and the adjacent areas were provided which were based on the GNSS and levelling measurements. Finally, the research on the Earth's magnetic field in Poland with a special focus on the Baltic Sea was performed.

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*Review paper*

# Research on GNSS positioning and applications in Poland in 2015–2018

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**Abstract:** This review paper presents research results on geodetic positioning and applications carried out in Poland, and related to the activities of the International Association of Geodesy (IAG) Commission 4 “Positioning and Applications” and its working groups. It also constitutes the chapter 4 of the national report of Poland for the International Union of Geodesy and Geodynamics (IUGG) covering the period of 2015-2018. The paper presents selected research, reviewed and summarized here, that were carried out at leading Polish research institutions, and is concerned with the precise multi-GNSS (Global Navigation Satellite Systems) satellite positioning and also GNSS-based ionosphere and troposphere modelling and studies. The research, primarily carried out within working groups of the IAG Commission 4, resulted in important advancements that were published in leading scientific journals. During the review period, Polish research groups carried out studies on multi-GNSS functional positioning models for both relative and absolute solutions, stochastic positioning models, new carrier phase integer ambiguity resolution methods, inter system bias calibration, high-rate GNSS applications, monitoring terrestrial reference frames with GNSS, assessment of the real-time precise satellite orbits and clocks, advances in troposphere and ionosphere GNSS remote sensing methods and models, and also their applications to weather, space weather and climate studies.

**Keywords:** precise positioning, troposphere, ionosphere, GPS, Galileo, GNSS, PPP

## 1. Introduction

Research on positioning and applications covers important activities of the International Association of Geodesy (IAG). In order to coordinate this research, IAG has established its Commission 4 on "Positioning and Applications". Since IAG recognizes the central role of Global Navigation Satellite Systems (GNSS) in providing high accuracy positioning information today and into the future, Commission 4 focuses on research for improving models and methods that enhance and assure the positioning performance of GNSS-based positioning solutions for a range of geodetic applications (Drewes et al., 2016). The research starts from different aspects of positioning and continues into remote GNSS atmosphere sounding. These topics are primarily investigated by IAG Sub-Commissions: 4.1 "Emerging Positioning Technologies and GNSS Augmentation", 4.3 "Atmosphere Remote Sensing" and 4.4 "Multi-constellation GNSS". It is worth to notice that many Polish researchers very often take part in activities of Commission 4 working and study groups, frequently taking leading roles. Therefore studies related to GNSS positioning and atmosphere remote sensing are very popular in Poland. And this in turn results in large number of published research results. Nevertheless, in this review, the authors tried to select the most interesting ones. Additional selection criteria were: the rank of the journal and participation of the authors in IAG working and study groups.

## 2. Advances in relative positioning

The content of this section summarizes selected recent contributions devoted to precise positioning algorithm development and applications conducted at the University of Warmia and Mazury in Olsztyn, Warsaw University of Technology and Gdansk University of Technology. In this field, the papers concern selected issues, such as integration of multi-constellation signals, inter-system biases handling, mitigation of ionospheric delays and disturbances, ambiguity resolution and validation methods, stochastic modeling, studies on Network Real-Time Kinematic (Network RTK) reliability as well as monitoring the terrestrial reference frames with relative GPS (Global Positioning System) and GNSS positioning.

### *2.1. Study on multi-GNSS observables integration and inter system bias problem in relative positioning*

Initial contributions concerning multi-constellation relative positioning revealed important influence of the differences between receiver hardware delays caused by acquisition of multi GNSS signals. Thus, this phenomenon was investigated in detail. Theoretical background of the receiver differential Inter System Bias (ISB) estimation and handling was given in (Paziewski and Wielgosz, 2015). In this paper, the tightly combined multi-constellation model and method of estimation of receiver ISB were presented. Taking advantage of developed methodology, the short and long term stability of ISBs, as well as magnitude of between GPS – Galileo-IOV inter system biases was characterized on the basis of data derived from several pairs of multi-GNSS receivers. The results justified the thesis on the receiver ISB stability. In specific the stability of ISBs proved that it is feasible to calibrate phase and code ISBs for a particular pair of receivers using zero or short baseline and introduce them as corrections to GPS+Galileo tightly combined positioning (Paziewski and Wielgosz 2015). Hence, in practice we can use one receiver as reference one and determine the relative values of receiver ISBs using subsequent receivers. Such approach combined with the application of previously calibrated ISBs strengthens the observational model, which is beneficial for reliability of ambiguity resolution, and in consequence, performance of positioning.

Detailed studies on the receiver ISBs have also revealed the existence of the quasi-periodic effect in the time series of phase ISB estimates (Paziewski and Wielgosz, 2015). Thus, the frequency, amplitude, as well as the potential source of the phenomenon was investigated in the following publication (Paziewski et al., 2015). The detailed studies exposed that the oscillations were caused by PRN E11 and E12 Galileo-IOV satellite observations. The time-frequency analysis indicated that these small scale oscillations with similar amplitude and frequency present in phase ISB time series are caused by raw phase observations of E11 and E12 satellites. Borio et al. (2016) indicated the problems with initial algorithm applied for the integration of the frequency references provided by the couple of clocks simultaneously operated in Galileo PRN11 and PRN12 satellites as a potential source of the phenomena.

The continuation of studies in the field of multi-GNSS precise positioning was the development of the strategies for multi-GNSS signals integration in medium range relative positioning with ionosphere and troposphere weighted parameters. The analyses were supported by practical performance assessment based on GPS, Galileo and BeiDou Satellite System (BDS) signals (Paziewski and Wielgosz, 2017; Paziewski and Sieradzki, 2017). It was clearly demonstrated that both GPS+Galileo tightly combined with previously calibrated ISBs and loosely combined strategies are superior to single system solution. This was especially clear in the ambiguity resolution domain. Benefits from multi-GNSS signal processing were also noticeable in the coordinate domain, specifically considering the precision of float solution. Both loosely and tightly combining strategies provided comparable results in the ambiguity resolution and coordinate domains, assuming that the latter approach is supported by the previously calibrated receiver ISBs. The developed functional models were applied to instantaneous multi-baseline positioning with real BDS signals. The study of Paziewski and Sieradzki (2017) is concerned with the analysis of BDS and GPS signal noise, the definition of the functional and stochastic models of multi-GNSS medium range RTK positioning and empirical positioning performance assessment. The stations used in this experiment were located at the territory of China, which ensured as much as high number of available BDS satellites. It was justified that combined GPS+BDS positioning is superior to the solution based on single GNSS system with regard to ambiguity fixing. This holds especially true in an obstructed observing environment. However, in the case of high number of tracked satellites, there were no important differences in the performance of GPS and integrated GPS+BDS positioning in terms of the ambiguity resolution domain. They have, however, experienced deterioration of the ambiguity resolution success rate and coordinate accuracy for BDS-only positioning with respect to GPS-only based. This was caused by relatively small number of available BDS satellites signals in comparison to GPS.

Another study related to the field of multi-GNSS data processing is concerned with potential contribution of the couple of Galileo FOC satellites injected to highly eccentric and thus incorrect orbits to high precision surveying and geodetic applications (Paziewski et al., 2018). The analyses were carried out in the field of stochastic properties of GNSS observations including the carrier-to-noise density ratio and signals noise. The study exposed that the signal power of PRN E14 and E18 satellites was higher with respect to other Galileo satellites, what was caused by the satellites' lower altitude over the test area. However, the differences in the noise of the signal of all Galileo satellites were negligible. The subsequent analyses were devoted to selected indicators of instantaneous high precision medium range positioning performance: ambiguity resolution success rate and coordinate accuracy as well as a level of post-fit observation residuals. Experiment revealed that E14 and E18 satellites did not influence in a high extent on the performance of integer ambiguity resolution and coordinate accuracy. Hence one can conclude that the Galileo satellites with highly eccentric orbits are fully applicable to high precision geodetic applications and many others. This claim holds true providing precise ephemeris of satellites in a post processed mode.

### *2.2. Advances in functional models taking advantage of observation and parameter constraining*

Another way of improving the performance and reliability of precise GNSS positioning apart from application of multi constellation signals is the development of the mathematical models which take into account the relations between observables and parameters of the model as additional constraints. An original approach presented in (Paziewski, 2015) takes the advantage of the closely located antenna relations to improve the real-valued ambiguity solution, and consequently, the integer ambiguity resolution performance. In the novel approach, not only the ambiguity relationships, but also similar ionospheric and tropospheric conditions at multiple receiver configuration stations are used to improve the atmospheric delay modelling. The solution strengthens the observational model, and thus enhances the reliability and effectivity of the ambiguity resolution process. In (Paziewski, 2015) it was clearly demonstrated that an enhancement in the ambiguity resolution domain can be achieved taking the advantage of multi-rover receiver processing with novel algorithms. A clear improvement up to ~5% was observed in the ambiguity success rate against the standard single baseline positioning in all verified cases using baselines up to 70 km.

### *2.3. Study on ionosphere delay handling in relative positioning*

The ionospheric refraction is still considered as one of the dominating source of errors in the GNSS positioning. On the other hand, the ionosphere is the dispersive medium for frequencies employed in GNSS systems; hence this property can be used for monitoring its state.

Therefore, the properties of the network ionospheric corrections supporting RTK positioning as well as their impact on time to fix in RTK positioning were examined in (Paziewski, 2016). In this specific issue, an attempt was also made to derive the threshold accuracy of the ionospheric corrections, which allow reliable integer ambiguity resolution with the use of observations of single-epoch and baselines up to ~100 km. This characteristics of the ionospheric corrections accuracy may be beneficial for the definition of the stochastic model of the ionospheric corrections in the ionosphere-weighted positioning model. The empirical studies were based on analysis of the double differenced ionospheric delay corrections taking the advantage of networks established in the frame of the Polish active reference network ASG-EUPOS (Active Geodetic Network – European Position Determination System) and different ionospheric activity. From the results one can learn that to obtain reliable and precise RTK solution based on single-epoch observations we should provide ionospheric corrections with the error less than 1/3 of carrier-phase length (Paziewski, 2016).

The elimination, or reduction, of ionospheric disturbances' impact is still one of unsolved issues in precise GNSS positioning (Sieradzki and Paziewski, 2018). This is particularly crucial in a rapid mode performed with raw dual-frequency phase and code measurements and thus, the improvement in this field was also the goal of investigations conducted at the University of Warmia and Mazury in Olsztyn. In order to eliminate the influence of disturbances, manifesting in GNSS data as dynamic variations of Total Electron Content (TEC), an original algorithm was proposed. It utilizes rate of TEC (ROT) corrections derived from geometry-free combination to modify raw phase and code observables. These corrections are applied at the data preprocessing step. As the result, the ionospheric delay for each observational arc becomes constant and may be parametrized as a single unknown parameter. Thus, the evaluation of the algorithm involving the relative GPS positioning performed with an ionosphere-weighted model, can be also applied to multi-GNSS positioning including also functional models. The conducted tests reported its efficiency during disturbed periods for different ionospheric regions. The extreme case study for high latitudes (Sieradzki and Paziewski, 2016; Paziewski and Sieradzki, 2018) revealed almost 10 times increase of the ambiguity resolution success rate (ASR), and ASR increased up to 59%. The investigations for mid-latitudes, which are affected by the occurrence of medium traveling disturbances (MSTID), demonstrated the growth of ASR up to 90% (Sieradzki and Paziewski, 2015). According to these works the application of the algorithm does not distort the results for quiet ionospheric conditions. Furthermore, it implicated the continuous increase of ASR depending on session length. Another issue investigated at UWM (as a part of working group 4.3.4 "Ionosphere and Troposphere Impact on GNSS Positioning" of the International Association of Geodesy) and related to the ionosphere was the impact of high-order ionospheric terms. In the work of Banville et al. (2017) the authors proposed a modified approach of precise point positioning (PPP) including the estimation of the first- and second-order ionospheric terms in the positioning filter. Its implementation confirmed that proper modelling of higher-order ionospheric terms leads to the improvement of results. On the other hand, as shown in theoretical background and the results presented in the above-mentioned paper, neglecting of different code biases (DCB) causes the biases at the level of a few millimeters.

### *2.4. Advances in integer ambiguity resolution methods*

In the last decade, the new approach of precise positioning has been developed. This approach has been named Modified Ambiguity Function Approach (MAFA). First time the Ambiguity Function Method (AFM) was proposed in 1981 by Counselman and Gourevitch. However, this approach in its classical form was considered as less efficient and with poorer theoretical foundations than the prevalent recent approach based on three stages: float solution, ambiguity resolution and fixed solution (e.g. the Lambda method). However, the MAFA method provides meaningful improvements on the classical form of AFM. There were also observed some advantages of this approach over the methods based on searching for solution in the ambiguity domain. Unlike the Lambda method where the search procedure is conducted in ambiguity domain, the MAFA method is conducted in the coordinate domain. The main advantage of searching for a fixed solution in coordinate domain is the constant dimension of a search space. Thus, unlike the Lambda method, the computational complexity is independent from the number of satellites. The crucial problem in search procedure conducted in the coordinate domain is setting correct search region and grid of candidates inside it. It was proposed in (Cellmer et al., 2018) to assume the error ellipsoid of the approximate position as the search region. In the same article, the length of the search step (density of the grid of candidates) was set empirically based on simulated data for different configurations of satellites. In Cellmer et al. (2017), the analytical derivation of the length of the search step is considered for the extreme unfavourable shape and arrangement of the Voronoi cells of points respecting the integer ambiguities in relation to the orientation of the grid of candidates inside the search region.

The detailed discussion on the MAFA method as a non-conventional mixed integer-real least squares (MIRLS) estimation was presented in (Nowel et al., 2018), whereas some other issues related to the MAFA method were presented on the international conferences held in 2016 and 2017 (Kwaśniak et al., 2016; Kwaśniak et al., 2017ab; Nowel et al., 2017).

### *2.5. Stochastic modeling of GNSS observations*

Research on stochastic modelling of GNSS observations was carried out at the Warsaw University of Technology (WUT). These studies dealt with the improvement of the stochastic model for instantaneous Network Real-Time Kinematic (RTK) positioning, called the Network-Based Stochastic Model (NBSM) (Prochniewicz et al., 2016). The NBSM is a kind of weighted model which used network-based variance estimations to capture the characteristics of ionospheric and geometric residual errors. What is essential for this model compared to other solutions of this type is the possibility of describing residual errors on the basis of single-epoch observations. This model also does not require observations from an additional monitoring station. These features predispose NBSM instantaneous positioning applications which utilized single epoch measurements. Figure 1 presents the Network RTK positioning scheme with three groups of algorithms: network solution, network correction and positioning model. The extension of these algorithms with additional data flow included by the NBSM has been marked in red.

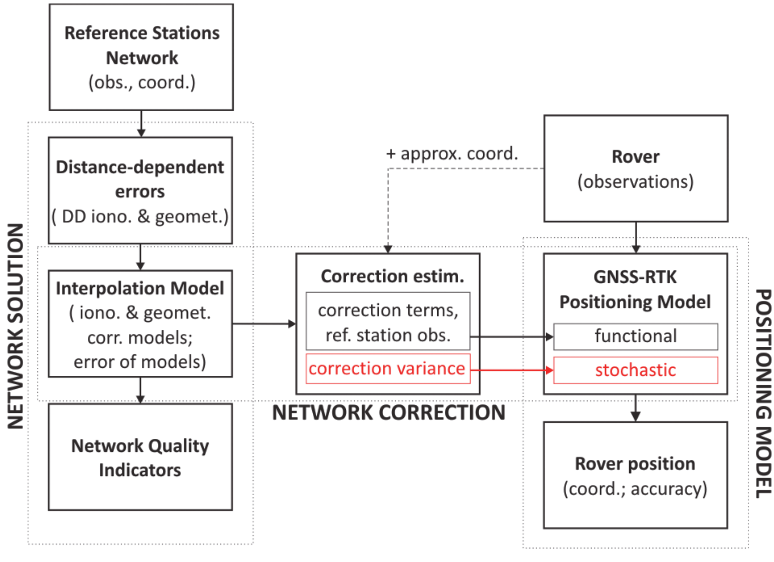


Fig. 1. Network RTK positioning model based on NBSM

Comparative tests of the proposed weighted NBSM model with the ionosphere-fixed troposphere-fixed model were carried out for singe-epoch performance. The results lead to the conclusion that the ambiguity integer estimation and its validation can be achieved with a significantly higher success rate compared to the use of the standard fixed model. Application of the NBSM can also reduce positioning errors by 15-30% (Prochniewicz et al., 2016).

### *2.6. Reliability of GNSS Network RTK positioning*

These studies were focused on developing of a new method for describing the positioning reliability for Network RTK technique. The method based on the so-called network solution quality indicators (QI) which depict the impact of dispersive and non-dispersive errors on rover positioning accuracy and reliability. The impact of these errors in Network RTK positioning is significantly mitigated by the use of ionospheric and geometric network corrections, thus QI mostly reflects the correction estimation accuracy. However, from the practical point of view, the existing QIs do not give the indications when the reliability of rover's position can be challenging to achieve. This is due to the undefined accurate critical values for these parameters.

In the paper (Prochniewicz et al., 2017), the new methods of deriving the QI, the so-called solution accuracy and solution availability, were proposed. The solution accuracy describes the accuracy of rover's position, and it is calculated as an estimated fixed baseline solution error for each epoch (for confidence level of $1\sigma$) with the assumption of correct ambiguity resolution. The solution availability describes the reliability of carrier-phase ambiguity resolution, and it is derived as an hourly ASR indicator with the confidence level of 95%. Both of them depend only on the variance-covariance observation matrix and the design matrices which do not require any actual measurements. However, the proper handling of the residual ionospheric and geometric errors in the stochastic model is crucial to their precise estimation. And this can be achieved by applying the NBSM methods (Prochniewicz et al., 2016).

A part of the regional ASG-EUPOS reference station network was used to test the proposed new QI for single-epoch Network RTK performance. The analysis of the variability of solution availability clearly indicated the periods when the correct ambiguity resolution was difficult to achieve, e.g. when only 5 satellites were observed (ASR was below 50%). The tests showed that for GPS-based instantaneous Network RTK positioning the alarm value of ASR set at 90% allows identifying the period with low reliability of ambiguity resolution. Also the solution accuracy index effectively identified the periods for which the position accuracy was reduced.

Compared to the existing indicators, e.g. I95, RIM, RIU, the proposed availability and accuracy, QIs are much more effective, and their indications are much easier to interpret. They are based not only on residual errors, like other indexes, but take into account the satellite geometry, applied method of the ambiguity resolution and the measurement noise of observations. Therefore, these features make them a useful tool for the reliability monitoring of Network RTK solution.

### *2.7. Monitoring the terrestrial reference frames with relative GNSS positioning*

Since 2017, at the Faculty of Civil and Environmental Engineering of Gdansk University of Technology (GUT) a new scientific group focusing on satellite geodesy, was formed. A brief review of the currently proceed studies is presented below.

One of the major tasks is monitoring the terrestrial reference frame using GNSS. This in particular concerns the International Terrestrial Reference Frame (ITRF) and the International GNSS Service (IGS) frame. In Figurski and Nykiel (2017), results related to the influence of ITRF2014/IGS14 frame on positioning of reference stations were presented. They found high consistency between ITRF2014/IGb14 and ITRF2008 solutions. Despite the great consistency of the ITRF solution itself, the introduction of the

IGS14 antenna phase center calibrations, both for ground and satellite antennas, cause insignificant differences of stations' coordinates. The updated calibrations cause change in the network scale, which was estimated about 0.7 ppb. In turn, using new IGS14 antenna models leads to changes of the vertical coordinates of the stations, which reach up to several millimetres. This is caused mainly by the introduction of new and updated absolute calibrations. These coordinate changes have impact on the realization of the European Terrestrial Reference Frame (ETRF). In order to show how much the ITRF2014/IGS14 and improved antenna calibrations affect the stability of the EUREF Permanent GNSS Network (EPN) stations, they present coordinate time series for POTS00DEU (Potsdam, Germany), where type mean calibration (in IGS08.atx) was changed to the individual (in IGS14.atx). For this station the authors estimated two solutions: (i) in IGb08 frame with IGS08.atx from the GPS weeks 1928 through 1937 (Figure 2, black line), and (ii) in IGS14 frame with IGS14.atx from the GPS weeks 1928 through 1933 (Figure 2, green line). They obtained significant shifts for North and Up components which amounted about 5 mm. They concluded that only new reprocessing of archived observations can remove the discontinuities caused by the new calibrations.

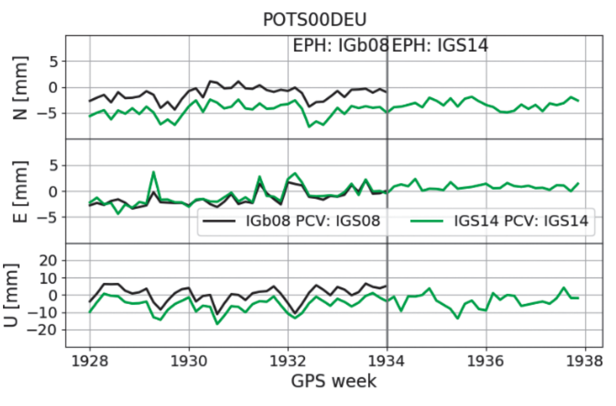


Fig. 2. Topocentric coordinates (top: North, middle: East, bottom: Up) of station POTS00DEU (Potsdam, Germany) estimated w.r.t. IGb08 cumulative solution from EPN. Results obtained in IGb08 frame with IGS08.atx are marked by black line, while the green line denotes results in IGS14 frame with IGS14.atx

During the research carried out at GUT, the researchers also focus on the impact of the Galileo observations on the multi-GNSS positioning. In the paper of Nykiel and Figurski (2017), positioning results with different combinations of the GNSS systems were presented. The authors tested the following solutions: GPS-only, Galileo-only, GPS/Galileo, GPS/GLONASS and GPS/GLONASS/Galileo. They stated that Galileo-only positioning were characterized by the highest standard deviation compared to the other solutions. This was caused by the low number of the Galileo satellites during the analyzed period of the time. However, despite the incomplete constellation of Galileo system, the Galileo-only positioning was performed with the precision below 1 cm for both horizontal and vertical components (Figure 3). In Figure 3 it can be seen that

Galileo observations have noticeable impact on the multi-GNSS results. The highest horizontal precision was obtained for GPS/Galileo solution and amounted to 1.95 mm for North and 1.96 mm for East coordinates. The obtained results were even better than GPS/GLONASS. However, for this solution the better precision was characterized for the Up component (5.35 mm). This was due to the fact that in the analyzed period there were more GLONASS satellites than Galileo, resulting in better geometry of the GLONAS system. Despite this, GPS/Galileo observations allowed to achieve lowest bias for all topocentric coordinates.

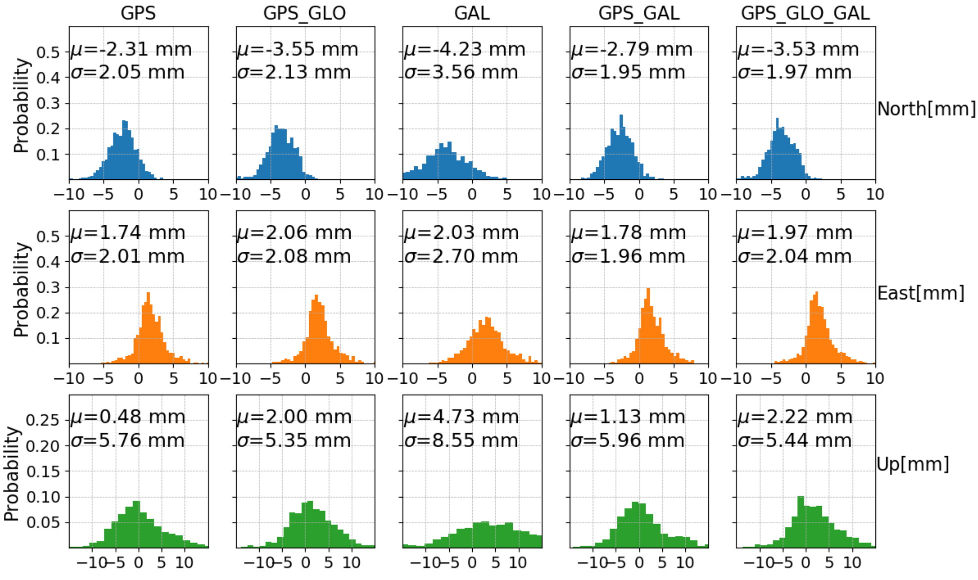


Fig. 3. Residuals for analyzed solutions (from left to right: GPS-only, GPS/GLONASS, Galileo-only, GPS/Galileo, GPS/GLONASS/Galileo) after the GPS week 1920. From the top: North, East and Up components

In Nykiel and Figurski (2017), the authors also analyzed the ambiguities resolution for wide-lane (WL) and narrow-lane (NL) linear combinations (Figure 4). After the EOC (1920 GPS week) and the few weeks earlier, the average percentages of Galileo ambiguities resolution were $80.85 \pm 4.31\%$ for WL and $70.97 \pm 5.68\%$ for NL linear combinations. For the multi-GNSS solutions, the higher ambiguity resolutions were obtained when GPS and Galileo observations were processed jointly (GPS WL: $79.15 \pm 3.45\%$, GAL WL: $93.14 \pm 2.45\%$). Based on the presented results, the authors concluded that GPS/Galileo solution allows for obtaining the best results in the case of ambiguity resolution and the position determination as well. The results are better even when all GNSS systems were used (GPS/GLONASS/Galileo).

In the paper Nykiel and Figurski (2017), the differences of antenna phase center corrections (PCC) between individual calibrations for Galileo E5 and for GPS L2 frequencies were also presented. The authors achieved differences between −6 mm and 8 mm, which show that copying calibration from L2 to E5 causes significant errors. They also

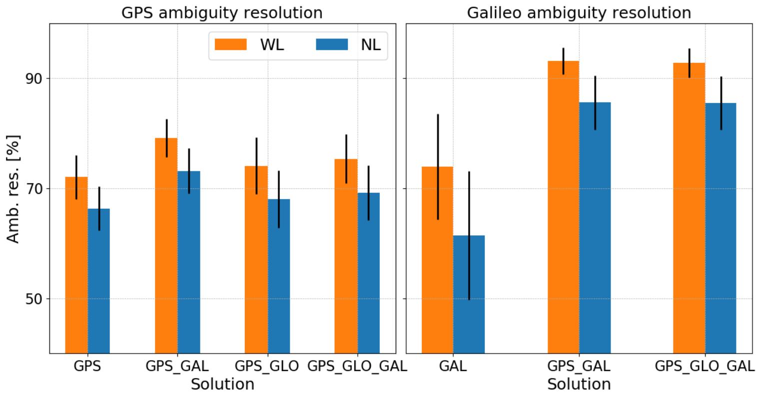


Fig. 4. Average percentage of the ambiguity resolutions (GPS (left) and Galileo (right)) for the analyzed solutions. WL and NL linear combination are marked by orange and blue, respectively

presented Galileo-only positioning results with antenna calibration for E5 frequency. Its usage caused Up shifts for all tested stations during comparison to the solutions where calibrations were copied from GPS L2. The authors conclude that this was caused by the propagation of the network errors, because for some stations (for which there was no calibration for Galileo E5 signal) the GPS L2 calibration was used. It seems that, in differential positioning, usage of antenna calibrations for Galileo signals makes sense only if all stations in the processed network support it.

## 3. Advances in Precise Point Positioning

This section presents summary of studies contributing to the subject of Precise Point Positioning which were conducted at the Wroclaw University of Life and Environmental Science, the University of Warmia and Mazury in Olsztyn and the Koszalin University of Technology. Moreover, algorithm development related to indoor and integrated positioning and navigation is presented.

### *3.1. Assessment of the real time precise orbits and clocks and optimal weighting scheme development supporting PPP*

PPP technique relies on external products, namely satellite orbits and clock corrections, the quality of which directly affects its quality. Since April 2013, IGS is running the real-time service (RTS) that allows for realtime PPP. A very first complex assessment of the IGS RTS products was presented in (Hadas and Bosy, 2015). Moreover, the algorithm of RTS product application was described in detail, focusing on issues important for final users, i.e. compatibility with broadcast ephemeris, reference frame and reference point. Analyses of availability, latency and accuracy of realtime orbits and clocks were performed over a week period for two streams, namely IGS01 and IGS03, which are GPS-only and GPS+GLONASS streams respectively, by comparison with ESA/ESOC final products. It was found that the availability of realtime corrections is over 92% for both GNSS streams, however, for GLONASS satellites during the eclipse the availability is reduced to 40%. The latency of the products, which reflects the time required for data processing and combining at the Analysis Centers and for data transfer to the end user, was found to be 28 s and 31 s for IGS01 and IGS03 streams, respectively. From the comparison of RTS products with ESA/ESOC final products (Table 1), it was confirmed that the RTS orbits are of high accuracy – in general, it is 48 mm for GPS and 132 mm for GLONASS. The accuracy of real-time clocks is 84 mm (0.28 ns) and 245 mm (0.82 ns) for GPS and GLONASS, respectively. Therefore the estimation of real-time GLONASS clocks requires further development to reach the target level of 0.3 ns.

Table 1. Root-mean-square errors (RMSE) for GPS and GLONASS products with respect to final ESA/ESOC products [m]

| | GPS (IGS01 stream) | GLONASS (IGS03 stream) |
|---|---|---|
| Radial | 0.015 | 0.031 |
| Along | 0.039 | 0.106 |
| Cross | 0.025 | 0.079 |
| 3D Orbit | 0.048 | 0.134 |
| Clock | 0.084 | 0.245 |

The research was further continued in (Kaźmierski et al., 2018b), which presents a complex analysis of the quality of GPS, GLONASS, Galileo and BDS, real-time orbits and clocks, that are provided by the CNES (Centre National d'Études Spatiales) – one of the IGS analysis centres. Multi-GNSS products were investigated by means of their availability over time, the accuracy of orbits and clocks, consistency of orbital arcs, residuals with respect to satellite laser ranging (SLR) observations and clock stability analysis with modified Allan deviation. Analyses confirmed the high availability of real-time products (over 90% for all systems). Compared to final CODE MGEX (Multi-GNSS experiment) products (Fig. 5), the accuracy of real-time orbit and clocks is 0.03 m for GPS and 0.08 m for GLONASS. For Galileo, the accuracy of orbits is 0.12 m and accuracy of clocks is 0.09 m. For BDS it is 0.20 m and 0.10 m, respectively, however, for geostationary BeiDou satellites, the accuracy of products is not assessed, due to the missing information in final products. However, analyses of the SLR residuals indicated the poor quality of geostationary satellite orbits. Finally, the real-time positioning results with PPP were presented in several variants of GNSS combination, which revealed limited improvements of multi-GNSS PPP with respect to GPS-only solution, neither in static nor kinematic case.

Unsatisfactory results of real-time multi-GNSS PPP stimulated research towards the improvement of the inter-system weighting (Kaźmierski et al., 2018a). Using information on pseudorange and carrier-phase noises (Cai and Gao, 2013) and multi-GNSS

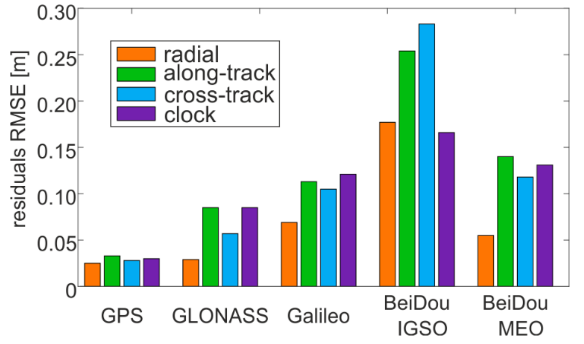


Fig. 5. Root-mean-square errors (RMSE) of real-time orbits and clocks compared to the CODE MGEX solutions

real-time products quality assessment results to calculate Signal in Space Range Error (SISRE, Montenbruck et al., 2015), five weighting schemes for real-time multi-GNSS PPP processing were proposed. The PPP results were compared against GPS-only solution by means of a posteriori error of estimated coordinates, coordinate repeatability and time required for static solution to converge below 1 cm precision level (Table 2). It was found that equal weighting in multi-GNSS solution leads to degradation of coordinate repeatability by up to 50%, even when their formal error is reduced. Among the proposed weighting schemes, the one based on SISRE coefficients occurs to be superior. In this scheme, smaller weights are imposed on both pseudoranges and carrier phases for GLONASS, Galileo and BeiDou compared to GPS. As a result, a coordinate repeata-

Table 2. Coordinate formal errors, coordinate repeatability and 1 cm level convergence time for selected inter-system weighting variants

| | GPS-only | Equal weights for all GNSS | Superior inter-system weighting scheme |
|---|---|---|---|
| Mean formal errors of coordinates [mm] | | | |
| North | 0.9 | 0.7 | 0.6 |
| East | 2.0 | 1.5 | 1.2 |
| Up | 3.8 | 3.0 | 2.3 |
| Mean coordinate repeatability [mm] | | | |
| North | 4.2 | 6.5 | 3.9 |
| East | 8.4 | 14.0 | 8.0 |
| Up | 11.0 | 16.1 | 10.1 |
| Mean convergence time to reach 0.01 m accuracy level [hours] | | | |
| North/East | 3:34 | 2:31 | 2:11 |
| Up | 5:43 | 3:34 | 3:01 |

bility from daily solutions was improved by 6% on the average, the formal error was reduced by 39% on the average, and the convergence time was reduced on the average by 39% and 47% for horizontal and vertical components, respectively.

### *3.2. Troposphere delay modelling for Precise Point Positioning*

An alternative approach to improve the real-time PPP performance has been proposed in (Wilgan et al., 2017a), where a numerical weather prediction model was used as an additional source of information on the troposphere state. For zenith total delay (ZTD) modelling, GNSS observations and short-term weather forecasts are combined (Wilgan et al., 2017b). Then, the ray-tracing technique was used to deliver coefficients of mapping functions that allows calculating tropospheric delays in a satellite direction. It was found that using the external troposphere models in static positioning could reduce the systematic error of receiver height by 20 mm on the average, at a cost of a worse coordinate repeatability by 1.5 mm (Fig. 6). No significant differences were observed for horizontal coordinates. In the kinematic positioning, both systematic error and coordinate repeatability of the vertical component were improved, but the quality of horizontal coordinates was slightly degraded. Systematic error of 3D coordinates was reduced by 10 mm, and coordinate repeatability for all processing variants differed within the 4 mm range. Moreover, a significant reduction of the initialization time was observed: 13% for the horizontal components and 20% for the vertical component. The choice of mapping function was insignificant because differences were noticeable only for very low elevation angles.

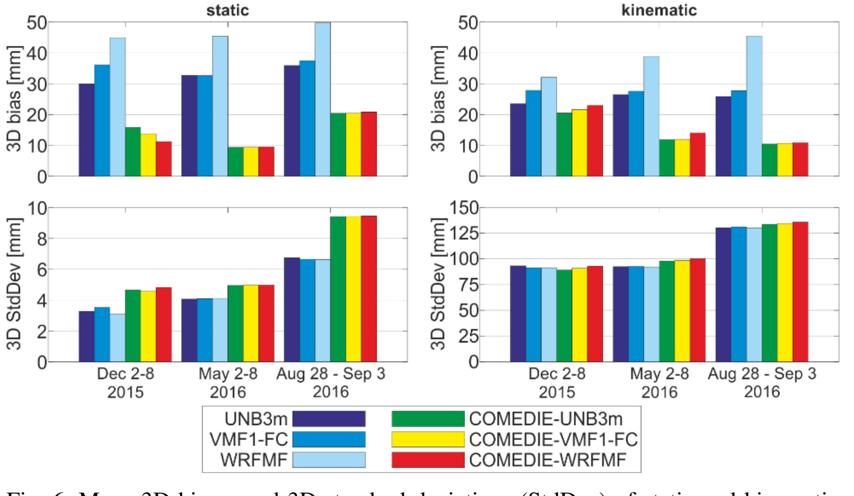


Fig. 6. Mean 3D biases and 3D standard deviations (StdDev) of static and kinematic coordinate residuals (estimated – EPN official) averaged from 14 Polish EPN stations

The research focused on analyzing impact of initial tropospheric delay estimates on the quality of PPP (Kalita and Rzepecka, 2017). During first minutes of PPP processing the initial biases of the a priori estimates can be significantly amplified while passing through the filter. In the analysis, PPP solution for several tropospheric models, i.e. MOPS (Minimum Operational Performance Requirement), GPT2w (Global pressure and temperature 2 wet) and VMF1 (Vienna Mapping Function 1), was referenced to the solution that uses IGS Final tropospheric product with several variants of initial filter variances appropriate for each tropospheric model. During the first 10 minutes of processing, the differences between the analyzed models can generate respective differences in the PPP solution that reach up to 30 cm and extend the initial bias several times. Using VMF1 model in PPP increases the height components' accuracy by about 35% when comparing to the GPT2w and MOPS. The improvement in horizontal components is up to 30%. The results show that the difference between applying blind and numerical weather prediction (NWP)-based tropospheric models plays an important role during convergence of PPP.

### *3.3. Developments in high-rate PPP*

The advances in algorithm development optimized for high-rate multi-GNSS data processing were presented in the study of Paziewski et al. (2018) performed at the University of Warmia and Mazury in Olsztyn. The paper provided not only the methodology, but also assessed the performance of millimetre level dynamic displacements determination. The novelty of the paper was the application of several modified or newly developed methods such as Precise Point Positioning, relative kinematic positioning, as well as novel direct phase observations processing method to high-rate multi constellation observations (up to 50 Hz). Since current regular kinematic PPP as well as medium to long baseline RTK do not offer position solution at millimetre level accuracy, the processing techniques were extended and these were applied to dynamic displacements determination. In the experiment the authors have processed 50 Hz observational data collected with the use of in-house developed shake-table ensuring periodic horizontal motion of GNSS antenna with amplitude of ~3 cm and frequency of ~4.5 Hz. The developed algorithms of high-rate PPP, RTK of medium range and direct phase observation processing method demonstrated to be capable of providing consistent and reliable results at the millimetre level precision of the dynamic displacement estimates.

### *3.4. Using PPP to analyze periodic signals in GNSS position time series*

Recently, GNSS measurements can provide position components estimation with millimetre accuracy. Processing of GNSS observations repeated periodically shows that methods and algorithms are constantly improving. This applies particularly to modelling and removing errors which are a source of inaccuracy of GNSS measurements. The above-mentioned increase of accuracy of GNSS observations processing reveals some jumps undetected so far and periodic signals. Discovered phenomenon can be a result of errors, still present in applied models (e.g. tidal models, solar radiation pressure models). Inaccuracies in GNSS antenna phase center variation models can be also one of the sources of these periodicities (jumps).

In Dawidowicz and Krzan (2016, 2017), it was investigated how differences present in GNSS antenna phase center correction models (individual and type mean) affect position estimates. Sub-daily solutions were analyzed using PPP technique. Obtained results proved that visible in PCC model differences affect GPS-only (as well as GLONASS-only) solutions and can be a source of periodic variations mentioned earlier. In the case of GPS-only solutions a periodicity equal to half of a sidereal day was found. The amplitude of the discovered periodicity was up to 10 mm. For GLONASS-only solutions the periodicity was close to 3 cpd which can be associated with the number of GLONASS orbital planes. Additionally, position component offsets caused by using individual PCC instead of type-mean PCC were estimated. For example, estimated up position component offset reach up to 5 mm for different stations with the same type of antenna. This proves that the same type antennas have different phase characteristics and cannot be represented with high accuracy by type-mean PCC. In Dawidowicz (2018) similar analysis was performed using daily GPS observation windows.

### *3.5. Determining normal heights with the use of Precise Point Positioning*

Normal heights determination using PPP method was analyzed in Krzan et al. (2017). For the purposes of the analysis, GNSS observations covering one week were processed using NAPEOS software. Processing of the observations was based on the standard PPP method as well as using Multi-Station PPP approach (with ambiguity fixing). Seven days of observations were divided into 1 hour, 30 minutes and 15 minutes sessions. This allows to examine the correlation between session duration and position determination precision. Geoid undulations were determined based on PL-geoid-2011 model. Obtained results proved that PPP method derived normal heights can have similar accuracy as Relative GNSS Positioning derived normal heights.

### *3.6. The application of ZigBee phase shift measurements to indoor positioning*

In modern society, industry and business, more and more attention is paid to indoor navigation. The main purpose of indoor navigation is to provide a function similar to the GNSS function, but in places where satellite signals are not available. There are many algorithms and concepts for indoor positioning systems: inertial systems, pseudolite systems or computer vision systems. In addition, there are other technologies that allow positioning and navigation inside buildings. Radio Frequency (RF) technology has become the concept of indoor positioning in the last few years. There are two basic methods for obtaining distances in RF networks – flight time (and its variants) and algorithms based on Radio Signal Strength Indicator (RSSI). Compared to other systems, the communication networks used to accomplish this task have many advantages. One can use existing infrastructure and devices. These devices are usually inexpensive and widely available, and besides navigation they can also be used for other purposes. However, a significant disadvantage is the low accuracy of the results obtained by these systems. The most commonly used systems based on RSSI can be accurate up to several meters, and these are not expected and satisfactory values (ideally 1–2 metres). In addition, it strongly depends on the environment, thus the functionality of these systems is very limited in a changing environment. The new method of obtaining distances between nodes in an RF network is a new approach based on the measurement of phase shift.

The new approach based on the ZigBee protocol and phase shift measurement shows promising results in this area (Rapiński, 2015; Rapiński and Śmieja, 2015; Janicka and Rapiński, 2016). Assessing the results, it was noted that a large number of distances is disturbed and significantly differs from the reference values. To obtain the correct distance, filtering the measurement results was applied. Therefore, RANSAC (Random sample consensus) and FIR (Finite impulse response) algorithms have been tested and the results have been analyzed (Rapiński and Janicka, 2015). Besides the accuracy of the measurement itself, the selection of the appropriate algorithm affects the final positioning result. Therefore, it was proposed to use Nelder–Mead symplex method for optimization of the objective function, which allows to obtain better results than methods based on the linearization of observation equations (Rapiński and Cellmer, 2015). Furthermore, it was also proposed to solve the problem of phase ambiguity, which also occurs during the positioning inside buildings (Rapiński and Janicka, 2017).

### *3.7. Integrated multi-sensor navigation*

Augmentation of satellite navigation is one of the current research trends studied by research centers around the world. There are several augmentation methods that are used in recent times. They can be divided into two types. The first type is based on the processing of other signals sent from external sources (Wi-Fi, Zigbee). The second type is based on the use of integrated inertial navigation systems (INS) and GNSS systems, which enable the augmentation of satellite systems with the results from inertial measurement unit (IMU).

The research done for the needs of improving integrated systems was the analysis of the observational data of the IMU inertial module. The most important part of conducted research was to develop and determine the accuracy of the attitude heading reference system (AHRS) algorithm. This algorithm is used to determine INS attitude alignment (Tomaszewski et al., 2015). In this process the initial position of the inertial module relative to the north direction and the direction of gravity is determined. Inertial navigation sensors alignment if defined by specifying Euler angles (pitch, roll, yaw) which are an unambiguous orientation of the sensor coordinate system relative to external coordinate system. The Kalman filter developed as part of the AHRS algorithm allows to determine these quantities (Tomaszewski et al., 2017). As part of the latest research, the integrated navigation algorithm was implemented. Next, practical tests of the use of an algorithm integrated in car navigation were performed (Tomaszewski, 2017). Studies have shown that the applied solutions increase the accuracy, reliability and integrity of the navigation system.

## 4. Troposphere studies

### *4.1. Improvements in the estimation strategy of GNSS troposphere products*

Stepniak et al. (2018) investigated main factors leading to outliers in ZTD time series obtained from the processing of GPS regional networks. It was found that the continuity and quality of ZTD time series strongly depends on the baseline design strategy in a double-difference processing. An alternative baseline strategy was proposed. This minimizes network disconnections, preventing gaps and outliers in ZTD time series. The reprocessed ZTD time series obtained with the developed strategy implemented in the Bernese GNSS Software v.5.2 occurred to be more continuous and homogeneous compared to the common strategies (Table 3).

Table 3. Statistics of ZTD estimates and formal errors (STD) after outlier rejection based on the range check on ZTD [0.5 m; 3.0 m] and on sigma [0 m; 0.1 m]; results from one year of processing data from 104 ASG-EUPOS stations

| Strategy | Rejected data | Used data | Mean STD (ZTD) | Mean STD (sigma) |
|---|---|---|---|---|
| standard | 148 | 468332 | 14.2 mm | 1.19 mm |
| obs-max | 109 | 471666 | 13.3 mm | 0.67 mm |
| new | 84 | 469534 | 12.9 mm | 0.79 mm |

Other studies focused on the accuracy, stability, and homogeneity of the estimated tropospheric parameters obtained with 1) double-difference (DD) processing of a network of stations and 2) zero-difference PPP processing of a single stations (Gołaszewski et al., 2017a). For short baselines in DD mode, the estimated ZTD are correlated and may be biased in their absolute values. Although the errors are not propagated between stations in PPP, the quality of the obtained ZTD depends strongly on the quality of orbits and clocks. ZTD estimates from DD and PPP solutions were compared. The authors noted outliers in DD solution caused by very few observations common to other stations in the baseline, which were not seen in PPP ZTD time series.

### *4.2. Near real-time and real-time troposphere delay estimation*

Wroclaw University of Environmental and Life Sciences (WUELS) established an Analysis Centre that estimates ZTD and troposphere horizontal gradients in near real-time (NRT) regime for GNSS stations located in Poland (Fig. 7), Lithuania and Victoria state in Australia. Results are submitted hourly to the database of E-GVAP (The EUMETNET EIG GNSS water vapor programme, http://egvap.dmi.dk/). Within the framework of the COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate" (GNSS4SWEC, 2013–2017, http://gnss4swec.knmi.nl/), WUELS contributed to the developments towards ultra-fast service (15-minute of delay) and multi-GNSS solution, by participating in the dedicated benchmark. The benchmark has aimed to support the development and validation of advanced GNSS tropospheric products, in particular high-resolution and ultra-fast ZTD, slant troposphere delays (STD) and tropospheric gradients derived from a dense permanent network. Data and metadata were prepared for GNSS stations located in the Polish part of the benchmark. A complex data set was collected for the 8-week period when several extreme heavy precipitation episodes occurred in Central Europe which caused severe river floods in this area (Douša et al., 2017).

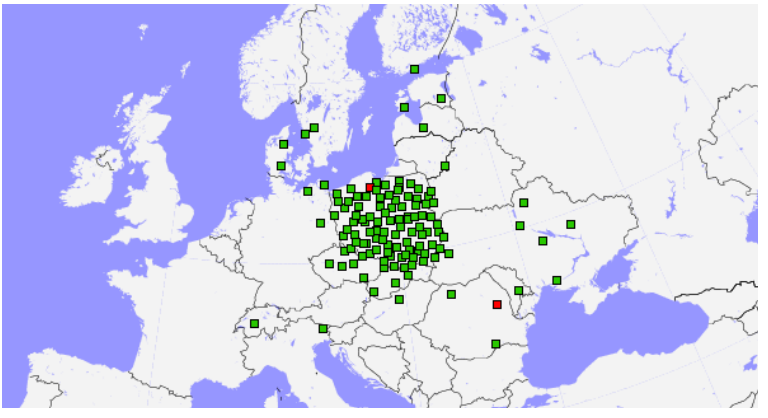

Fig. 7. GNSS stations in NRT ZTD solution for Poland, status on 7 November 2018

Dymarska et al. (2017) provided accuracy analyses of NRT GNSS ZTD validated against final IGS products, Weather Research and Forecasting (WRF) NWP model and radiosonde profiles. A biases of 3 mm to 11 mm with related standard deviations from 10 mm to 14 mm were found. Therefore, considering the data quality, the authors assessed that NRT ZTD products can be assimilated into NWP models.

An extensive validation of line-of-sight tropospheric standard deviations (STD) from GNSS, ray tracing in NWP model fields and microwave water vapour radiometer (WVR) was presented by Kačmařík et al. (2017). Seven institutions delivered GNSS STDs obtained with 5 different software and 11 strategies for 10 GNSS stations using data from almost 2 months in 2013 (including severe weather events). Evaluations demonstrated a good mutual agreement of various GNSS STD solutions ignoring post-fit residuals (mean bias and standard deviation scaled to zenith direction was $-0.6$ mm $\pm$ 3.7 mm), especially when compared to numerical weather model (NWM) and WVR STDs (10 mm $\pm$ 2 mm and 12 mm $\pm$ 2 mm, respectively). Although the post-fit residuals cleaned of visible systematic errors (multipath) generally showed a slightly worse performance, they contained significant tropospheric signal on top of the simplified model. They are thus recommended for the reconstruction of STDs, particularly during high variability in the troposphere.

The NRT ZTD obtained with GPS data from ASG-EUPOS network in January 2011 was used for verification of the implemented WRF-Chem model v3.5 over Poland, in which the main purpose was to quantify the direct and indirect feedback effects of aerosols on simulated meteorology and aerosol concentrations (Werner et al., 2016). ZTDs were recalculated to Integrated Water Vapour (IWV) above the GNSS stations with the meteorological data for three WRF simulations and used to verify the water vapour content.

Hadaś et al. (2017b) showed that the troposphere constraints in GNSS processing, modelled as a random-walk process, should have been time and location specific. Therefore, they proposed to take benefit from numerical weather prediction models to define optimum random walk process noise (RWPN) for the ZTD estimation in real-time. Using archived VMF-G grids, they obtained RWPN global grids for hydrostatic and wet parameter (Fig. 8), which can easily be implemented in a software as a look up table to define the optimum RWPN value for any station located worldwide. Alternatively, a short-term weather forecast can be used to perform ray-tracing in order to forecast ZTD and then to calculate RWPN dynamically in real-time. The advantage of this approach is that the wet RWPN is regularly adjusted to the expected tropospheric conditions. The approach utilizing the global grid can successfully replace the initial empirical testing for effective constraining, while the dynamic approach is even superior by up to 18% compared to the standard static approach.

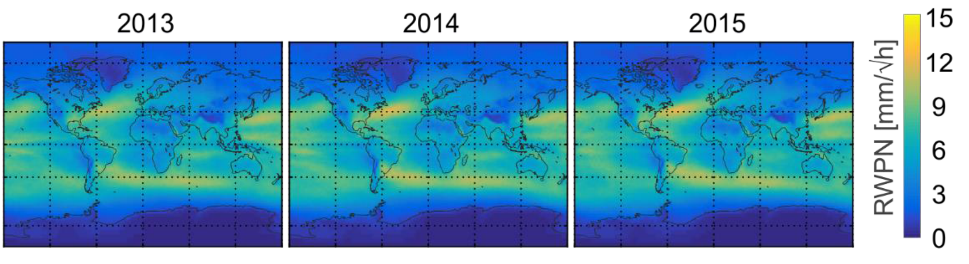


Fig. 8. Global maps of the optimum wet RWPN for years 2013, 2014 and 2015

### *4.3. Development of troposphere models supporting positioning and VLBI*

In Kaźmierski et al. (2017), UNB3m model was adjusted to the actual meteorological parameters from Europe. Although the same mathematical formulas were used as in UNB3m model, latitude-specific meteorological parameters were replaced by in situ meteorological measurements. In such a way a new UNBe.eu model was developed that covers the EGNOS (European Geostationary Navigation Overlay Service) augmentation system area. For over 70% of test stations an improvement was found in the consistency between UNBe.eu and radio sounding, however, for some locations near oceans and seas the new model was less accurate than original UNB3m model, which was probably related with the lack of relative humidity amplitude estimation from meteorological stations.

Wilgan et al. (2015) presented inter-comparison of tropospheric and meteorological parameters from different data sources: NWP model COAMPS (Coupled

Ocean/Atmosphere Mesoscale Prediction System), ZTD GNSS calculated from the ASG-EUPOS network, ground-based meteorological observations from EPN stations and radiosondes. The values of meteorological parameters from COAMPS were compared w.r.t. EPN and radiosondes. From the comparison of GNSS ZTD with NWP model it was concluded, that the troposphere model based on NWP may have insufficient accuracy for precise positioning (approx. 20 mm), but a high spatial resolution. Thus, the best solution for positioning is the integration of NWP models with GNSS products of high quality.

The troposphere delay model dedicated to real-time application was developed by Wilgan (2015), who presented the short-term predictions of NRT ZTD using autoregressive (AR) and autoregressive moving average (ARMA) statistical models. The forecasts were included in local (each station has a separate prediction model) and global (one statistical model provided for all stations simultaneously) mode. The statistical forecasts showed much better agreement with the reference GNSS data than ZTDs from GPT2 model or NWP model COAMPS. For the 5 h local forecasts, the statistical models exhibited the average bias close to 0 with standard deviations of 5–10 mm, the COAMPS model bias ranged from −20 to 20 mm with a standard deviations of 8–10 mm, and for the GPT2 the bias ranged from −40 to 40 mm with a standard deviation of approx. 10 mm. It was also concluded that there is no need to use the local mode, only the global one, which allows for the automation of the prediction process for all stations simultaneously, without the loss of accuracy.

Integrated models of troposphere based on the least-squares collocation technique were presented in Wilgan et al. (2017a). It was found that for mountainous areas (Switzerland) the highest agreement with reference radiosonde data was obtained when the total refractivity was calculated from meteorological measurements and ZTD from GNSS stations, but adding the horizontal gradients of ZTD did not improve the model. In the lowlands area (Poland) the height distribution of ground-based meteorological stations was too flat to reconstruct the refractivity profiles with the collocation technique. Thus, the best agreement was obtained when the troposphere model was built based on high-resolution NWP WRF model data integrated with GNSS data. The developed ZTD model was compared with NRT ZTD for 9 days in May 2014, during which a severe weather event occurred. A bias of 3.7 mm with standard deviation of 16.7 mm was observed. In the following study the integrated troposphere model for Poland based on WRF and GNSS data was applied into real-time PPP (Wilgan et al., 2017b). The proposed model is a high-resolution alternative for the state-of-art models such as UNB3m or Forecast Gridded VMF1-FC model. It allowed for the reduction of coordinate bias and shortening of the convergence time. Please, see section 3 (Advances in Precise Point Positioning) for more details.

The tropospheric delay prediction method proposed by Rzepecka et al. (2015) can be placed between empiric and NWP-based models. It uses the fact that after removing annual and semi-annual signals from VMF1 time series the autocorrelation of the result residuals is significant for lags far exceeding one day. For the analyzed case, the zenith wet delays range from 0 to about 30 cm and the residuals range from −10 cm to +10 cm. After modeling the residuals as the ARMA processes, the result value is a sum of the linear regression functions and the models of residual processes. One-step forecasts based on the above models were estimated to be within ±2.5 cm to ±4 cm for 80% of confidence level.

Kroszczyński (2015) analyzed GPS waves propagation in the atmosphere, focusing on the low (< 20°) elevation angles. He noticed, that slant tropospheric delay is a function of azimuth, which reflects spatial heterogeneousness of the atmospheric state including the distribution of humidity, and may cause anisotropy of slant delays reaching 1 m. Atmospheric refraction model can be obtained by using the non-hydrostatic mesoscale model forecast data, which determines various atmospheric conditions.

Nykiel et al. (2018) conducted research related to the usage of water vapour derived from GNSS processing for very-long-baseline interferomatry (VLBI) applications. A correlation between the GNSS IWV obtained with several strategies and the atmospheric opacity ($\tau_0$) from the sky-dip method was greater than 0.94, with only small differences in linear regression coefficients and in standard error (Fig. 9). It is concluded that GNSS IWV can be successfully used for calibration of VLBI observations or validation of $\tau_0$. On the other hand, $\tau_0$ can be a valuable verification of estimated IWV.

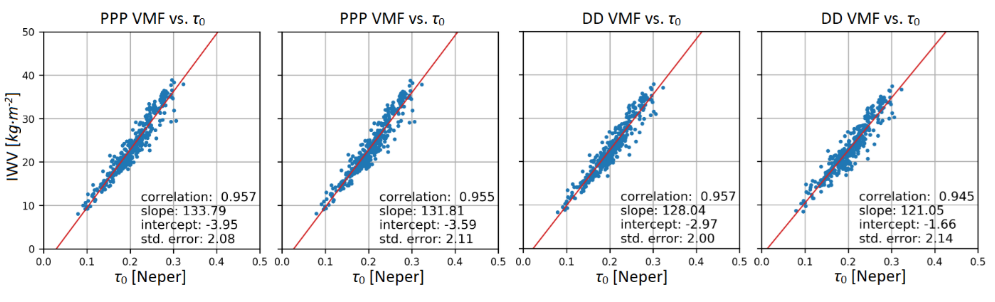


Fig. 9. Correlations between IWV derived from GNSS processing and $\tau_0$ from sky-dip method

### *4.4. Climate studies and meteorology*

Baldysz et al. (2015) investigated whether the long-term and seasonal changes of the ZTD parameter may reflect the real long term weather changes, or not. They found a correlation between the character of the ZTD time series and prevailing weather conditions occurring over a given region. Distribution of the ZTD linear trends characters (positive and negative) was found to result from the real tropospheric changes. Long-term changes of the ZTD parameter seemed to reflect some decadal variations which took place in the troposphere over the analyzed 16-year and 18-year time span. Therefore, Baldysz et al. (2016) presented a comparative analysis of the ZTD long-term changes obtained on the basis of two independently processed GNSS data, namely Repro 1 and Repro 2. Both reprocessing campaigns were different from each other in terms of tropospheric mapping functions, ionospheric delay modelling, applied tidal and non-tidal loadings. In vast majority, differences in the ZTD linear trends between solutions indicated smaller linear trends values for Repro2. It is concluded that adopted processing strategy affect estimated linear trends and in consequences, may disturb a proper and reliable usage of the GNSS products in a climate changes monitoring. These works were continued in (Baldysz et al., 2018) in order to identify factors affecting the estimated IWV time series the most. IWV was obtained using meteorological data from ECMWF (European Centre for Medium-Range Weather Forecasts) ReAnalysis (ERA-Interim) NWP model and ZTD obtained with 10 different processing schemes, and compared with radiosonde data. It was found out that the solutions obtained using PPP approach were characterized by higher consistency to the radiosonde observations than DD solutions, regardless of the used mapping function and the zenith hydrostatic delay (ZHD) *a priori* values.

Gołaszewski et al. (2017b) analysed the characteristics of water vapour surrounding an extreme weather event using high-resolution GNSS tropospheric estimates. GNSS results obtained with Bernese GNSS Software v.5.2 and G-Nut software were compared against IWV from ERA-Interim reanalysis and microwave radiometer collocated to GNSS station. Validation confirmed that both GNSS software provide high-quality tropospheric products that are with a very high agreement with the IWV from ERA-Interim and radiometer.

### *4.5. Application of Radio Occultation measurements in troposphere studies*

The GPS radio occultation (RO) technique utilizes a receiver on a low-Earth orbiting (LEO) satellite to derive profiles of geophysical parameters from a limb viewing geometry. Radio signals propagating from a GPS satellite experience a phase delay and gets refracted as a result of atmospheric density. The inversion process that attributes the measured excess phase to profiles of the bending angle, refractivity and further to dry pressure and temperature in the neutral atmosphere has been implemented in a retrieval software (Hordyniec et al., 2018). The occultation signals collected on-board FORMOSAT-3/COSMIC satellites are inverted by means of geometrical optics in the upper atmosphere and the tropospheric multipath is resolved with radio-holographic Full Spectrum Inversion (FSI) method. The statistical optimization compensates the higher order ionospheric noise using an adaptive weighting of bending angle profile based on measured signal to noise ratio (SNR). An excellent agreement with radiosonde data is observed within the upper troposphere and lower stratosphere (UTLS) region where the dry-air assumption in the retrieved pressure and temperature is no longer an issue.

Amongst a number of factors that contribute to the atmospheric refraction, the gaseous terms associated with pressure, temperature and water vapour dominate over liquid and solid particles. Contributions of frequently observed cloud water fractions as well as significant examples were studied in terms of induced retrieval errors in radio occultation profiles (Hordyniec, 2018). Clouds typically produce single-spike structures in the refractivity profiles with a fractional difference up to 1%, which corresponds to an error of 4% in the bending angle. The distribution of cloud water along the propagation plane allows for the application of Abel transform due to its spherically symmetrical characteristic. However, horizontal inhomogeneities should be considered in the case of a significant cloud content to avoid overestimation of propagation effects. The uppermost contribution of liquid clouds can exceed fractional differences of 10% in the bending angle and 2% in the refractivity, whereas the ice water is generally within 1% and 0.5%, respectively.

Lasota et al. (2018) used RO technique to examine the influence of dense clouds present in tropical cyclones on the GNSS signal. The RO technique is widely assumed to be insensitive to clouds, however, it was confirmed that positive mean biases of refractivity and bending angle anomalies are present and reach up to 0.5% and 1.6%, respectively. Furthermore, analysis of RO bending angle sensitivity on cloud ice and liquid water contents derived from collocated CloudSat profiles with respect to the RO bending error was performed. It was found out that clouds' influence exceeds bending angle uncertainty in 21 out of 50 examined cases. In general, for single observations, most of the clouds are detectable between 8 and 14 km while mean cloud impact is significant between 9.0 and 10.5 km with a mean contribution to the total bending angle of 0.1%. Slightly less than 15% of the cases with detectable clouds' influence surpass a height of 16 km, which is assumed to be a minimum height of the tropopause in tropics.

The GPS RO technique utilizes a receiver on a LEO satellite to derive profiles of geophysical parameters from a limb viewing geometry. Radio signals propagating from a GPS satellite experience a phase delay and gets refracted as a result of atmospheric density. The inversion process that attributes the measured excess phase to profiles of the bending angle, refractivity and further to dry pressure and temperature in the neutral atmosphere has been implemented in a retrieval software (Hordyniec et al., 2018). The occultation signals collected on-board FORMOSAT-3/COSMIC satellites are inverted by means of geometrical optics in the upper atmosphere and the tropospheric multipath is resolved with radio-holographic FSI method. The statistical optimization compensates the higher order ionospheric noise using an adaptive weighting of bending angle profile based on measured SNR. An excellent agreement with radiosonde data is observed within the UTLS region where the dry-air assumption in the retrieved pressure and temperature is no longer an issue.

## 5. Ionosphere studies

Banville et al. (2017) investigated the effect of accounting for both first- and second-order ionospheric effects on the slant ionospheric delay parameter estimates when GPS observations are estimated within a static and kinematic PPP solution. They examined the approach of Zehentner and Mayer-Gürr (2016) introducing additional constraints on slant TEC and providing more numerical tests and examples. They employed four European permanent stations situated in mid-latitudes and auroral oval with observations covering high solar activity. Four cases were tested: (1) without higher-order ionospheric corrections applied, (2) higher-order ionospheric corrections added within PPP, (3) first and second-order corrections applied within the PPP filter and (4) the same as (3) but with additional constraints on the slant TEC added. The authors found that the PPP solution is affected by higher-order ionospheric effects. Especially, changes in the positions reaching up to few millimetres were observed. They recommended that the receiver differential code biases need to be properly handled to provide unbiased estimates of the receiver position. As the conclusion, they stated that the explicit estimation of higher-order ionospheric effects should not be performed within the PPP filter.

Araszkiewicz et al. (2015) examined the coordinates and baselines between 30 European EPN stations when different higher order ionospheric corrections (I2 and I3) added at the stage of the GPS processing. They observed, that for the northern part of Europe adding higher order ionospheric corrections causes the root-mean-square value of the North component to increase. For the remaining areas, the horizontal coordinates changed between 0.1 and 0.2 mm.

Hadaś et al. (2017a) employed GPS and GLONASS observations from a global and two regional networks in Poland and Brazil to examine the impact of the higher order ionospheric (I2+) terms on the GNSS products, i.e. satellite orbits, satellite clock corrections, Earth rotation parameters, troposphere delays, horizontal gradients and receiver positions. They employed a global GNSS solution, RTK and PPP algorithms. They developed a Web service (http://www.smartnetleica.pl/o-nas/horion/#horion-pl) which helps to remove the I2+ effects directly from the RINEX (Receiver Independent Exchange System) file. They examined two different areas, i.e. the low-latitude network in Brazil and the mid-latitude network in Poland, with three test periods to evaluate various ionosphere conditions with high solar maxima, minima and a geomagnetic storm. They found that the I2+ corrections are tightly related to the signal frequency (L1/L2) and dependent on the TEC level; the greatest corrections ranged, for the L1 signal, between −15 mm and 2 mm during the geomagnetic storm and, for the L2 signal, between −24 mm and +23 mm for the high TEC level period. The satellite orbits and satellite clock corrections reached up to 20 mm when I2+ corrections were applied. The impact of higher order ionospheric terms was found to be insignificant for ZTD and horizontal tropospheric gradients estimated within the GNSS data processing. However, the I2+ corrections influence the positions' estimates leading to their shift up to −11 mm for the most active ionosphere conditions.

Krypiak-Gregorczyk and Wielgosz (2018) presented a completely new approach, suitable for ionospheric modelling on global and regional scales, to estimate the carrier phase bias of the scaled L1 and L2 differences. Their algorithm was based on the ambiguities, the ionospheric delay and hardware delays. Using varying ionospheric conditions, the authors proved that they are able to estimate the carrier phase bias of geometry-free linear combination with a very high accuracy. The uncertainty lower than 1 TECU was obtained for the TEC values.

Nykiel et al. (2017) employed a dense GNSS network to analyze the TEC variations over Central Europe and demonstrated that this kind of network allows to analyze a structure and temporal evolution of mesoscale ionospheric irregularities. They focused on a special type of plasma inhomogeneities, which is called MSTID. A usage of dense GNSS network allowed to obtain MSTID characteristics as spatial dimensions, velocities, and directions of their movement. They analyzed two days of magnetic storm, i.e. $17^{th}$ March 2013 and 2015, and proved that the TEC values form a dynamic structures during the magnetic storms which do significantly differ from the dynamics of ionospheric processes on quiet days. The authors found a clear, easily observable boundary of TEC variations increase during the storm, situated at 52° N. Hernández-Pajares et al. (2017b) presented disturbances in precise GPS processing. They employed a network of GNSS receivers in Poland operating during two days: one in winter and one in summer, and demonstrated that the direct GNSS Ionospheric Interferometry (dGII) technique helps to obtain a reliable RTK position faster of 13 to 30 s comparing to uncorrected observations. They concluded that their MSTID mitigation methodology is suitable for spare GNSS networks and helps to reduce the error up to 90%. The dGII algorithm can also be applied in real-time conditions under MSTID activity and depends only on reference ionospheric data from a single permanent receiver.

Krypiak-Gregorczyk et al. (2017a) proposed to employ the un-differenced multi-GNSS carrier phase data to estimate the TEC values and dense the existing ionospheric maps, especially on a regional scale. They also derived the slant-TEC-based methodology to analyze the self-consistency of the ionospheric products. These ionospheric maps were compared to global solutions for different ionospheric conditions, including also the geomagnetic storm. The authors showed that the accuracy of their regional solution is better than 1 TEC unit and at least 2 times better than the global products. Global ionospheric maps were also computed by Sun et al. (2017) who employed the a set of ground-based GNSS receivers and FORMOSAT-3/COSMIC GPS occultation experiment to construct the TEC map named Taiwan Ionosphere Group for Education and Research (TIGER) Global Ionospheric Map (GIM). This map was built applying the Kalman filter and spherical harmonic formula. As a result, a map of 5 min temporal resolution and $2.5° \times 5.0°$ spatial resolution was obtained. They proved that this map correlates well with global GIM published by international institutes. GIMs were also discussed in details by Hernández-Pajares et al. (2017a) who characterized the observations and methods employed for their construction and assessment. They analyzed the consistency of GIM-derived TEC using the vertical TEC delivered from altimetry measurements and the difference of slant TEC based on the 26 GPS observables. Both measurements were collocated to each other. This kind of comparison between altimetry- and GPS-derived TEC values was also performed by Roma-Dollase et al. (2018) to prove a consistency of various GIMs during one solar cycle. The authors compared all IGS-delivered GIMs and concluded that despite different various GIM techniques and algorithms are applied, all maps are very consistent to each other.

A usage of the least-square collocation method with a noise variance was presented by Krypiak-Gregorczyk et al. (2017b) to model the TEC values on a regional scale. In this way, they obtained the high accuracy ionospheric maps with a high spatial and temporal resolution of TEC variations. To examine the new TEC regional solutions, the authors derived the double-difference ionospheric corrections directly from these maps and analyzed their accuracy, comparing to IGS and UPC global and CODE regional maps. Moreover, they also applied the ionospheric corrections to GNSS positioning and analyzed the ambiguity resolution. Tests were performed for ionospheric storms. Results prove that the accuracy of the relative ionospheric corrections is better than 10 cm in most cases. Based on that, the authors concluded that their newly delivered regional TEC maps can support the ambiguity resolution in kinematic GNSS positioning.

A completely new IGS ionospheric product named as Rate of TEC Index (ROTI) Maps was introduced to geodetic community by Cherniak et al. (2018). This product presents the irregularities and intensities of ionosphere for high and middle latitudes of the Northern Hemisphere and allows to monitor it continuously. It is based on the ground-GPS 30-s sampled measurements collected at the number of 700 permanent stations. The assessment of ROTI Maps performance was provided for the geomagnetically quiet period and for the geomagnetic storms.

A new field of study is the use of the LOw-Frequency ARray (LOFAR) to perform solar and space weather studies was proved by Dąbrowski et al. (2016). They described a set of 50 European LOFAR stations, 3 of which are situated in Poland, and discussed their role to observe a radio source. A great attention was paid to the ionosphere layer, which causes a delay and therefore, also, the phase errors. This topic was further investigated also by Kotulak et al. (2017) who stated that LOFAR is not able to estimate the ionospheric corrections in a proper way due to too long baselines. Therefore, is should be combined with other dataset, which provide accurate ionosphere observables. Nowadays, the geodetic community is supported with the GNSS technology which permanently sounds the ionosphere. On this basis, using a wide range of GNSS stations, vertical TEC measurements can be interpolated into a continuous fields and successfully used to accompany LOFAR observations.

The state of the high-latitude ionosphere was also the subject of intensive studies presented in (Sieradzki, 2015; Sieradzki and Paziewski, 2018). In the first paper it was confirmed that the current distribution of the GNSS stations allows permanent monitoring of the ionosphere with subdaily temporal resolution. Moreover it was revealed that ROTI values strongly depend on the orientation of the GNSS signal in space. In the second paper the researchers proposed an innovative method suitable for detection of the large scale ionospheric disturbances. The method was applied to the characterization of the interhemispheric patches during St. Patrick geomagnetic storm. The paper justified high applicability of the method and consistency of the results with other techniques such as SWARM mission.

## 6. Summary and conclusions

This report provides selected examples of research activities on GNSS positioning and atmosphere remote sensing carried out at Polish research institutions during years 2015–2018. In particular, improvements in the mathematical and stochastic models and carrier phase ambiguity resolution, together with advances in troposphere and ionosphere modelling were demonstrated. It shall be noted that these research were often carried out in the frame of IAG Commission 4 working and study groups, and their results were published in high-quality scientific journals. The most active research groups in these fields of studies are affiliated with the Gdansk University of Technology, the Military University of Technology (Warsaw), the University of Warmia and Mazury in Olsztyn, the Warsaw University of Technology and the Wroclaw University of Environmental and Life Sciences.

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*Review paper*

# Global Geodetic Observing System 2015–2018

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**Abstract:** Global Geodetic Observing System (GGOS) was established in 2003 by the International Association of Geodesy (IAG) with the main goal to deepen understanding of the dynamic Earth system by quantifying human-induced Earth's changes in space and time. GGOS allows not only for advancing Earth Science, including solid Earth, oceans, ice, atmosphere, but also for better understanding processes between different constituents forming the system Earth, and most importantly, for helping authorities to make intelligent societal decisions. GGOS comprises different components to provide the geodetic infrastructure necessary for monitoring the Earth system and global changes. The infrastructure spreads from the global scale, through regional, to national scales. This contribution describes the GGOS structure, components, and goals with the main focus on GGOS activities in Poland, including both the development of the geodetic observing infrastructure as well as advances in processing geodetic observations supporting GGOS goals and providing high-accuracy global geodetic parameters.

**Keywords:** GGOS, GNSS, SLR, VLBI, EPOS-PL

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## 1. Introduction – GGOS structure and most recent activities

A highly accurate and stable reference frame is necessary to monitor various geophysical phenomena affecting the system Earth and global society. These phenomena include: eustatic sea level rise, glacier melting and changes in the cryosphere, plate tectonic motion and post-seismic deformations, volcanology, postglacial uplift and loading displacements due to the changing climate and secular variations in the land hydrosphere, oceans, and atmosphere. According to Plag and Pearlman (2009), the required measurement accuracies of the international reference frame are 1 mm for positions and 0.1 mm/yr for velocities. Monitoring of these small and short-term and long-term variations, especially the eustatic sea level rise that assumes the level of about 3.4 mm/yr, needs a stable reference frame as otherwise reference frame errors will propagate into the estimates. Proper geodetic infrastructure is essential for monitoring the phenomena directly affecting the society such as natural earthquakes and anthropogenic tumbles in mining areas, flooding, tsunamis, volcanic activities, and other kinds of natural and anthropogenic hazards. To provide a corresponding international reference frame, the Global Geodetic Observing System (GGOS, Gross et al., 2009) was established first in 2003 as a pilot project and in 2007 as a full component, assuming the role of the observing system of the International Association of Geodesy (IAG). GGOS is built upon the foundation provided by the IAG Services, Commissions, and Inter-Commission Committees (see Figure. 1) with cooperation with the International Earth Rotation and Reference Systems Service (IERS).

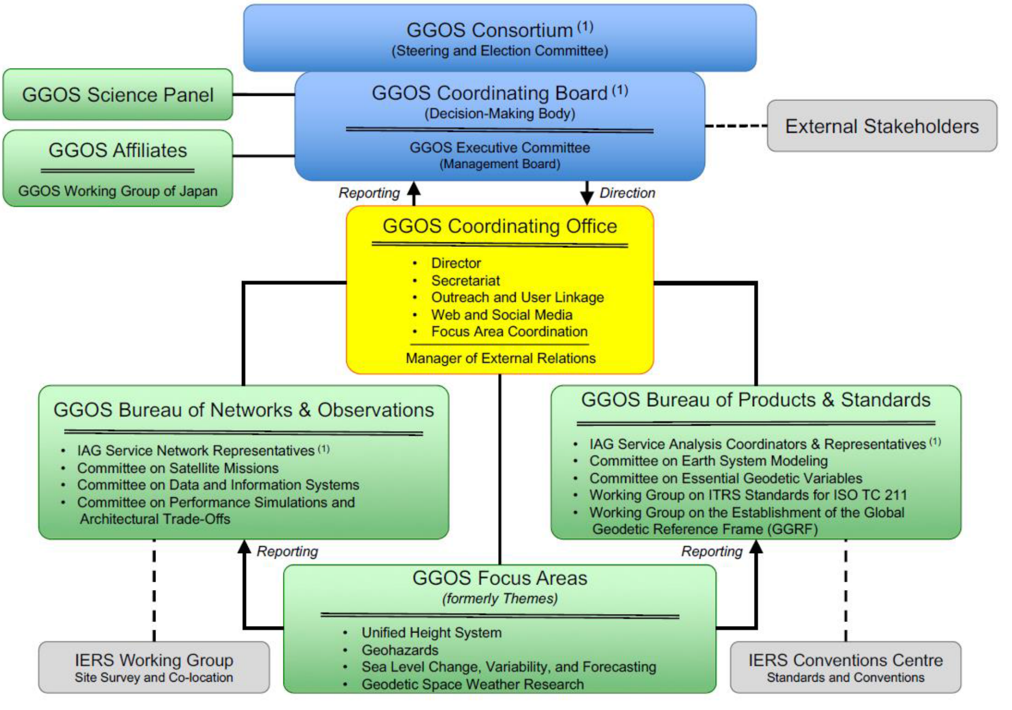


Fig. 1. GGOS structure, after Gross (2018)

In February 2015, the United Nations (UN) General Assembly adopted the resolution on a Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) that recognizes the importance of a globally coordinated approach to geodesy. The UN Committee of Experts on Global Geospatial Information Management decided to formulate and facilitate a resolution for a global geodetic reference frame and established a working group on the Global Geodetic Reference Frame (GGRF). The task of the working group was to formulate the resolution and prepare a roadmap for GGRF for sustainable development according to the UN GA resolution[1].

[1] http://ggim.un.org/knowledgebase/KnowledgebaseArticle51654.aspx

The GGRF roadmap addresses each of the key areas of action described in the UN General Assembly resolution[2]:

– Data sharing: Development of geodetic standards and open geodetic data sharing that are required to enhance and develop the GGRF.
– Education and capacity building: Appropriate geodetic skills and educational programs that are essential for the development, sustainability, and utilization of the GGRF.
– Geodetic infrastructure: A more homogeneous distribution of geodetic infrastructure that is needed to develop and utilize an accurate GGRF.
– Communication and outreach: developing communication and outreach programmes that enable the GGRF to be more visible and understandable to society.
– Governance: The development and sustainability of the GGRF that is reliant on an improved governance structure.

In 2017, the new UN Subcommittee on Geodesy was inaugurated in Mexico City in the aftermath of the decision of the UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) to elevate the GGRF working group to a permanent Subcommittee on Geodesy. On the 4th August 2017, the UN-GGIM seventh session in New York endorsed the terms of reference and formally established the first permanent UN-GGIM Subcommittee on Geodesy.

In 2018, a new initiative within GGOS has been established with a goal to officially define the so-called Essential Geodetic Variables (EGVs; Gross, 2018). EGVs are observable variables that are essential to characterize the geodetic properties of the Earth and that are key to sustainable geodetic observations. Examples of EGVs might be Earth orientation parameters, ground- and space-based gravity measurements, and the positions of reference objects including ground stations and radio sources. EGVs will be associated with requirements that might be accuracy, latency, or spatial and temporal resolution. The EGV requirements can also be used to derive requirements on the systems that are used to observe the EGVs, helping to lead to a more sustainable geodetic observing system for reference frame determination and numerous other scientific and societal applications. A dedicated IAG Committee on EGVs currently works in the framework of GGOS activities (Gross, 2018).

This review paper covers important activities of Polish research groups representing the Wroclaw University of Environmental and Live Sciences, University of Warmia and Mazury in Olsztyn, Institute of Geodesy and Cartography in Warsaw, Technical University of Koszalin, Warsaw University of Technology, Space Research Centre of the Polish Academy of Sciences in the frame of GGOS activities.

## 2. GGOS – three pillars, observational techniques, and geodetic parameters

The main three pillars of geodesy, thus also of GGOS, can be summarized as follows (Rothacher, 2003, see Figure. 2):

[2]http://ggim.un.org/knowledgebase/Attachment1393.aspx?AttachmentType=1

– precise determination of geometrical three-dimensional positions and velocities in pre-defined global, regional, or local reference frames,
– determination of the Earth's gravity field and its temporal variations,
– modeling and observing of geodynamical phenomena (such as tectonic plate motion, loading crustal deformations), including also the rotation and orientation of the Earth that are characterized by polar motion, Earth rotation angle or UT1-UTC, precession and nutation parameters.

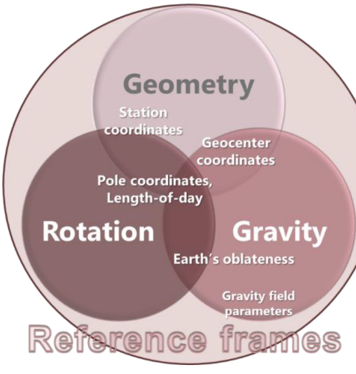


Fig. 2. Three pillars of geodesy as GGOS components integrated by reference frames

Furthermore, GGOS and satellite geodesy contribute to physics and astronomy by deriving the fundamental constants, e.g., the gravitational product GM, and by proving the effects of general relativity, i.e., the geodetic precession (de Sitter effect), and the Lense-Thirring frame dragging (Ciulfonini and Pavlis, 2004; Zieliński and Wielgosz, 2018).

GGOS includes four basic observation techniques that are used for the realization of the International Terrestrial Reference Frames (e.g., ITRF2014; Altamimi et al., 2015), namely:
– Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR),
– Very Long Baseline Interferometry (VLBI),
– Global Navigation Satellite Systems (GNSS),
– Doppler Orbitography and Radiopositioning Integrated by Satellite (Determination d'Orbite et Radiopositionnement Integre par Satellite, DORIS).

All techniques are coordinated and managed by corresponding services, that is: the International Laser Ranging Service (ILRS; Pearlman et al., 2002), the International VLBI Service (IVS; Schlüter and Behrend, 2007), the International GNSS Service (IGS; Dow et al., 2009), and the International DORIS Service (IDS; Willis et al., 2010).

Three techniques employ observations in the radio (or microwave) domains: VLBI, GNSS, DORIS. One technique is based solely on laser observations in visible domain or near-infrared: SLR/LLR. Three techniques are satellite-based techniques: SLR/LLR, GNSS, DORIS, whereas VLBI primarily observes extragalactic radio sources, the so-called quasars, thus, belongs to "space geodesy" and not directly to "satellite geodesy".

The absolute orientation of the figure Earth in the celestial reference frame can be provided only by VLBI and LLR, whereas satellite-based techniques can provide relative orientations (e.g., changes of UT1-UTC or changes of nutation parameters in time).

Within the GGOS, other techniques are also adopted for geodetic monitoring of the system Earth to provide complex observations of all three pillars:

- satellite altimetry: based on microwaves (e.g., Topex/Poseidon, Jason-1/2/3, ENVISAT, Cryosat-2, HY-2A, Sentinel-3A/B) and based on laser observations (ICESat-1/2),
- Interferometric Synthetic Aperture Radar missions (InSAR, e.g., ERS-1/2, ENVISAT, TerraSAR-X, TanDEM-X, PAZ, Sentinel-1A/B),
- satellite gravimetry (e.g., CHAMP, GRACE-A/B, GOCE, GRAIL, GRACE-FO-1/2),
- satellite optical imagery (e.g., Landsat-7/8, Sentinel-2A/B, Sentinel-3A/B),
- satellite geomagnetic field mapping (CHAMP, Ørsted, SWARM-A/B/C),
- radio-occultation missions (e.g., COSMIC-1/2, CHAMP, GRACE-A/B),
- inter-satellite communication missions supported by SLR (SNET-1/2/3/4),
- general relativity missions (Gravity Probe B, LARES, Galileo-E14/E18),
- VLBI observations from space (RadioAstron).

The four fundamental GGOS observational techniques are co-located on the Earth using the so-called local ties at core GGOS sites. Local ties constitute precisely measured vectors between reference points of different techniques, e.g., a 3D vector between the intersection of two major SLR telescope axes and the antenna reference point of a GNSS antenna. The alternative for the ground co-location is the co-location in space, i.e., onboard satellites employing different techniques. A series of missions integrating different techniques has been launched:

- SLR and GNSS: Galileo (all satellites), GLONASS (all satellites), QZSS (all satellites), IRNSS (all satellites), GPS (2 satellites), BeiDou/COMPASS (selected satellites), CHAMP, GRACE-A/B, GOCE, SWARM-A/B/C, ICESat-2, COSMIC-2, Terra-SAR, TanDEM-X, etc.
- DORIS and SLR: TOPEX/Poseidon, ENVISAT, CRYOSAT-2, SARAL, Jason-1 (after 2009),
- VLBI and SLR: RadioAstron,
- VLBI, SLR, and GNSS: APOD,
- DORIS, GNSS, and SLR: Jason-2/3, HY-2A, Sentinel-3A/B,
- SLR, VLBI, GNSS, and DORIS: GRASP, E-GRASP (proposed missions).

Figure 3 shows missions that co-locate or integrate onboard satellites different observational techniques of space geodesy. SLR retroreflectors are passive and relatively cheap devices, thus, they are installed onboard many low and high-orbiting satellites. Many low-orbiting satellites for ocean monitoring are equipped with DORIS and GNSS receivers for precise orbit determination, and SLR retroreflectors for orbit validations (e.g., Arnold et al., 2019) DORIS receivers are not installed on satellites orbiting above 2000 km. Gravity field missions are typically equipped with GNSS and SLR (Strugarek et al., 2019). Most of GNSS satellites are equipped with SLR retroreflectors (except for GPS, Sośnica et al., 2015c). VLBI telescopes are typically slow as they are dedicated to track extragalactic quasars. Hence, many VLBI telescopes have problems with tracing fast-moving low-orbiting targets that are planned for the co-location onboard satellites. However, first experiments using APOD satellite with a VLBI transmitter and SLR retroreflector was successful in Australia (Hellerschmied et al., 2018). Unfortunately, the APOD GPS receiver failed soon after the satellite launch.

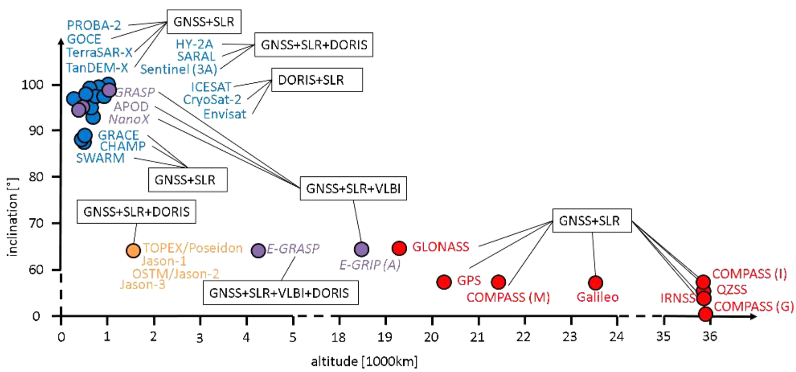


Fig. 3. Available satellites for co-location in space ordered by their altitude and inclination; planned missions are set in italics; after Maennel (2016)

A series of mission co-locating all four fundamental GGOS techniques have been proposed: GRASP, E-GRASP/Eratosthenes, E-GRIP. GRASP was proposed in NASA's Earth Venture Mission Program in 2011 with the goal of the envisaged orbit accuracy of 1 mm in the radial component with a stability of 0.1 mm per year to meet the GGOS requirements. However, the mission was not selected for funding. The mission E-GRASP/Eratosthenes can be seen as a European alternative to GRASP with a different inclination angle, orbital height, and eccentricity (see Figure 3).

Table 1 provides a list of global geodetic parameters that are derived using different space geodetic techniques. There is no single technique that is sensitive to all GGOS parameters. Moreover, none of the techniques can be eliminated without deterioration of most of the geodetic parameters. Many space geodetic parameters can be confronted with geophysical models (e.g., Winska et al., 2017; Wińska and Śliwińska, 2018) or ground-based observations, such as using the ring laser gyroscope (Tercjak and Brzeziński, 2017).

The absolute orientation of the Earth can be determined using only VLBI (or LLR). However, VLBI products are given session-wise, thus, there are some days with missing VLBI products (Wielgosz et al., 2016). Therefore, satellite techniques, GNSS and SLR, are used to provide the Earth rotation parameter UT1-UTC by deriving relative changes of this parameter – excess of the Length-of-Day. VLBI is also used for the realization of the global scale, together with SLR, because VLBI directly links the scale to the speed of light.

GNSS contains different navigation systems: GPS, GLONASS, BeiDou, and Galileo. Various regional navigation systems support GNSS, such as QZSS, NAVIC or

Table 1. Geodetic parameters and space geodetic techniques used for deriving particular parameters. XXX – a major technique, XX – a supporting technique, X – a capability for a parameter determination. Modified version after Sośnica (2015b)

| Parameter type | SLR | LLR | VLBI | GNSS | DORIS | Altimetry, InSAR | Gravity missions |
|---|---|---|---|---|---|---|---|
| Quasar coordinates | | | XXX | | | | |
| Nutation | X | XX | XXX | X | | | |
| Polar motion | XX | X | XX | XXX | X | | |
| UT1-UTC | | XX | XXX | | | | |
| Length-of-Day | XXX | XX | XX | XXX | X | | |
| Sub-daily Earth rotation and tides | XX | X | XX | XXX | X | X | |
| Sea level | | | | XX | | XXX | XX |
| Coordinates and velocities | XXX | X | XXX | XXX | XXX | X | |
| Earth surface deformations | XX | X | XX | XXX | XX | XXX | XX |
| Global scale | XXX | XX | XXX | XX | XX | X | |
| Gravity prod. GM | XXX | XXX | | X | X | | |
| Geocenter | XXX | XX | | XX | XX | X | XX |
| Gravity field | XXX | X | | X | XX | XX | XXX |
| Orbits | XXX | XX | | XXX | XXX | X | XX |
| Ionosphere | | | XX | XXX | XX | XX | X |
| Troposphere | X | X | XX | XXX | XX | XX | X |
| Timing | XXX | | XX | XXX | X | X | |
| General relativity | XXX | XXX | XXX | XXX | X | X | XX |

IRNSS, SBAS. GNSS is indispensable in the densification of the global reference frames to regional and national geodetic frames (e.g., Bosy, 2015). Only some of them are used for the ITRF realization (see Figure 4). GNSS is also the best technique for deriving pole coordinates, troposphere tomography, deriving high-precision orbits of low-orbiting satellites, and ionospheric mapping (e.g., Hernández-Pajares et al., 2017; Hadas et al., 2017a, 2017b). Today, there are tens of thousands active GNSS stations tracking GPS or GPS and GLONASS. Newly installed stations have also the capability of tracking all systems. The development of GNSS can be tracked on the IGS Multi-GNSS Experiment (Montenbruck et al., 2017) web site[3].

DORIS is used mostly for precise orbit determination of altimetry missions. Moreover, DORIS ground-based transmitters are used for the ITRF realization because of the

[3] http://mgex.igs.org/analysis/index.php

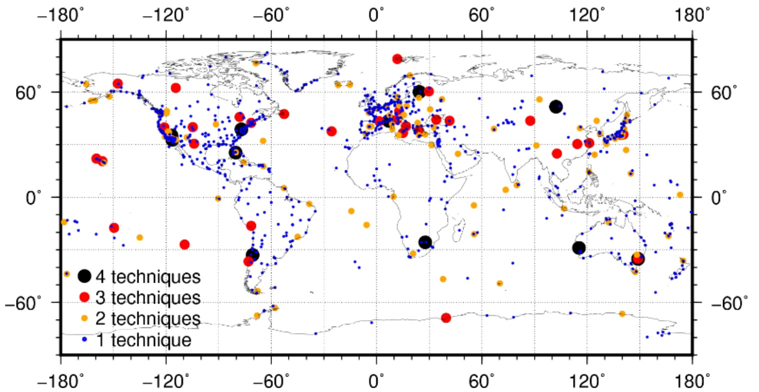

Fig. 4. Distribution of co-locations of four techniques used in ITRF2014 (Maennel, 2016)

worldwide even distribution of stations. In the latest realization of ITRF, DORIS was not used for the scale and origin (geocenter) realization. However, after removing errors related to orbit modeling deficiencies due to mismodeling of the solar radiation pressure and atmospheric drag, DORIS will possibly contribute to ITRF scale and origin in future.

SLR is the only optical-based technique. Therefore, SLR observations are free from ionospheric delays (as opposed to microwave-based GNSS, VLBI, and DORIS), whereas troposphere delays can be easily modeled because the wet troposphere delay is about 70 times lower than in case of microwave observations (Drożdżewski and Sośnica, 2018). SLR does not require any active devices onboard satellites. Thus, satellites can be covered by dedicated retroreflectors or single corner cubes. When the GNSS receiver onboard APOD failed, SLR was the only technique that could be used for precise orbit determination and thus allowed for successful termination of the mission. Geodetic satellites used for the ITRF realization have spherical shapes and very low cross-section area-to-mass ratio which minimizes the impact of non-gravitational perturbing forces. Moreover, SLR, as an optical technique, does not require satellite and receiver antenna calibrations. As a result, SLR is the only technique used today for the ITRF origin realization which should be located in the mean long-term Earth's center of mass. SLR is also used for the scale realization, however, some SLR stations are affected by range biases (Appleby et al., 2016), therefore, in ITRF2014 the SLR and VLBI-derived scales disagreed at the level of 7–8 mm (Altamini et al., 2016).

The main disadvantage of SLR is the weather dependency which means that SLR observations can only be performed under blue skies because the laser is subject to dispersion when passing through clouds. SLR telescopes can track only one target at a time. Today, there are about 120 satellites with retroreflectors. Therefore, SLR stations have to properly select targets according to the ILRS priority list and visibility. SLR can be also employed for tracking inactive satellites and providing the spin and rotation evolution of space debris (Kucharski et al., 2017, Lejba et al., 2018a).

## 3. Gravity field – from static to time-variable solutions

Gravity field missions, dedicated to the recovery of the time-variable field, such as GRACE and GRACE-FollowON, or missions dedicated to the recovery of the static gravity field, such as CHAMP and GOCE, dramatically changed the observation accuracy of the terrestrial gravity field, geoid heights, and water cycle in the global scale. GOCE, equipped with a precise gradiometer, was the lowest orbiting satellite at the height reduced from 250 to 230 km in 2013, which was only possible due to ion engines onboard spacecraft to compensate for the atmospheric drag. GRAIL – GRACE's sister mission to the Moon – provided unprecedented models of the lunar gravity field. In 2018 a new mission – GRACE-FollowON has been launched with a goal of continuing deriving temporal changes of the gravity field.

The project European Gravity Service for Improved Emergency Management (EGSIEM, Jäggi et al., 2018) was founded by the European Union's Horizon 2020 research and innovation programme in 2015–2018. Many European institutions providing temporal gravity field changes participated in the EGSIEM initiative to finally provide the most precise combined gravity field models. In 2018 the EGSIEM initiative was transformed to the new IAG service called the Combination Service for Time-Variable Gravity Field Solutions (COST-G).

Originally the EGSIEM solutions included only the GRACE-derived models, however, the initiative was extended to provide also SLR-derived models. As of 2018, three European institutions contributed to the combined EGSIEM SLR solutions: Astronomical Institute, University of Bern (AIUB), Technische Universität München (DGFI-TUM), and the Institute of Geodesy and Geoinformatics, Wrocław University of Environmental and Life Sciences (Bloßfeld et al., 2018).

SLR-derived gravity field models are characterized by a lower spatial resolution, because the expansion of the SLR-gravity fields are sensitive to the degree and order of about 6/6 with a selective sensitivity to 10/10 and higher degree/order coefficients (Sośnica et al., 2015a), whereas the GRACE models are typically expanded to at least 60/60. The major secular changes in the Earth's gravity field can be well determined from SLR despite lower spatial resolution (Figure 5).

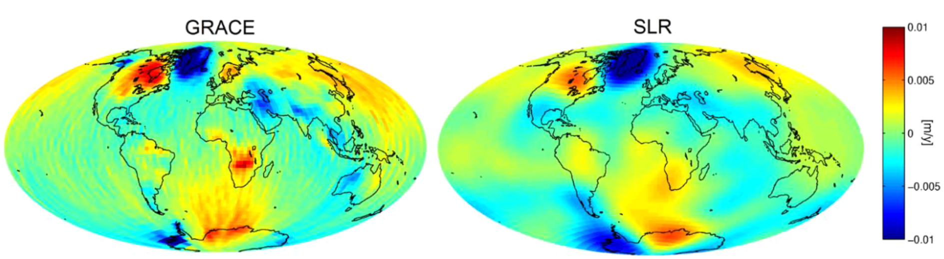


Fig. 5. Secular gravity field changes from GRACE and SLR observations, after Sośnica et al. (2015a)

GRACE K-band observations are in principle insensitive to the geocenter motion coefficients that are equivalent to gravity field parameters of degree 1. Moreover, the

Earth's oblateness term $C_{20}$ is also best derived from SLR observations. Therefore, geocenter coefficients and $C_{20}$ are typically replaced in the GRACE solutions by SLR products. GRACE and SLR solutions agree well in the recovery of the geoid height changes due to the ice mass depletion in Greenland, West Antarctica and Patagonia (Figures 5 and 6). The postglacial rebound in North America and hydrological changes in the Caspian region are also recoverable from SLR. However, due to the lower expansion of the SLR solutions, using scaling factors is needed when calculating the ice mass changes e.g. in Greenland (Meyer at al., 2018). SLR is eventually used for the recovery of the tidal displacements of the solid Earth (Jagoda et al., 2018; Jagoda, 2019).

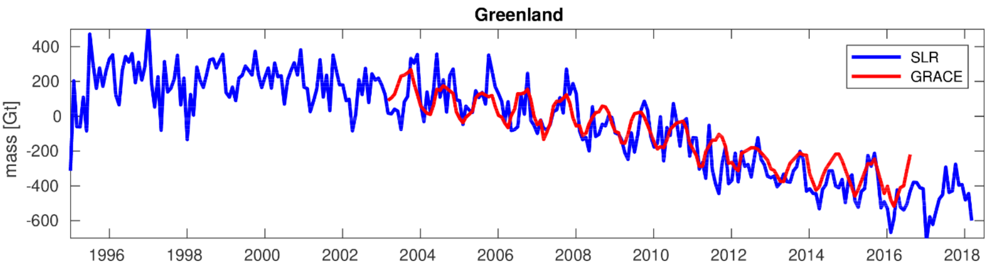


Fig. 6. Ice mass depletion in Greenland from 14 years of GRACE observations and 23 years of SLR observations, after Meyer et al. (2018)

## 4. Station coordinates and new GNSS constellations

Despite that different space geodetic techniques can be used for the determination of station coordinates: GNSS, SLR, VLBI, DORIS, and to some extent also InSAR, the largest and the quickest development for station coordinate determination in the period 2015–2018 was observed in the GNSS technique due to new and emerging GNSS systems. Nowadays, the multi-GNSS constellation consists not only of Medium Earth Orbiters

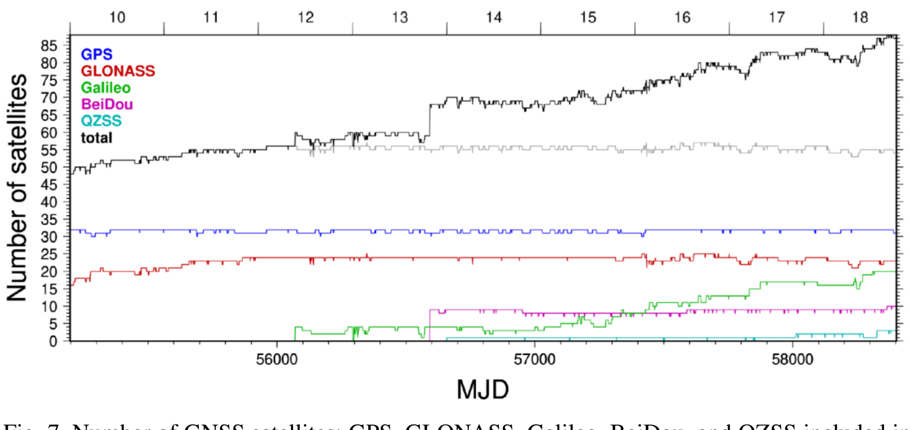


Fig. 7. Number of GNSS satellites: GPS, GLONASS, Galileo, BeiDou, and QZSS included in CODE MGEX solutions in the period 2010.0 and 2018.8, after Dach et al. (2018)

(MEO) but also, as in the case of Chinese BeiDou System, of Geosynchronous Earth Orbiters (GEO) and Inclined Geosynchronous Orbiters (IGSO).

The Multi-GNSS Experiment (MGEX) has been established in order to fully integrate all multi-GNSS constellations, ensure the access to all satellite navigation systems and provide high-precision science and application products (Montenbruck et al., 2017).

Today, the GPS constellation comprises 31 operational MEO satellites. GPS was the first global navigation system that achieved a Full Operational Capability (FOC) in July 1995. GPS satellites are allocated into blocks which correspond to satellites of a certain generation launched within a certain period. The first eleven satellites of Block I were launched between 1978 and 1985. Blocks II and IIa were developed between the 80's and 90's with two satellites equipped with laser retroreflectors for SLR (Bury et al., 2019a). The currently operating GPS satellites comprise Blocks IIR, IIR-M, and IIF. The first GPS of Block III was launched at the end of 2018.

The GLONASS constellation consists of 24 operational MEO satellites and reached its FOC in December 2011. The first phase of the Russian navigation system was introduced in the 80's. The second and modernized generation called GLONASS-M has been being developed since 1990 with the first M-type satellite launched in 2001. The latest GLONASS-M+ satellites transmit signals on the additional frequency L3 and are capable of performing the time transfer in space. The latest generation of GLONASS satellites comprises the K-type spacecraft. GLONASS K satellites also broadcast signals on L3 frequency.

The first prototype Galileo In-Orbit Validation (GIOVE) satellites were launched in 2005 and 2008, i.e., GIOVE-A and GIOVE-B. After the decommissioning of these test satellites, the operational phase has started with the first four operational satellites also denoted as the In-Orbit Validation (IOV) spacecraft. Due to power supply issues of E20, the satellite started transiting signal on only one frequency in 2014, whereas three out of four IOV satellites are still fully operational today. After a series of launches, 22 Fully Operational Capability (FOC) joined the constellation, out of which the first pair was accidentally launched into highly eccentric orbits. The two satellites cannot be used for navigation, however, they are well suited for geodesy and may serve as a tool for the investigation of gravitational redshift (Sośnica et al., 2018b; Paziewski et al., 2018). Today, the Galileo constellation includes 26 satellites, however, one IOV satellite transmits signal on just one frequency, one FOC had serious problems with onboard atomic clocks and thus was deactivated in December 2017. Thus, 24 Galileo satellites are fully useful for geodesy and 22 satellites for navigation. The fully operational capability of the Galileo constellation is planned for 2022.

The BeiDou constellation is being upgraded from regional BeiDou-2 (BDS2) to global BeiDou-3 (BDS3). The current set of operational BDS2 satellites contains 6 GEO satellites, 6 IGSO satellites, and 3 MEO satellites. In December 2018, 18 BDS3 MEO satellites launched so far have been set healthy, which yields a total of 21 MEO satellites for the global service and an additional 12 BDS2 GEO and IGSO satellites for the regional system[4]. At this stage, IGS infrastructure and data processing chains

[4]http://www.csno-tarc.cn/system/constellation&ce=english

can only offer limited support for the new BDS3 satellites. Even though BDS3 has two signals (B1I and B3I) in common with BDS2, dual-frequency tracking for the new MEO satellites is only supported by a limited number of stations. The generation of precise orbit and clock products is also hampered by incomplete satellite metadata information.

The QZSS constellation consists of 3 IGSO and 1 GEO satellites. The Indian NavIC constellation is a regional navigation system that consists of 7 (including 6 operating) GEO and IGSO satellites that cover with its range southern part of Asia, eastern regions of Africa, and north-west part of Australia.

Due to that fact of the increasing number of GNSS satellites with retroreflectors for SLR tracking, in 2014 the ILRS established a study group: LAser Ranging to GNSS s/c Experiment (LARGE) in order to develop GNSS tracking strategy for SLR stations. In the frame of the LARGE project, three special GNSS-tracking campaigns were held between 2014 and 2017 as well as several campaigns devoted to the other GNSS satellites. All campaigns resulted in substantial growth of the number of SLR observations to multi-GNSS satellites not interrupting in the ordinary proceedings on SLR stations which were adapted to the tracking of geodetic satellites.

In March 2017, a new ILRS Associated Analysis Center (ACC) has been established (Zajdel et al., 2017; Otsubo et al., 2019). The ILRS ACC is hosted by the Institute of Geodesy and Geoinformatics at the Wroclaw University of Environmental and Life Sciences. The new ILRS ACC validates the MGEX CODE orbit products, including Galileo, BeiDou, GLONASS, and QZSS precise orbits, and provides an online service called multi-GNSS Orbit Validation Visualizer Using SLR (GOVUS[5], see Figure 8). The GOVUS system not only fulfills a function of a web tool but also acts as the advanced computational center, which generates unique operational products, delivered every day to the end-user. GOVUS provides information on multi-GNSS orbit quality, changes of parameters in the GNSS constellations, characteristics of SLR ground segment, as well as on quality and quantity of SLR observations to multi-GNSS constellations (Zajdel et al., 2017). The GOVUS service and the corresponding scripts were used by the French Space Agency CNES to evaluate their implementations of Galileo ambiguity resolution and the quality of Galileo-derived orbits (Katsigianni et al., 2019).

Figure 8 shows that the orbit accuracy of Galileo satellites measured by SLR was 70 mm in the period 2012–2014. The orbit quality was improved when the new orbit model ECOM2 was introduced in January 2015 (Arnold et al., 2015), and in August 2017 when albedo and antenna thrust modeling were activated for precise orbit determination at CODE (e.g., Bury et al., 2018). The Galileo orbit quality after August 2017 is at the level of 30 mm (1-sigma level). Currently, many activities are conducted to increase the accuracy of Galileo orbits using box-wing analytical models and hybrid models, instead of fully empirical models as used presently by most of the MGEX analysis centers (Bury et al., 2019b). The potential contribution of Galileo onboard accelerometers is also currently considered (Zieliński et al., 2015; Kalarus et al., 2016; Lucchesi et al., 2016).

[5] www.govus.pl

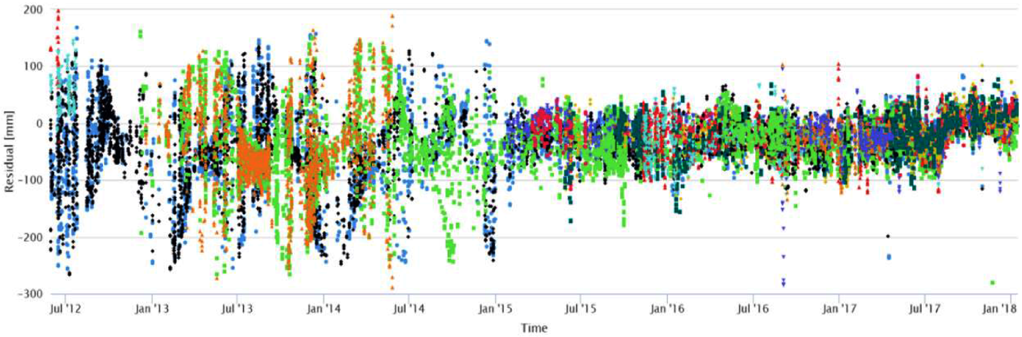


Fig. 8. Evolution of Galileo orbit accuracy as measured by SLR. Figure generated in the GOVUS service (Zajdel et al., 2017)

Kaźmierski et al. (2018a) performed a complex analysis of the quality of real-time orbits and clocks of new GNSS systems provided by the French Space Agency CNES with a comparison to final IGS MGEX products. The authors found that the 3D orbit errors when compared to CODE MGEX products, is 5, 10, 18, 18 and 36 cm for GPS, GLONASS, Galileo, BeiDou MEO and BeiDou IGSO, respectively. The error of BeiDou geostationary orbits is above the 1-m level. Moreover, the quality of orbits and clocks is a function of the satellite system, orbital plane and the elevation of the Sun above the orbital plane, the satellite altitude, as well as the satellite block and generation. Kaźmierski et al. (2018a) used all available GNSS systems for static precise point positioning (PPP) solutions. However, it turns out that the equal weighting of various GNSS systems does not significantly improve the multi-GNSS solutions when compared to GPS-only solutions.

Subsequently, Kaźmierski et al. (2018b) tested the impact of different approaches of multi-GNSS solution weighting. The authors found that improper or equal weighting may improve formal errors but decrease coordinate repeatability when compared to the GPS-only solution. Intra-system weighting based on satellite orbit quality allows for a reduction of formal errors by 40%, for shortening convergence time by 40% and 47% for horizontal and vertical components, respectively, as well as for improving coordinate repeatability by 6%. The weighting scheme that provided the best possible solution was based on the so-called signal-in-space ranging errors (SISRE), which take into account the orbit accuracy (especially in the radial direction) and the quality of satellite clocks (see Figure 9).

Kaźmierski (2018c) used the developed technology of proper multi-GNSS weighting using SISRE information for the kinematic multi-GNSS solutions employing a 26 km-long car route through villages, forests, the city of Wrocław, crossing under viaducts and a high voltage line. Thanks to the usage of the multi-GNSS constellation, the number of positioning epochs possible to determine increased by 10% for the whole route and from the level of 20% to 70% in the city center (see Figure 10). Therefore, the author concluded that new GNSS systems require a proper weighting to improve the combined

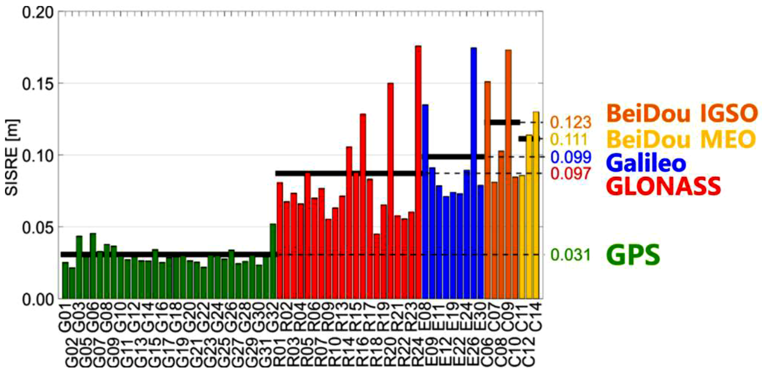


Fig. 9. Signal-in-space ranging errors (SISRE) for CNES multi-GNSS real-time products in 2016, after Kaźmierski et al. (2018b)

multi-GNSS solutions, however, the benefit for kinematic and static solutions due to new GNSS systems is remarkable.

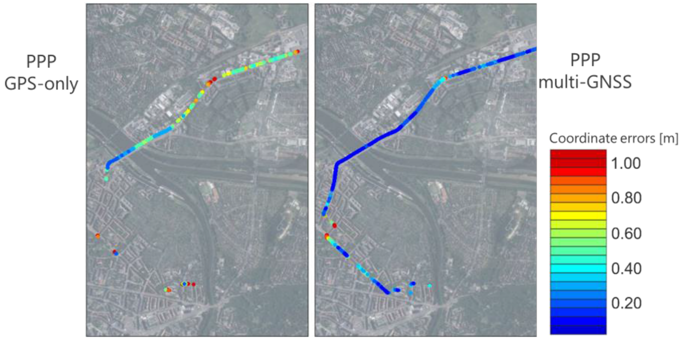


Fig. 10. Precise point positioning (PPP) solutions in a kinematic environment based on GPS-only solutions (left) and multi-GNSS solutions (right) using streamed CNES products and simulated real-time conditions, after Kaźmierski (2018). The experiment was performed in the city of Wrocław using a precise multi-GNSS receiver with a precise antenna installed on the roof a car in January 2018. Empty fields denote epochs without solutions due to the insufficient number of tracked GNSS satellites

In theory, all satellite geodetic techniques should be able to recover the geocenter coordinates. However, global GNSS and DORIS observations can be used for the determination of equatorial X and Y components of geocenter motion, but they are typically limited in the recovery of the Z-geocenter coordinate due to the correlation with orbit parameters related to the solar radiation pressure modeling.

Zajdel et al. (2019) analyzed differences in GNSS-based global geodetic parameters, such as station coordinates, Earth rotation parameters, geocenter coordinates, and satellite orbits delivered from the double-difference multi-GNSS (GPS, GLONASS and Galileo) processing. The differences arise from using a homogenous and inhomogeneous networks of multi-GNSS stations, different approaches to the ITRF realization using minimum constraint conditions, and different approaches to the handling of geocenter motion in GNSS global processing. Zajdel et al. (2019) found that the incomplete constellation of Galileo can provide geocenter coordinates, whose quality correspond to the GPS series (see Figure 11). Moreover, the geocenter coordinates from Galileo are of better quality than those based on GLONASS data, despite the same number of nominal orbital planes and a much lower number of active satellites.

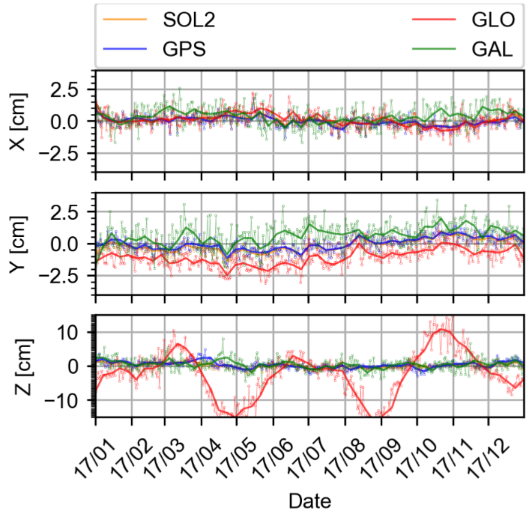


Fig. 11. GNSS system-specific geocenter coordinates. Scale for the Z geocenter component is changed for the sake of readability. GLO denotes GLONASS, GAL denotes Galileo, SOL2 denotes a combined GPS+GLONASS+Galileo solution, after Zajdel et al. (2019)

Zajdel et al. (2019) found that when the No-Net-Translation constraint is not applied on the GNSS network, the station coordinate repeatability is worsened by about 70, 55 and 25% for the North, East, and Up components, respectively compared to the solution when applying No-Net-Translation and when having the network origin consistent with the ITRF. Imposing an extra No-Net-Translation condition on the network and the estimation of geocenter as a parameter in the GNSS processing has no impact on the other estimated parameters, such as Keplerian orbit elements, Earth rotation parameters, or troposphere parameters. The GNSS-derived geocenter motion can be shifted depending on the network of stations, which are used in the processing. The geocenter offset in the solution with the inhomogeneous distribution of multi-GNSS stations is generally closer to the SLR time series, which indicates the “network effect” due to the fact that there are more stations from Europe and Australia which is a similar situation to the core SLR network. Zajdel et al. (2019) concluded that the results of the Galileo-only geocenter coordinates analysis based on the constellation of up to 18 Galileo satellites are very promising. Therefore, in future, GNSS satellites can possibly be used for the realization of the ITRF origin.

## 5. Earth rotation parameters from integrated techniques

The Earth rotation parameters are typically defined as a set of parameters: the pole X and Y coordinates, and UT1-UTC or its first derivative in time denoted as Length-of-Day, LoD. Earth rotation parameters along with the precession and nutation parameters define a set of the Earth orientation parameters used for the transformation from the terrestrial (Earth-fixed) to the celestial (inertial) frames through a transformation matrix. Polar motion and LoD values can be derived from all space-geodetic techniques, whereas UT1-UTC can only be derived from VLBI or LLR observations, due to the direct correlation between UT1-UTC with satellites' ascending nodes.

GNSS is the best technique for deriving pole coordinates. This is due to a large number of ground tracking stations and high quality of horizontal station coordinate components from GNSS. Thus, the daily realized terrestrial reference frame is well linked to the long-term ITRF in GNSS solutions. On the other hand, GNSS provides observations to many targets up to about 90 GNSS satellites which provide a good realization of the celestial reference frame (with constraining nutation, precession, and one value of UT1-UTC to external sources). The accuracy of GNSS-derived pole coordinates is at the level of 30 µas (about 1 mm on the Earth surface) when using a network of about 50 evenly distributed GNSS stations (Zajdel et al., 2019).

Sośnica et al. (2018b) generated a solution that is based not only on SLR observations to passive geodetic satellites (LAGEOS-1/2), as typically practiced for the ITRF realization, but also using SLR observation to new GNSS systems: Galileo, GLONASS,

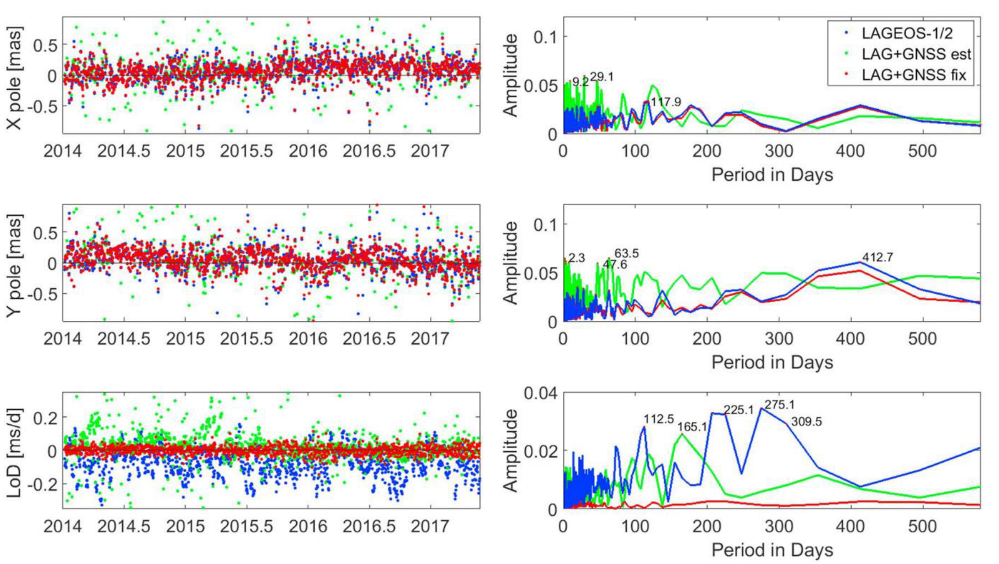


Fig. 12. Pole coordinates and length-of-day excess (LoD) differences with respect to IERS-14-C04 (Bizouard et al., 2018) series (left) and the spectral analysis of the differences (right). "GNSS fix" denotes fixing GNSS orbits to MGEX solutions, whereas "GNSS est" denotes estimating GNSS orbits based on SLR data. After Sośnica et al. (2018a)

QZSS, and BeiDou. Sośnica et al. (2018b) found that incorporating GNSS observations to standard LAGEOS solutions improves the estimation of Earth rotation parameters through the reduction of correlations between LAGEOS empirical orbit parameters, the drift of the ascending node and LoD. The SLR-derived pole coordinates and LoD become more consistent with GNSS microwave-based results with the RMS errors of length-of-day reduced from 122.5 μs/d to 43.0 μs/d and the mean offsets reduced from −81.6 μs/d to 0.5 μs/d in LAGEOS only and in the combined LAGEOS+GNSS solutions, respectively. The pole coordinates did not, however, improve when adding GNSS targets (see Figure 12).

Further improvement of Earth rotation parameters is expected from using more active and passive satellites and many observations, including, e.g., GNSS observations collected onboard low orbiting satellites (e.g., GRACE, Sentinel, Jason), SLR observations to low orbiting satellites, using all new GNSS systems with a proper weighting, and using geodetic satellites which currently are not considered in ITRF (e.g., LARES, Starlette or BLITS-M and LARES-2 in near future, Pearlman et al., 2019; Schillak et al., 2018).

## 6. GGOS-PL

The existing GGOS infrastructure in Poland has constantly been developed. The activates include the upgrade of the Polish SLR station Borowiec by incorporating two lasers for geodesy and space debris (Lejba et al., 2018b), installations of new GNSS receivers and upgrades of the ASG-EUPOS network to track new GNSS systems (today all ASG-EUPOS stations are capable of GLONASS tracking and more than the half of all stations track also Galileo and BeiDou), determination of geoid heights for Poland and selected Polish regions (Kuczynska-Siehien et al., 2016; Trojanowicz et al., 2018), and finally the upgrades of the GGOS infrastructure funded in the framework of the European Union programs, including the European Plate Observing System for Poland (EPOS-PL).

The GGOS-PL infrastructure is currently being extended in order to fulfill the goals of the EPOS-PL by providing reliable geodetic reference frames (Sośnica et al., 2018c). The project EPOS-PL was launched in January 2017 with the main objective of observing surface land deformations and seismicity affecting environment, inhabitants, infrastructure, and buildings in two mining regions of Upper Silesia in Southern Poland, in the so-called Multidisciplinary Upper Silesian Episodes (MUSE-1/2). These regions are subjected to present or former intensive coal exploitation activities. EPOS-PL engages scientists and industry experts from various fields of Earth sciences: geophysics, seismology, geodesy, mining, geology, geomagnetism, and gravimetry with a common goal of providing comprehensive and complementary information on the measured consequences and possible reasons of surface land deformations.

The goal of task 8 in EPOS-PL is to expand the existing GGOS-PL infrastructure to provide homogeneous, accurate, quickly accessible, and reliable geodetic reference frames by integrating surface deformation and geophysical observations, which only together may fully explain the surface deformations by an analysis of the both: sources and measurable effects of geodynamic processes. Therefore, various instruments are co-located: multi-GNSS receivers, gravimeters, seismometers, InSAR reflectors, inclinometers, radiometers, and atomic clocks.

The goal of the gravimetry-devoted task 6 in EPOS-PL is the analysis of temporal geoid height variations obtained from ground-based and GRACE-based models over the area of Poland (Godah et al., 2017). In this task, the absolute gravity data are used for the validation of satellite-borne global geopotential models and for improving quasigeoid heights determined from satellite-only models (Godah et al., 2017).

The new GGOS-PL infrastructure includes multi-GNSS permanent stations, radiometers, tidal gravimeters, seismometers, and ground reflectors for the synthetic aperture radar (SAR) observations. In total, eight new GNSS receivers were installed and launched in August 2018 (see Figure 13); four of which serve as reference receivers installed in stable areas and another four receivers in the area, where surface displacements are expected MUSE-1/2. The receivers have the capability of tracking multi-GNSS signals which include six GNSS and RNSS systems: GPS, Galileo, GLONASS, BeiDou, SBAS, and QZSS with the possibility of 20 Hz to 50 Hz data recording. Multi-GNSS data will be processed providing station coordinates and GNSS troposphere delays in real-time and near real-time regime.

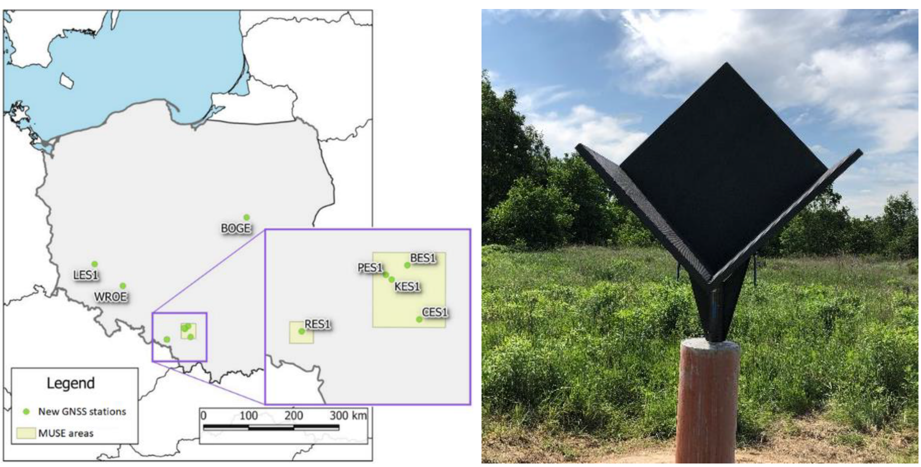


Fig. 13. Newly installed multi-GNSS stations in Poland in the framework of EPOS-PL (left), an example of an InSAR reflector co-located with GNSS receivers (right)

The high-rate GNSS data shall be compared with seismic records for the integrated near real-time seismic wave detection. The seismic records will be confronted with signals recorded by tidal gravimeters. Two GNSS receivers will be supported by radiometers for integrated GNSS-SAR troposphere modeling and improved GNSS positioning. One reference GNSS receiver will additionally be supported for future experiments with an external frequency standard realized by an atomic clock with the clock parameter stability in multi-GNSS real-time PPP solutions. Finally, the surface mass displacements in long and medium timescales will be measured using SAR solutions and validated using results from multi-GNSS permanent stations (Figure 14). The local ties between GNSS receivers, SAR reflectors, and geodetic control points will be monitored on a regular basis at least once per year.

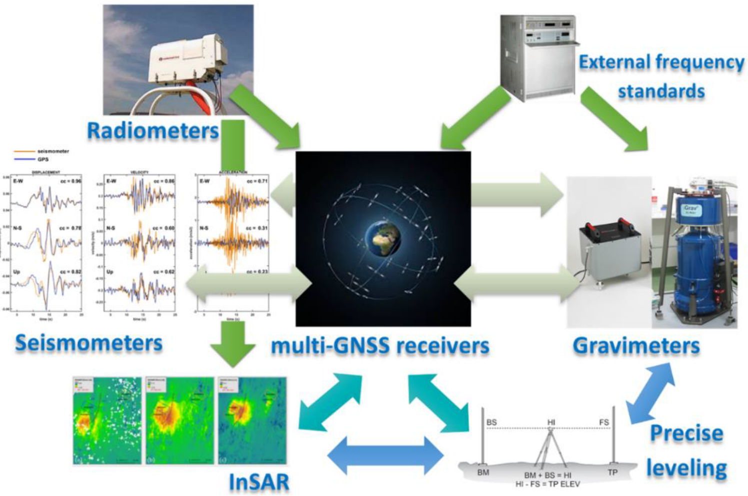


Fig. 14. Co-location of various space geodetic techniques for surface displacements and earthquake monitoring in the framework of GGOS-PL (task 8) in EPOS-PL

The project EPOS-PL aims at building the national research infrastructure for solid Earth Science and its integration with international databases and services implemented under the European Plate Observing System. The same phenomena, such as anthropogenic earthquakes or land subsidences, should be observed by ground measurements and space-borne satellite observations. Moreover, the same phenomena should be registered using various instruments: permanent displacements by GNSS, InSAR, inclinometers, and leveling, whereas mining tumbles by seismometers, gravimeters, and GNSS.

## 7. Summary and conclusions

In February 2015, the UN adopted the resolution on a Global Geodetic Reference Frame for Sustainable Development that recognizes the importance of a globally coordinated approach to geodesy and enhances the importance of GGOS for Earth science and global society.

GGOS essential parameters can be divided into three pillars: geometry which includes the determination of geometrical three-dimensional positions and velocities, gravity which includes the determination of the Earth's gravity field and its temporal variations, and rotation which includes modeling and observing of various geodynamical phenomena, including the rotation and orientation of the Earth. The GGOS parameters are derived using various techniques ground-based, airborne, satellite and space geodetic techniques. Four techniques are essential for the realization of the ITRF: SLR, VLBI, GNSS, and DORIS. A dedicated missions support the geodetic observations of the system Earth providing information on the gravity field, sea and ice level changes (altimetry), magnetic field changes, Earth surface displacements (InSAR), as well as troposphere and ionosphere monitoring (e.g., by radio-occultation missions). Integration of geodetic techniques and parameters at different scales helps in unifying geodetic observations collected in national and global reference frames, e.g., the global gravity field models allow for a proper and direct georeferencing of ground-based geodetic observations in global reference frames (Osada et al., 2017a; 2017b).

In the period between 2015 and 2019, the main GGOS improvement originated from the new GNSS systems, which have been being substantially expanded and improved, and the co-location of various geodetic sensors both onboard satellites, as well as on the ground. The integration of various and independent techniques is indispensable for identifying and elimination of systematic errors in essential geodetic parameters. For example, installing SLR retroreflectors onboard Galileo satellites allowed for the identification of systematic errors in GNSS-derived orbits and to eliminate them by using improved orbit models. The integration of various co-located sensors, such as in the case of EPOS-PL project, with co-located multi-GNSS receivers, gravimeters, seismometers, and InSAR reflectors, allows for a complex analysis of geodynamical and geophysical phenomena, such as anthropogenic earthquakes and Earth surface displacements.

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***Review paper***

# Geodesy: General theory and methodology 2015–2018

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**Abstract:** The summary of research activities concerning general theory and methodology performed in Poland in the period of 2015–2018 is presented as a national report for the 27$^{th}$ IUGG (International Union of Geodesy and Geophysics) General Assembly. It contains the results of research on new or improved methods and variants of robust parameter estimation and their application, especially to control network analysis. Reliability analysis of the observation system and an integrated adjustment approach are also given. The identifiability (ID) index as a new measure for minimal detectable bias (MDB) in the observation system of a network, has been introduced. A new method of covariance function parameter estimation in the least squares collocation has been developed. The robustified version of the Shift-M$_{split}$ estimation, termed as Shift-M*$_{split}$ estimation, which enables estimation of parameter differences (robustly), without the need of prior estimation of the parameters, has been introduced. Results on the analysis of geodetic time series, particularly Earth orientation parameter time series, geocenter time series, permanent station coordinates and sea level variation time series are also provided in this review paper. The entire bibliography of related works is provided in the references.

**Keywords:** Robust estimation, reliability, time series, polar motion, least squares collocation

## 1. Introduction

The general theory and methodology are not mentioned explicitly as the subject of any IAG (International Association of Geodesy) commission. However, this issue seems to be an important pillar for many research investigations in the framework of geodetic science. This review paper provides an outline of Polish researcher activities in the period from 2015 to 2018 that are related to general theory and methodology. It is a follow-up work of a previous report (Borkowski and Kosek, 2015) that covers the time span from 2011 to 2014. Two main topics are reported here: geodetic parameter estimation and geodetic time series analysis. The robust parameter estimation continues to be intensively developed. It seems to be the speciality of the group representing the University of Warmia and Mazury in Olsztyn. The M-estimation and the R-estimation have been deeply studied in the mentioned period. New variants of the Huber's approach have also been introduced. The well-established Baarda's concept of minimal detectable bias (MDB), i.e., the minimal magnitude of the error that can be detected as an outlier, has been revisited as well. Geodetic control networks are the main application area of the mentioned solutions. Some new aspects of the integrated adjustment of geodetic networks have been investigated as well.

The second part, comprising geodetic times series analysis, is related to the Commission 3 activities. Within the Polish researcher community, this topic is dominated by investigations related to Global Navigation Satellite System (GNSS) permanent station coordinates. Significant progress in Global Positioning System (GPS) position time series modelling has been made, especially by the group of researchers at the Military University of Technology in Warsaw. Various stochastic noise models and modelling approaches have been utilised to separate stochastic components of the time series. The most important achievements of the Polish researchers accomplished in the last four years are highlighted in the summary of this publication.

## 2. Geodetic parameter estimation

### *2.1. Robust estimation and its variants*

Adjustment of the observational system biased by gross errors has been studied by many researchers since this issue was introduced by Baarda (1968). Baarda also introduced the concept of MDB that can be expressed by the following formula:

$$\mathrm{MDB}_i = \sigma_i \sqrt{\frac{\lambda}{r_i}}, \qquad r_i = \left\{ \mathbf{H}^{\mathrm{T}} \mathbf{C}_{\mathrm{S}}^{-1} \mathbf{H} \right\}_{ii} \tag{1}$$

with $\mathrm{MDB}_i$ in the $i$-th observation, $\sigma_i$ the standard deviation of the $i$-th observation, $\lambda$ the non-centrality parameter (as in the global model test), $r_i$ a generalised reliability number for the $i$-th observation, $\mathbf{H}$ the modified reliability matrix and $\mathbf{C}_{\mathrm{S}}$ the correlation matrix of observations (e.g., Prószyński, 2015).

Recently, this concept was revisited by Prószyński (2015). In the paper, he defined the terms detectable gross error, identifiable gross error and unidentifiable gross errors, and developed a method of evaluating the chances to identify a gross error. This method exploits the information contained in the modified reliability matrix of the Gauss–Markov model. Based on this matrix and conditional probability, the ID index was introduced. This index allows for an *a priori* analysis of the probability of identifying a gross error of MDB magnitude in the first adjustment iteration. Concerning pairs of observations, partial ID indices were introduced when one observation is contaminated by gross error and another observation is error free.

The most popular estimation method applied for adjustment of geodetic observational material contaminated by gross errors is the M-estimation based on the iterative least squares application with a robust weight function. This function allows for penalising of outlier contaminated observations. An alternative approach represents the class of the R-estimation based on ranks. One of the basic variants of R-estimation is the Hodges–Lehmann estimation. It is a relatively simple concept, for instance the Hodges-Lehman estimate of the shift, Δ, between two independent samples, $x_1, x_2, \ldots, x_m$ and $y_1, y, \ldots, y_n$, is given by

$$\Delta = med(y_i - x_j), \tag{2}$$

when the Wilcoxon test is applied and the samples are realisations of the random variables $X_j(1 \leq j \leq m)$ and $Y_i(1 \leq i \leq n)$, and *med* is a median.

However, since the R-estimation is based on ranks, the law of variance propagation cannot be applied and the accuracy assessment of estimated values is challenging. Usually, an assumption about the distribution of observation errors is necessary. Duchnowski and Wiśniewski (2017) studied the issue of the accuracy assessment of R-estimates by means of the Monte Carlo method under the assumption of particular error distribution. The accuracy results were computed in relation to the accuracy of the least squares estimates. The authors figured out that the accuracy of the Hodges–Lehmann estimates is similar to the least squares estimates. The differences between the corresponding standard deviations were between 5 and 12%. These results have been achieved for the normal distribution of observations. Taking into account distributions with kurtosis different from zero, the authors found that the accuracy of R-estimates is better than the accuracy of the least squares estimation in the case of leptokurtic distribution. The comparison is reverse in the case of the platykurtic distribution. Moreover, the study revealed that the accuracy of R-estimates becomes better in relation to the least squares accuracy when the number of observations increases.

$M_p$-estimation is the maximum likelihood solution based on a modified influence function and the explicit family of distribution. Also, the M-estimation is contained in the class of the $M_p$-estimation as one of its variants. Wiśniewski (2017) adopted this estimation to platykurtic sets of geodetic observations. The mentioned paper provides the solution of the optimisation problem received with the use of the Pearson platykurtic distribution of types I and II.

Properties of the solution have been studied as well. The weight function in the considered variant of the estimation is convex. It might lead to some estimation problems for small sets of observations. Moreover, the author found that the asymmetry of the empirical distribution of observation errors degrades the solution significantly. However, in most cases, the $M_p$-estimation with platykurtic distributions yields similar results like the $M_p$-estimation for leptokurtic distribution.

Several tens of robust M-estimation variants have been developed in the last decades. A robust weight function is that which distinguishes different variants from each other. Osada et al. (2017a) have proposed another realisation of the M-estimation that uses modified robust Huber's mean error function. In contrast to the original Huber's approach, the proposed implementation is based on the linearly modified standard deviation that consists of the sum of the standard deviation resulting from *a priori* observation errors and the distance, $v - r\sigma_v$. $v$ and $\sigma_v$ are the observation correction and its standard deviation, respectively. $r$ is a constant value that defines the range of outliers, usually equal to 1.5. The authors demonstrated the proposed approach performance on the adjustment of the levelling network with possible unstable control points (Osada et al., 2017a). The same method, after the small modification, was used for successful robust adjustment of a precise planar network that was referenced to unstable control points (Osada et al., 2018). The performed numerical tests showed that the ability of outliers detection of the proposed approach is better than several other tested robust weight functions.

### *2.2. Control network analysis*

Control network analysis, i.e., displacement and deformation analysis, has been one of the fundamental subjects of investigation within the field of engineering surveying for the last decades. This field has primarily concentrated on two problems, i.e., detecting and/or reducing impact of outlying observations on adjustment results in both horizontal and vertical networks, as well as detecting (and later eliminating) or damping instabilities of a reference system. Attempts of solution of the mentioned problems are dominated by robust estimation methods, particularly, by the most popular M-estimation, but also R-estimation and, rarely, other approaches. M-estimation is usually performed by means of iteratively reweighted least squares. It relies on using adaptive weights suppressing the impact of observations with large values of standardised residuals in subsequent iterations according to an adopted weighting function.

In their study on fitting a precise levelling network to the national control network, benchmarks, which are subject to vertical movements induced by underground mining (Osada et al., 2017a), construct and use a modified Huber's M-estimator as its classical version produces results that could not be accepted in deformation monitoring. Apart from possible gross measurement errors, which are significantly reduced by the use of modern measuring devices, the vertical movements of control points inevitably produce blunders that require a special adjustment strategy. The authors promote the adjustment strategy that reduces impact of both blunders in observations and blunders induced by unstable control points (the focus is on the latter case). The strategy includes a classical least squares adjustment, free network adjustment and robust adjustment separated by inspecting criteria based on standardised residuals. The newly introduced modification of Huber's estimator is also tested against other M-estimators. The same modification of Huber's M-estimator was used for the purpose of fitting a horizontal network to unstable control points within the area of a power plant (Osada et al., 2018). The authors emphasise that nearly half of the control points may be considered as outliers due to instability of reference coordinates. Such a number of suspected control points calls for the use of robust methods, but even with their use it may turn out to be a challenging task. It is claimed that the Huber's estimator may lead to unreliable results when accepting small values of initial reference coordinate standard errors. The modification of the estimator is free from this drawback and a comparison to other robust estimators proves the usefulness of this new method.

Another approach to control an impact of an unstable reference system on the adjustment results (and deformation analysis), is to check the stability of control points. Cymerman et al. (2016) use R-estimates (in particular Hodges–Lehmann estimates) for this purpose. In their work, the levelling network is an object under study. The presented R-estimate of a point displacement depends on model residuals which are secondary in relation to model parameters. Hence the authors' main objective in the study is to check how the selection of initial values of parameters (heights of points) affects the R-estimates of vertical displacements, and also to compare different strategies to initial point heights computations. A number of numerical tests, including Monte Carlo simulations, are provided. Taking all the results into account, it is concluded that adjustment of the first-epoch observations gives initial values of point heights that guarantee sufficient accuracy of the R-estimates of points' displacements.

For the same purpose, Zienkiewicz (2015) uses $M_{split}$ estimation, originally introduced in works by Wiśniewski. $M_{split}$ estimation is a generalization of M-estimation, hence the resistance to outliers is its natural feature. However, it is emphasised that the most characteristic and distinguishable feature of $M_{split}$ estimation is the allocation of observations to one of two or more ($M_{(q)}$) competing functional models and the use of cross-weighting in the optimisation procedure. As for competing models for the purpose of deformation analysis, one may adapt functional models from two measurement epochs. This two-epoch deformation model may be extended with an additional one (virtual) consisting of observations that do not match either mentioned and, hence, clean the main two-epoch model from extraneous noises. The advocated method is compared with the least squares estimation and classical M-estimation. The results confirm that the constructed adjustment model may be an alternative to traditional displacement determination methods. Besides controlling the instability of a reference system, the method proved its usefulness in the presence of gross measurement errors in the observation set.

Wiśniewski and Zienkiewicz (2016) notice that a substantial part of computational algorithms applied in different aspects of deformation analysis are based on least squares estimation, which is known for its non-robustness to outlying data. Blunders in observations or instabilities of reference points pose a serious problem in the field of deformation analysis, hence, the outlier-resistant methods found its permanent place in deformation analysis and, among them, the mentioned M-estimation and its extensions and enhancements. Such extensions and enhancements are, e.g., $M_{split}$ estimation and, particularly important in the field of deformation analysis, its variant termed Shift-$M_{split}$ estimation. This variant was developed for direct estimating of a shift (a displacement vector) between parameters rather than parameters themselves. In fact, the evolution of $M_{split}$ estimation concept may be investigated in the previous report (Borkowski and Kosek, 2015) apart from the original sources. The observation that squared Shift-$M_{split}$ estimation is not robust to disturbances in observation set, led the authors to its robustification and this resulted in its extended version termed Shift*-$M_{split}$ estimation. In fact, the robustification of Shift*-$M_{split}$ estimation follows the same lines as in the aforementioned study (Zienkiewicz, 2015), i.e., it relies on introducing an additional functional model that absorbs outliers. He also presents a concept of control variable that allows for the determination of proper number of competitive models in $M_{split(q)}$ estimation.

Kwaśniak (2015), on the other hand, uses a different approach of identifying stable/unstable control points. He extends the usability of "all-pairs method" from studying vertical displacements (vertical networks) to horizontal displacements (horizontal networks). The method attempts to identify points that remained fixed from one measurement epoch to another one. The irrelevance of mutual displacements of points is checked in all combinations of point pairs on the basis of a two-step procedure. First, a criterion on the insignificance of displacements based on a distance change is checked generating a subset of possibly mutually fixed points. Second, the found subset is inspected component-wise (i.e., in x and y directions) based on a similar criterion as previously mentioned. The criteria are dependent on standard deviations and an adopted confidence level. The proposed method is simple conceptually and easy to implement computationally.

Nowel (2015) extends the applicability of the previously introduced method (by the same author) called Robust Estimation of Deformation from Observation Difference (REDOD), and limited in use for free control networks only. REDOD uses $L_1$-norm as a cost function in estimating vectors of displacements. The extension of the REDOD method, called Generalized REDOD (GREDOD), applies to both absolute (points inside and outside a deformable object) and relative (points inside a deformable object only) control networks and any loss function in the class of M-estimators. The author compares two approaches used in deformation analysis, namely, a coordinate-oriented one in which a displacement vector is obtained from differences of adjusted coordinates, and an observation-oriented one in which the displacement vector is determined from differences of unadjusted observations. The series of numerical tests conducted by the author proves that both approaches give the same results as to the displacement vector and its statistical significance test.

Nowel (2015) also recalls special cases when the GREDOD method outperforms the coordinate-oriented approach, i.e., when the magnitude of displacements only slightly exceeds the magnitude of measurement errors and when deformation measurements are contaminated by a systematic error (constant value and sign in both epochs). The same author (Nowel, 2016b), searches for the particular M-estimator (a weighting function) that will assure the highest efficiency of the newly introduced GREDOD method. The efficiency has been verified in a series of tests with different weighting functions and under different conditions as to the displacement vectors. The efficiency of the method itself was measured by the mean success rate (MSR) in thousands of simulation trials (Monte Carlo method). This measure is defined as a ratio of the number of sets where blunders were properly identified to the overall number of generated sets. Among tested methods, i.e., $L_1$-norm, Huber and Danish, the combination of Danish weighting function with GREDOD method reveals the highest MSR.

Nowel (2016a) took up a relevant subject in the field of deformation analysis concerned with statistical testing whether the estimates of displacements are the displacements themselves or just the effect of random errors. Conventionally, the F-test is used in this respect. This holds for both least squares based deformation analysis and M-estimation based deformation analysis. The author uses global and local F-tests. The global test answers the question whether all points in the network may be considered fixed. If this fails, the local test is performed answering the question which point is suspected of instability. The author finds that the use of F-tests in the M-estimation approach is defective and unreliable and cannot be satisfactorily applied in deformation analysis. He uses a Monte Carlo simulation as a remedy for the weakness of the F-test applied with M-estimators. He also advocates that problems with other conventional statistical tests (based on strong distributional assumptions, e.g., normality) may be solved in simulation way.

### *2.3. Reliability analysis of observation system*

Since the late sixties of the $20^{th}$ century, a substantial literature has accumulated on the theory of design and optimisation of geodetic networks. The subject still remains a vital problem in geodesy and surveying engineering. Optimally-designed networks are reliable, i.e., possess the ability of proper detection of blunders or remaining resistant against undetected ones and a low cost product (comparing to other possible geometries). In a more detailed sense, network optimization may be explained following an intuitive definition given by Dermanis, i.e., how to best analyse data in their adjustment stage (zero order design, the datum problem), what to observe (first order design, the configuration problem), how to observe (second order design, the weight problem) and how to improve existing information with additional data (third order design, the improvement problem).

In their work, Pachelski and Postek (2016) use a computer simulation to optimize an observation plan, a task within the scope of the first order design of a geodetic network. The method is characterised by a low computational cost. They propose a strategy based on updating a covariance matrix (a carrier of accuracy of the network) after adding a new observation without the need of re-estimation of the adjustment model as a whole. The approach is borrowed from a sequential estimation used within the framework of Kalman filtering. After adding a single observation, its impact on the covariance matrix is verified and a decision is made whether the observation should be included or discarded.

Such a procedure is repeated in different configurations of observations and the one that satisfies, assumed accuracy criteria with a minimal number of observations, is accepted as an optimal observation plan for a given network.

Nowak and Odziemczyk (2018) concentrate on optimization of weighting scheme (problem belonging to the second order design) to make a geodetic network reactive to outlying observations. The ability to react to outliers is often measured by the diagonal elements of the residual marker matrix (reliability matrix containing redundancy numbers on the main diagonal). But since the residual marker matrix differs from the hat matrix only by a constant (identity) matrix the authors use the latter to shorten the formulas without loss of information. The authors examine an impact of changing the weight (standard deviation) of a single observation at a time on diagonal entries of hat matrix. They iteratively try to control a transfer mechanism which has a form one-to-many, i.e., a change of weight in a single observation takes effect in many entries of the hat matrix. The proposed procedure requires inversion of the normal equations matrix after every single change of observation standard deviation (weight). To avoid a computationally expensive matrix inversion, they use Sherman–Morrison–Woodbury formula to update a matrix inverse what makes the solution much less troublesome.

Prószyński and Kwaśniak (2016) study an effect of increase of observation correlation on the behaviour of various measures of geodetic network reliability. They consider the effect of increasing correlation on detectability and identifiability of a single gross error measured by MDB and ID index. They examine sensitivity of w-test for uncorrelated and correlated observations and also response-based measures of internal reliability under these circumstances. In order to study this effect in a controllable way the authors introduce a correlation matrix of a special structure, i.e., every off-diagonal entry is equal to a constant (arbitrariness of these constants is limited by the condition of positive-definiteness of the correlation matrix). They term this simplified structure a uniform correlation. Every considered reliability characteristic is presented as a function of a design matrix (representing the network structure), a vector of observations' uncertainty and, the most important from the standpoint of their work, a correlation matrix (representing dependencies among observations). By successively changing the magnitude of uniform correlation, i.e., a constant, the authors are able to draw some conclusions on the effect of the increasing observation correlation on the mentioned characteristics. They point out that the collected empirical material may become useful in discussion whether or to what degree the formula for a MDB, presented therein, can be a measure of blunder detectability in networks with correlated observations. By their numerical tests, they show that the increase of observation correlation strongly limits the ability of w-test for uncorrelated observations to identify a contaminated observation. On the other hand, they prove the usefulness of the test for correlated observations. Numerical experiments revealed also that the effect of increasing correlation on ID index and on response-based reliability measures is of negligible character.

In Prószyński and Kwaśniak (2018), the above discussion is extended to correlation matrices of any structure. They introduce a global measure of correlation among observations in a network that allows for a specific representation of the correlation matrix.

Since the global measure provides no information on the magnitudes of non-diagonal elements, the authors have also proposed the associated measures, based on off-diagonal elements, of such a matrix, i.e., maximum absolute value and their quadratic mean value. They proved that each positive-definite correlation matrix may be factorized into a scale factor and a so-called internal weight matrix. This factorization of the correlation matrix may be particularly helpful in investigating the impact of observation correlation on network reliability measures. Basic measures of network reliability (both internal and external) are easily rewritable in terms of newly introduced factorization and it is easy to verify which measures are dependent on the global correlation index and which are not. The examples presented therein refer only to MDB, reliability number and a variance of standardised least squares residual, quantities that are dependent on the global correlation coefficient. The authors classify the strength of the global correlation coefficient into particular intervals, i.e., up to 0.3 (weak), from 0.3 to 0.6 (moderate) and from 0.6 to 1.0 (strong).

### *2.4. Integrated adjustment*

The integrated adjustment of a geodetic network comprised of both terrestrial and satellite observations have been studied for decades. Several alternative approaches are possible to build the functional model of the combined adjustment. One of them, quite typical, is the conversion of GNSS vectors and other observations into so-called geodetic pseudo-observations on a reference ellipsoid (azimuth, length). Kadaj (2016a), in his recent investigation, found out that such an adjustment can be biased by systematic errors that exceed the level of stochastic errors of observations. Moreover, he has shown that this problem can be avoided when original GNSS vectors are adjusted in the ellipsoidal space. Also, corresponding modified ellipsoidal observation equations for terrestrial observation are provided in the mentioned publication. The numerical tests have been performed on the territory of Poland using reference stations of the national GNSS permanent network.

The issue of observation reductions from the physical observation space to the mathematical (adjustment) space has been investigated in the work of Kadaj (2016b). The author figured out that the known algorithms and formulas for reduction and mapping onto cartographic space are not suitable for very long GNSS vectors. Therefore he proposed an empirical method for geodetic observation reduction. This method replaces the classical multistage approach and is realised in one step iteratively using Gauss-Newton procedure. Approximate station coordinates of the network are needed for this process. Several numerical examples for different kind of geodetic observations are given in (Kadaj, 2016b).

Least squares collocation is used frequently for filtering of geodetic and geophysical data or for investigating the ratio between signal and noise. Jarmołowski (2015) studied the estimation of *a priori* errors associated with non-correlated noise within one dataset. The author proposed a method that comprises cross-validation based on leaveone-out technique and restricted maximum likelihood estimation of *a priori* noise for different groups of observations. It means that the individual *a priori* variances are estimated data point by data point when only one single data point is omitted. To solve maximum likelihood equations numerically, the fast Fisher scoring technique is used. The method has been tested on the U.S. gravity database. Many observations, with errors several times larger than the average error value, have been found in the dataset. The fast estimation of covariance parameters in least squares collocation by means of the Fisher scoring and the Levenberg–Marquardt optimisation has been further investigated by Jarmołowski (2017). The author performed several numerical tests and figured out that the Fisher scoring technique optimised through Levenberg–Marquardt and applied in the parametrisation of the least squares collocation is much faster than any other technique. Moreover, this approach can be implemented in a fully automatic way. The mentioned paper provides also an extended review of techniques and approaches applied for covariance model parametrisation in least squares collocation in geodesy and geophysics.

The issue of integrated geocentric positioning has been studied by Osada et al. (2017b). The authors proposed an approach integrating total station measurements, GNSS positioning and plumb line direction calculated from the Global Earth Gravity Model EGM 2008. This approach allows for precise positioning in the global geocentric coordinate frame. The Gauss–Markov adjustment model is implemented for observation and data integration and for precise 3D coordinate determination. Numerical tests have been performed for several variants of observation combination and integration in order to determine coordinates of a spatial traverse. These tests demonstrated that the use of plumb line deflection parameters improves the coordinate quality significantly, i.e., up to 26 cm in the case study in question.

The mentioned approach has been further developed and applied to direct georeferencing of terrestrial laser scanners (Osada et al., 2017c). To determine orientation parameters of point clouds in the global reference points, GNSS observations and plumb line vertical deflection, components are utilised and integrated within the Gauss–Helmert adjustment model. The minimum number of GNSS measurements is the special feature of the proposed approach. Only two reference points have to be measured by GNSS in order to allow the point cloud transformation into a well-defined global reference frame.

### *2.5. Least fourth powers adjustment*

Minimising the sum of squares is the most popular objective function utilised for adjustment of geodetic observation. A robust estimation aims at the parameter estimation and, meanwhile, penalisation of observations biased by gross errors. Cellmer (2015) proposed a method that is in opposition to robust estimation and favours outliers. These properties have the solution of the optimisation problem $\mathbf{v}^{\mathrm{T}}\mathbf{v} \rightarrow \min$ with $\mathbf{v}^{\mathrm{T}} = [v_1^2, v_2^2, \ldots, v_n^2]^{\mathrm{T}}$ where $v_i$ are residuals of observations. The solution of this problem faces some numerical problems that are considered in the mentioned contribution. The proposed approach can be applied in particular engineering applications when a geometric figure has to be fitted to a set of points taking into account the worst scenario.

## 3. Geodetic time series analysis

### *3.1. Earth orientation parameters*

The differences between pole coordinates data and their least squares (LS) extrapolation and autoregressive (AR) predictions increase with prediction length and depend mostly on starting prediction epochs. The time series of differences for 2, 4 and 8 weeks in the future between pole coordinates data and their LS+AR predictions were analysed by the Fourier Transform Band Pass Filter (FTBPF). The FTBPF amplitude spectra revealed some power in the frequency band corresponding to the prograde Chandler and annual oscillations. This means that the increase of pole coordinates data prediction errors is partly caused by the residual Chandler and annual oscillations due to mismodelling them by the LS extrapolation model and chaotic oscillations with periods less than about 200 days (Brzezinski et al., 2016). This means that longer term polar motion prediction cannot be improved and shorter term prediction can possibly be improved by taking into account atmospheric and oceanic excitation.

### *3.2. Geocenter time series*

The geocenter motion model computed from the center of mass coordinates data determined from the Satellite Laser Ranging (SLR), GNSS and DORIS (Doppler Orbitography and Radiopositioning Integrated on Satellite) observations was used to compute the corrections to the sea level anomaly (SLA) data due to center of Earth mass variations. To compute this stochastic geocenter motion model, the centre of mass coordinates data were filtered by the wavelet based semblance filtering, which allows one to designate common signals in two time series. This kind of correction to SLA data of the order of a few millimetres should be applied to altimetric measurements to refer them to the International Terrestrial Reference Frame (ITRF) (Kosek et al., 2015a).

### *3.3. Permanent station coordinates*

For various GNSS applications, it is necessary to know the values of tropospheric delay in real time. To provide such estimates, the paper (Wilgan, 2015) presents a statistical approach to predicting a short-term zenith tropospheric delay (ZTD) from long time series. Several models have been used, such as AR model or autoregressive moving average model (ARMA). Fitting the stochastic correlated part (signal) into these models allows predicting the ZTD values (together with estimation of the deterministic trend). Depending on the purpose of the forecasts, different time series lengths and various prediction horizons have been considered (from 1 to 24 hours). Predictions were included in both global and local mode. In the local mode, each test station has a separate prediction model (degree and order). In global mode, one statistical model was provided for all the stations simultaneously. For the 5-hour local forecasts, the statistical models have the average bias close to 0 with standard deviations of $5 \div 10$ mm with respect to the actual GNSS time series. Accuracy of the global mode is similar to the local one. The average bias for the global mode ranges from $-2 \div 2$ mm with standard deviations at the level of $6 \div 8$ mm. It can be concluded that there is no need to use the local mode, only the global mode, which makes it much easier for the automation of the prediction process for all stations simultaneously (Wilgan, 2015).

Bogusz et al. (2016) presented the existence of long-range dependencies within the stochastic part of GPS position time series. They employed 130 Polish GPS permanent stations and analyzed them using rescaled-range method with Hurst exponent and detrended fluctuation analysis. Both results proved that there is a clear dependence between consecutive values of GPS residuals, indicating a power-law noise presence.

Gruszczynska et al. (2017) examined common seasonal time-varying signal for a set of European stations. They used the Multichannel Singular Spectrum Analysis (MSSA) and proved that common seasonal curves are better-fitted to the original series than the least squares estimates. Moreover, employing the MSSA approach leads to no reduction in the time series power, which constitutes another advantage of this methodology.

Similar to the daily GPS position time series (Klos et al., 2016a), the weekly-sampled data are characterized by power-law noise as shown by (Klos et al., 2015). However, due to their sparser sampling, the amplitudes of weekly observations are smaller than for the daily time series.

The impact that the pre-analysis has on the noise estimates, has been demonstrated by (Klos et al., 2016b) for the outliers. The authors focused on various methods to identify and remove values outlying from others, followed by noise analysis. They concluded that the outliers have to be identified and removed as reliably as possible, to provide the best estimates of noise character.

Klos et al. (2018a) focused on the estimates of noise character basing on the DORIS position time series. The authors divided the time span that the DORIS stations have been operating within into three different periods. For each of them, they estimated the character of noise. It was noticed, that this character changed thorough years from autoregressive process into pure power-law noise, with the quality of data significantly improved.

Klos et al. (2019) introduced into geodetic community, a completely new methodology to estimate the time-varying seasonal signals including the character of the original time series. This methodology is named as the Adaptive Wiener Filter (AWF). For the synthetic series, AWF has been confronted with the commonly employed Kalman Filter, Singular Spectrum Analysis, Wavelet Decomposition and least squares methods, demonstrating that it provides the accurate estimates for time-varying seasonalities, leaving the noise character intact. In this way, no artificial impact on the velocity estimates is noticed.

For the first time, the character of Zenith Wet Delay (ZWD) tropospheric series has been examined by (Klos et al., 2018b). The authors presented the appropriateness of various noise models to describe the ZWD residuals. They noticed that the first-order autoregressive noise process combined along with white noise is preferred over the widely employed white-noise-only approach. They also found that the ZWD trend uncertainty is largely underestimated (by $5 \div 14$ times) using the white-noise-only assumption.

Klos et al. (2018c) provided a General Dilution of Precision (GDP) estimates being the ratio of two uncertainties of velocities. Both uncertainties are determined from two different deterministic models while accounting for stochastic noise at the same time. The authors proved that adding more and more seasonal terms to the series, we increase the bias of the velocity uncertainties. They estimated that 9 and 17 years of continuous daily observations is needed for, respectively, flicker and random-walk noise to make the GDP decrease below 5%.

Analyses of seasonal signals in the GNSS coordinate time series using the iterative Least Squares Estimation approach (iLSE) have been presented by (Kaczmarek and Kontny, 2018a). Additionally, the correlation between coordinates and deformations of the Earth's crust from geophysical models provided by the BKG center was examined. Analysis has shown that the iLSE method is a good tool for detecting periodic components in time series, which was confirmed by the FFT (Fast Fourier Transform) method. In addition, the correlation coefficient between the deformations of the Earth's crust and the changes in coordinates is high for the Up component. However, for horizontal components, the correlation coefficient is low due to the phase shift between the deformation and coordinate signals (the cause is currently unknown to the authors). The final conclusion is that caution should be taken carefully to introduce deformation corrections from geophysical models to coordinates, and the annual and semi-annual periods are not constant for the analyzed time series (Wavelet analysis).

The methods of identifying the noise model in the time series of GNSS station coordinates using two methods: signal reconstruction using coefficients from Continuous Wavelet Transform (CWT), as well as classical modeling of the least squares estimation signal for annual and semi-annual period have been presented by Kaczmarek and Kontny (2018b). The spectral index was used to determine the type of noise. Analyzes have shown that the signal modeling method does not affect the type of noise occurring in the coordinate time series (the difference of the spectral index between the estimation methods is $0 \div 0.2$ for the analyzed GNSS stations) and the character of the noise is colored (flicker noise).

### *3.4. Sea level variations and hydrometeorology*

Using the FTBPF variable broadband seasonal and subseasonal oscillations were computed as a function of geographic location in the SLA data. The FTBPF analysis revealed that the annual frequency has a broadband character which creates oscillations with the frequencies being integer multiplicities of this frequency. The maxima of the annual and semi-annual oscillation amplitudes are located in almost the same geographic regions. The irregular amplitude and phase variations of the broadband annual oscillation computed by a combination of the FTBPF and the Hilbert transform occur in the same geographic regions where prediction errors of the SLA data for two weeks in the future reach the highest values. These predictions of the SLA were computed by a combination of the polynomial-harmonic model with the AR prediction as well as with the threshold AR model (Kosek et al., 2015b).

The research topic comprising sea level change problems with a particular emphasis put on the analysis of satellite altimetric data and sea floor modelling have been investigated by the group led by Tomasz Niedzielski. The Prognocean Plus system has been developed to predict altimetric SLA in real time. Three deterministic-stochastic data-based models are employed within a dedicated system which is implemented and run on the PLGrid infrastructure (grid supercomputing solutions for Polish science). The results have been compared with the established MyOceansystem and the previous version of Prognocean (Świerczyńska et al., 2016). The new method for reconstructing the depth-age curve has been proposed (Niedzielski et al., 2016) and the novel approach to estimate the reference ocean depth has been developed (Jurecka et al., 2016). The two methodological findings are important for modelling long-term sea level variation due to changes of ocean floor. The overview of different prediction methods in marine studies has been published by Niedzielski (2017).

## 4. Diverse algorithms

The planetary cartography uses predominantly a triaxial ellipsoid as a reference surface in order to map celestial objects with irregular shapes. Appropriate for that mapping functions are usually represented as functions of planetographic or planetocentric coordinates. Projections are complicated and comprise several steps. Pędzich (2017) described triaxial ellipsoid and map projections by means of reduced coordinates. The advantage of this approach is that the calculating of reduced coordinates is performed using the single algorithm that is based on solution of the elliptic integral of the second kind. In the paper in question, mapping functions based on reduced coordinates are provided for cylindrical, azimuthal and pseudocylindrical map projections.

## 5. Summary and conclusions

This review contribution provides an overview through the activities of the Polish researchers in the field of geodetic general theory and methodology in the period from 2015 to 2018. The investigations reported in this review paper are to some extent continuation of studies initiated in the previous years. The report (Borkowski and Kosek, 2015) preceding this one, covers the period from 2011 to 2014 and provides an outline of research activities for the respective period. Thus, a recapitulation can be found in the previous report.

In the last four years, several essential accomplishments have been achieved by researchers representing the Polish geodetic community. To sum up, the following issues can be emphasised as highlights:

– Revisiting the concept of minimal detectable bias and introducing the ID index that allow for an *a priori* analysis the probability of identifying a gross error (Prószyński, 2015).
– Improvement of the Huber's approach by introducing the linear weight function. It allows for fitting of geodetic network to unstable reference points (Osada et al., 2017a, 2018).
– Development of the covariance function parametrisation approach that is based on the Fisher scoring technique and the Levenberg–Marquardt optimisation (Jarmołowski, 2015, 2017).
– Development of various strategies of network adjustment in the presence of gross errors in observation sets and instabilities of reference system (Osada et al., 2017a, 2018; Zienkiewicz, 2015; Nowel, 2015, 2016a, 2016b).
– Introduction of robustified version of Shift-$M_{split}$ estimation termed as Shift-$M^*_{split}$ estimation, which enables to estimate parameter differences (robustly) without the need of prior estimation of parameters themselves (Wiśniewski and Zienkiewicz, 2016).
– Development of analytic tools for investigating the increase of observation correlation on network reliability measures. Introduction of new measures of observation correlation (Prószyński and Kwaśniak, 2016, 2018).
– Finding that stochastic models characterizing geodetic observations may vary depending on the type of observations one collect (Kadaj, 2016a, 2016b).
– Concluding that the stochastic model of geodetic observations evolves together with the quality of observations; the more precise observations are, the closer the noise is to white noise (Klos et al., 2016a, 2016b, 2018a, 2018b, 2019).
– Longer term polar motion prediction accuracy cannot be better and more emphasis should be put on shorter term prediction by taking into account atmospheric and oceanic excitation (Brzezinski et al., 2016).
– Showing that some data-based prediction methods can serve well the purpose of forecasting sea level anomalies, with higher accuracies than the physically-based method implemented in the European MyOcean system and, concurrently, lower correlations than the MyOcean-based predictions (Świerczyńska et al., 2016; Niedzielski, 2017).
– The approach to modelling the time series of GNSS coordinates does not affect the type of noise occurring in these data (Kaczmarek and Kontny, 2018a, 2018b).
– Forecasting the values of zenith total delays of GNSS signal is recommended by statistical autoregressive (AR) and autoregressive moving average (ARMA) models (Wilgan, 2015).

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