www.czasopisma.pan.pl PAN www.journals.pan.pl

GEODESY AND CARTOGRAPHY
Vol. 68, No. 1, 2019, pp. 121–144

DOI: https://doi.org/10.24425/gac.2019.126090

Review paper

Global Geodetic Observing System 2015–2018

Krzysztof Sośnica[1]*, Jarosław Bosy[2]

[1]Wroclaw University of Environmental and Life Sciences
Institute of Geodesy and Geoinformatics
53 Grunwaldzka, 50-357 Wroclaw, Poland
[1]e-mail: krzysztof.sosnica@upwr.edu.pl, ORCID: http://orcid.org/0000-0001-6181-1307
[2]e-mail: jaroslaw.bosy@upwr.edu.pl, ORCID: http://orcid.org/0000-0002-7004-6747

*Corresponding author: Krzysztof Sośnica

Received: 03 January 2019 / Accepted: 07 February 2019

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

---

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).

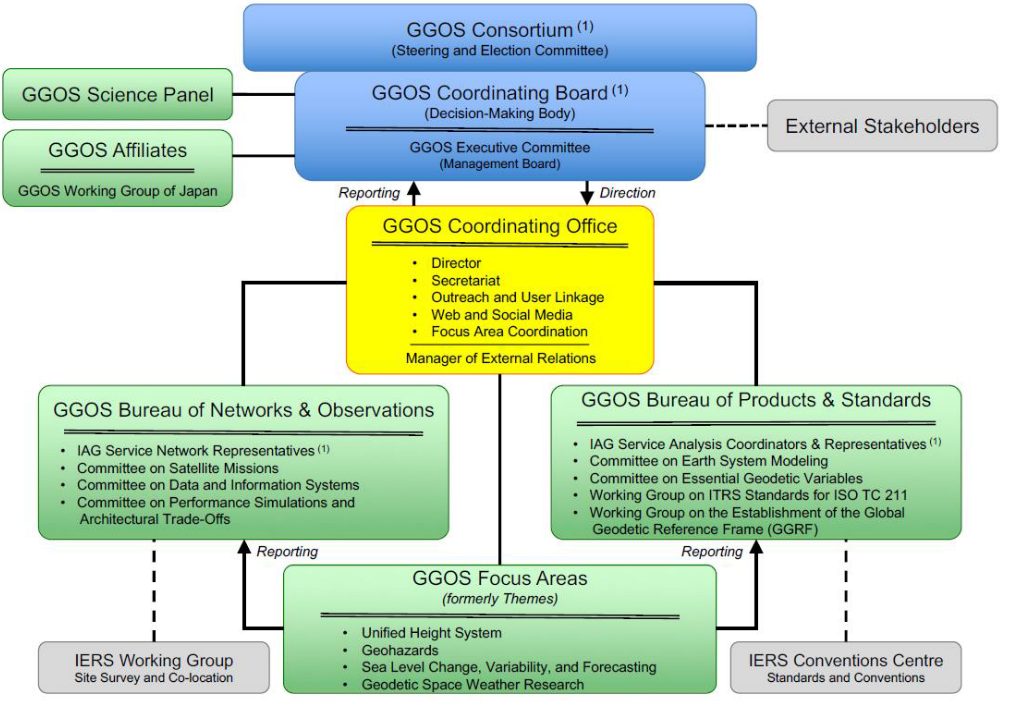

Fig. 1. GGOS structure, after Gross (2018)

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.

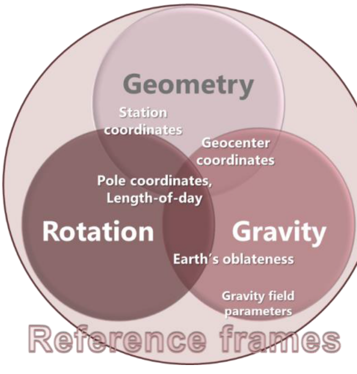

Fig. 2. Three pillars of geodesy as GGOS components integrated by reference frames

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.

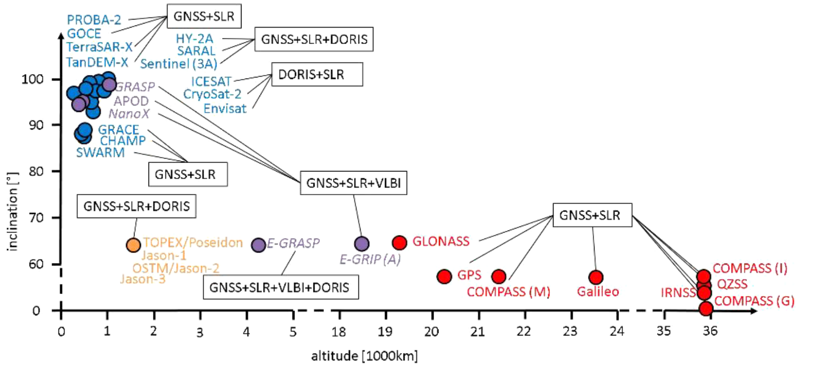

Fig. 3. Available satellites for co-location in space ordered by their altitude and inclination; planned missions are set in italics; after Maennel (2016)

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

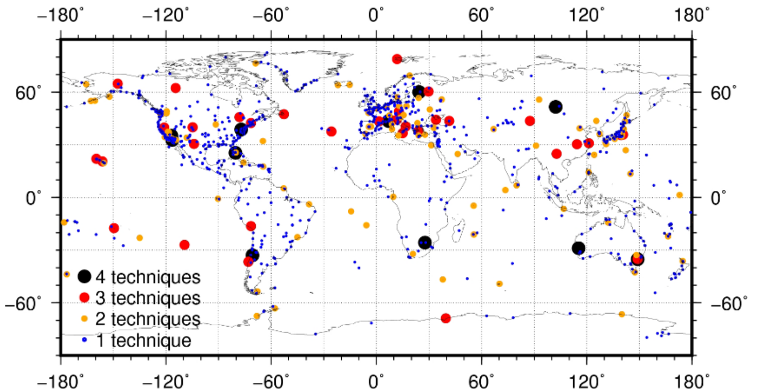

Fig. 4. Distribution of co-locations of four techniques used in ITRF2014 (Maennel, 2016)

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).

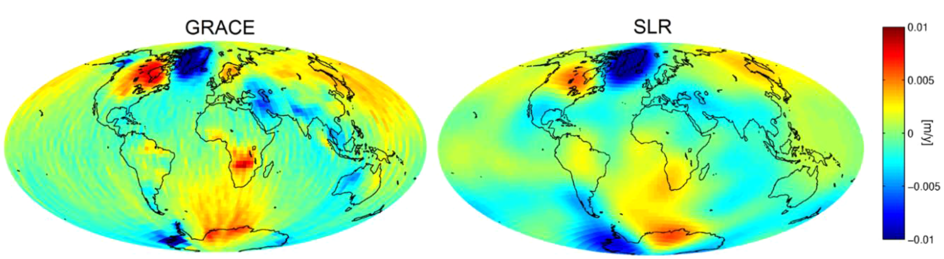

Fig. 5. Secular gravity field changes from GRACE and SLR observations, after Sośnica et al. (2015a)

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).

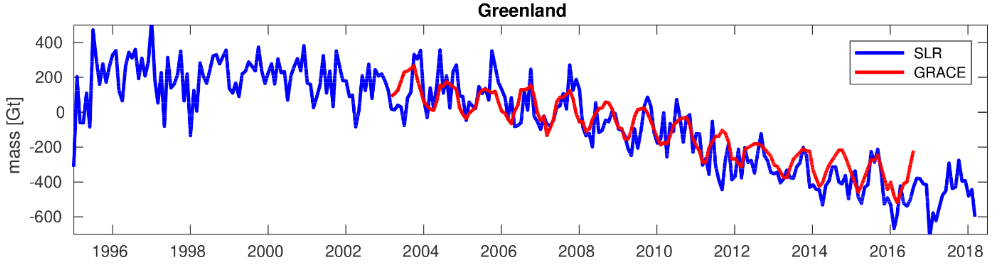

Fig. 6. Ice mass depletion in Greenland from 14 years of GRACE observations and 23 years of SLR observations, after Meyer et al. (2018)

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

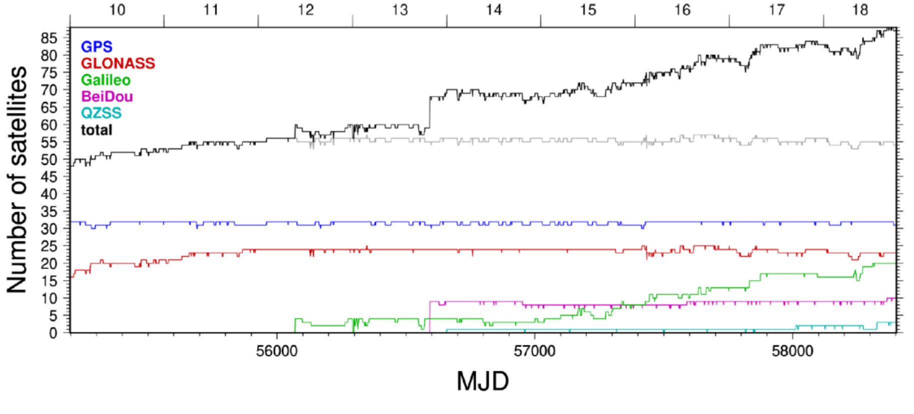

Fig. 7. Number of GNSS satellites: GPS, GLONASS, Galileo, BeiDou, and QZSS included in CODE MGEX solutions in the period 2010.0 and 2018.8, after Dach et al. (2018)

(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

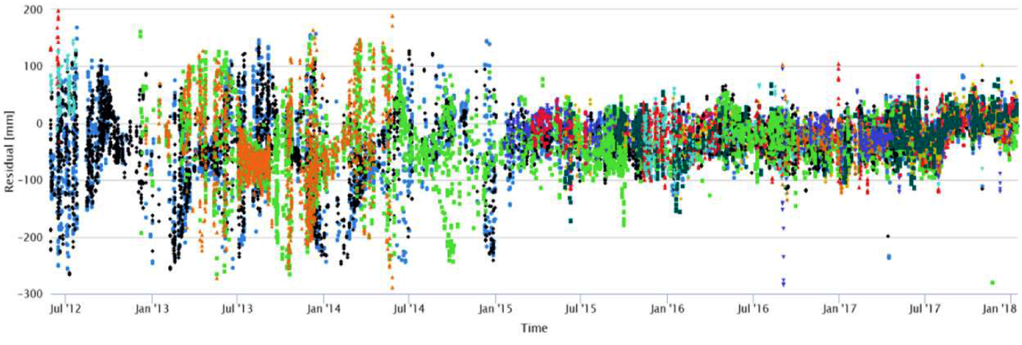

Fig. 8. Evolution of Galileo orbit accuracy as measured by SLR. Figure generated in the GOVUS service (Zajdel et al., 2017)

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

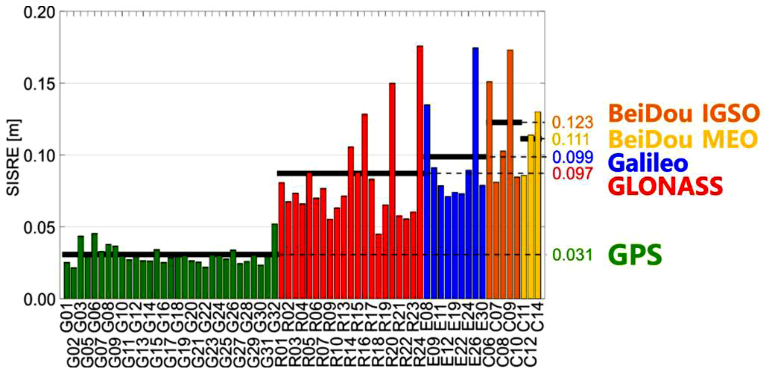

Fig. 9. Signal-in-space ranging errors (SISRE) for CNES multi-GNSS real-time products in 2016, after Kaźmierski et al. (2018b)

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

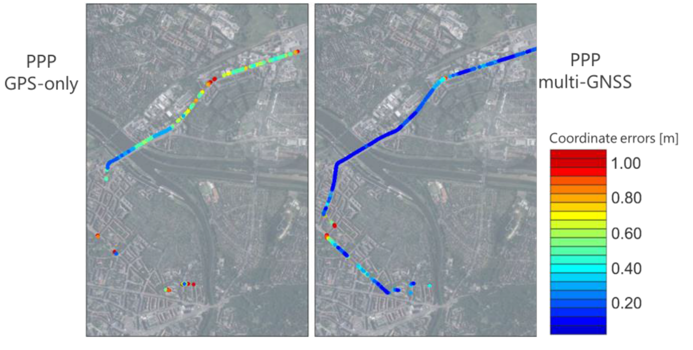

Fig. 10. Precise point positioning (PPP) solutions in a kinematic environment based on GPS-only solutions (left) and multi-GNSS solutions (right) using streamed CNES products and simulated real-time conditions, after Kaźmierski (2018). The experiment was performed in the city of Wrocław using a precise 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.

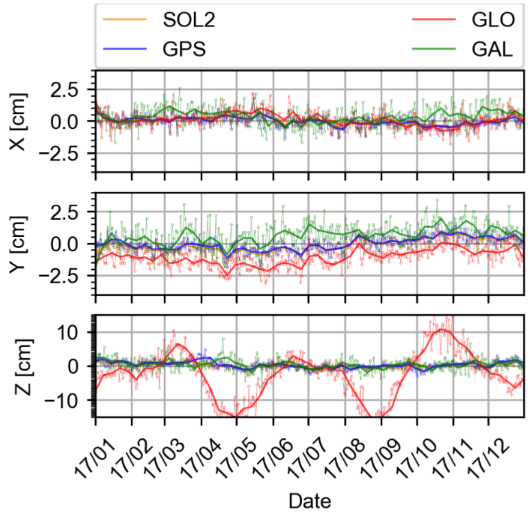

Fig. 11. GNSS system-specific geocenter coordinates. Scale for the Z geocenter component is changed for the sake of readability. GLO denotes GLONASS, GAL denotes Galileo, SOL2 denotes a combined GPS+GLONASS+Galileo solution, after Zajdel et al. (2019)

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,

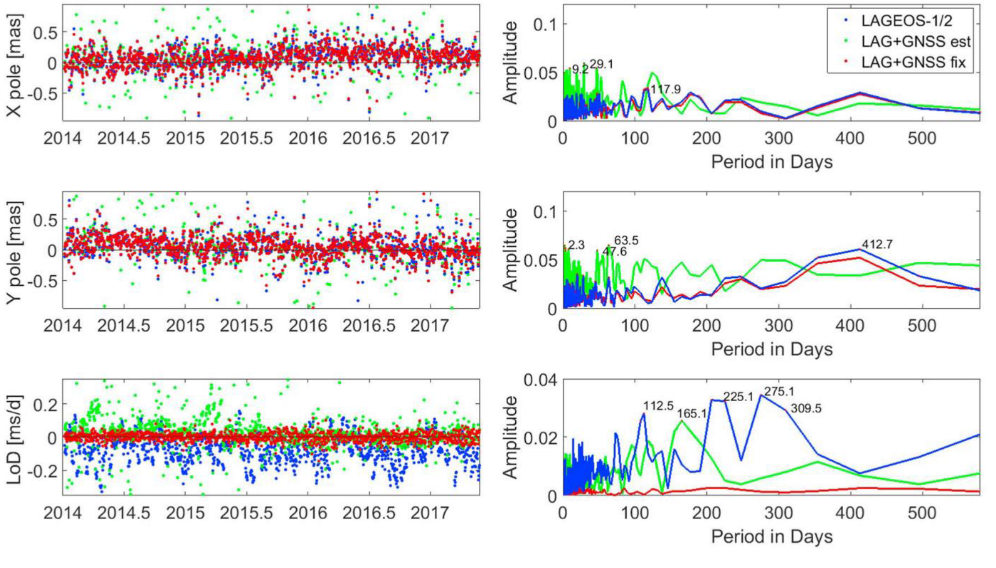

Fig. 12. Pole coordinates and length-of-day excess (LoD) differences with respect to IERS-14-C04 (Bizouard et al., 2018) series (left) and the spectral analysis of the differences (right). "GNSS fix" denotes fixing GNSS orbits to MGEX solutions, whereas "GNSS est" denotes estimating GNSS orbits based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

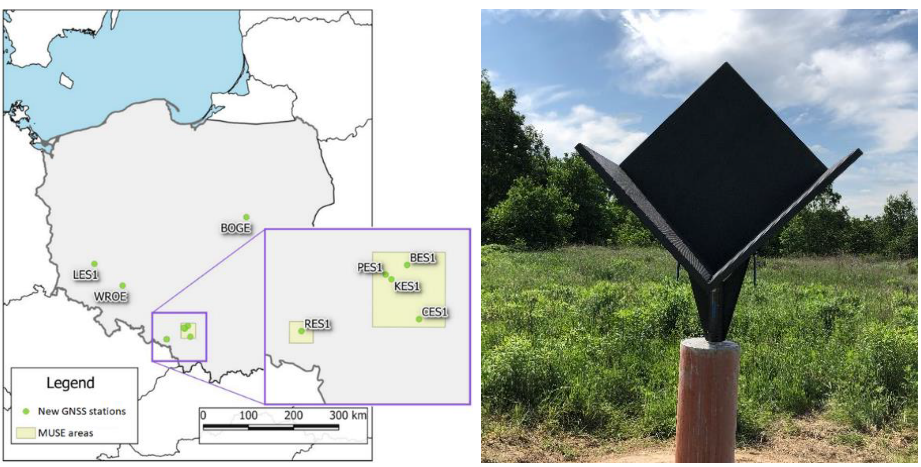

Fig. 13. Newly installed multi-GNSS stations in Poland in the framework of EPOS-PL (left), an example of an InSAR reflector co-located with GNSS receivers (right)

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.

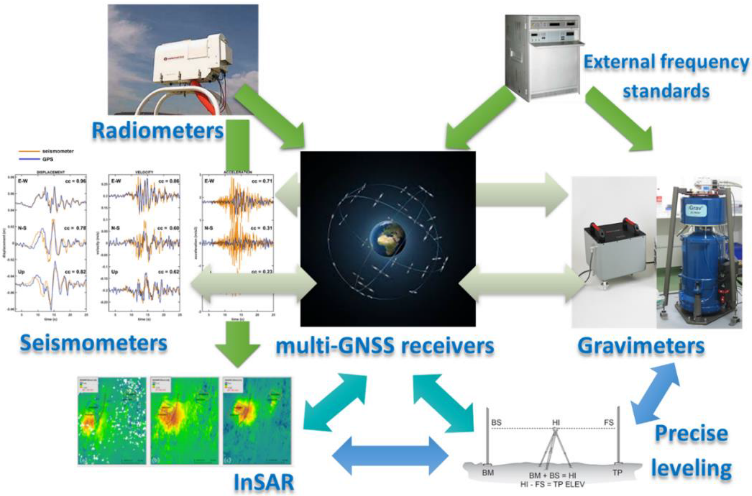

Fig. 14. Co-location of various space geodetic techniques for surface displacements and earthquake monitoring in the framework of GGOS-PL (task 8) in EPOS-PL

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.

Acknowledgments

IAG services: IGS, ILRS, IDS, and IVS are acknowledged for providing high-accuracy geodetic observations. The project EPOS – European Plate Observing System is funded within the Operational Programme Smart Growth 2014-2020, Priority IV, Action 4.2., Period of realization: 2016–2021, allocation of funds: 61 996 279.64 PLN, co-financing from European Regional Development Fund: 46 632 332.69 PLN. EPOS-PL project number: POIR.04.02.00-14-A003/16-00.

The review paper was elaborated in the framework of the Commission of Geodesy and Geodynamics of the Committee on Geodesy of the Polish Academy of Sciences.

Valuable help was provided by Grzegorz Bury, Mateusz Drożdżewski, Walyeldeen Godah, Marcin Jagoda, Paweł Lejba, Maciej Kalarus, Kamil Kaźmierski, Joanna Kuczyńska-Siehień, Edward Osada, Jacek Paziewski, Stanislaw Schillak, Dariusz Strugarek, Monika Tercjak, Marek Trojanowicz, Agata Wielgosz, Małgorzata Wińska, Radosław Zajdel, and Janusz Zieliński.

References

Altamimi, Z., Rebischung, P., Métivier, L. and Collilieux, X. (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *J. Geophys. Res.: Solid Earth*, 121(8), 6109–6131. DOI: 10.1002/2016JB013098.

Appleby, G., Rodrguez, J. and Altamimi, Z. (2016). Assessment of the accuracy of global geodetic satellite laser ranging observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations. *J. Geod.*, 90(12), 1371–1388. DOI: 10.1007/s00190-016-0929-2.

Arnold, D., Montenbruck, O., Hackel, S. and Sośnica, K. (2019). Satellite laser ranging to low Earth orbiters: orbit and network validation. *J. Geod.* DOI: 10.1007/s00190-018-1140-4.

Arnold, D., Meindl, M., Beutler, G., Dach, R., Schaer, S., Lutz, S., Prange, L., Sośnica, K., Mervart, L. and Jaggi, A., (2015). CODE's new solar radiation pressure model for GNSS orbit determination. *J. Geod.*, 89(8), 775–791. DOI: 10.1007/s00190-015-0814-4.

Bloßfeld, M., Jäggi, A., Kehm, A., Meyer, U. and Sośnica, K. (2018). Evaluating the potential of combined SLR gravity field solutions. In: 21 ILRS Workshop on Laser Ranging. Canberra, 5–9 November 2018.

Bizouard, C., Lambert, S., Gattano, C., Becker, O. and Richard, J.Y. (2018). The IERS EOP 14C04 solution for Earth orientation parameters consistent with ITRF 2014. *J. Geod.*, 1–13. DOI: 10.1007/s00190-018-1186-3.

Bosy, J. (2014). Global, regional and national geodetic reference frames for geodesy and geodynamics. *Pure Appl. Geophys.*, 171(6), 783–808. DOI: 10.1007/s00024-013-0676-8.

Bury, G., Sośnica, K. and Zajdel, R. (2018). Multi-GNSS orbit determination using satellite laser ranging. *J. Geod.* DOI: 10.1007/s00190-018-1143-1.

Bury, G., Sośnica, K. and Zajdel, R. (2019a). Impact of the atmospheric non-tidal pressure loading on global geodetic parameters based on Satellite Laser Ranging to GNSS. *IEEE Trans. Geosci. Remote Sens.* DOI: 10.1109/TGRS.2018.2885845.

Bury, G., Zajdel, R. and Sośnica, K., (2019b). Accounting for perturbing forces acting on Galileo using a box-wing model. *GPS Solut.* (in review).

Ciufolini, I. and Pavlis, E. C. (2004). A confirmation of the general relativistic prediction of the Lense-Thirring effect. *Nature*, 431(7011), 958–960. DOI: 10.1038/nature03007.

Dach, R., Montenbruck, O., Ziebart, M., Sośnica, K., Prange, L., Sidorov, D. and Schildknecht, T. (2018). Tracking of GNSS satellites –usage in the GNSS community. In: 21 ILRS Workshop on Laser Ranging. Canberra, 5–9 November 2018.

Dow, J.M., Neilan, R.E. and Rizos, C. (2009). The International GNSS Service in a changing landscape of Global Navigation Satellite Systems. *J. Geod.*, 83(3), 191–198. DOI: 10.1007/s00190-008-0300-3.

Drożdżewski, M. and Sośnica, K. (2018). Satellite laser ranging as a tool for the recovery of tropospheric gradients. *Atmos. Res.*, 212, 33–42. DOI: 10.1016/j.atmosres.2018.04.028.

Godah, W., Szelachowska, M. and Krynski, J. (2017). On the analysis of temporal geoid height variations obtained from GRACE-based GGMs over the area of Poland. *Acta Geophys.*, 65(4), 713–725. DOI: 10.1007/s11600-017-0064-3.

Gross, R., Beutler, G. and Plag, H.P. (2009). Integrated scientific and societal user requirements and functional specifications for the GGOS. In: Plag, H.P., Pearlman, M. (Eds.) *Global Geodetic Observing System*. Springer, Berlin, Heidelberg.

Gross, R. (2018). GGOS and Essential Geodetic Variables. In: 21 ILRS Workshop on Laser Ranging. Canberra, 5–9 November 2018.

Hadas, T., Krypiak-Gregorczyk, A., Hernández-Pajares, M., Kapłon, J., Paziewski, J., Wielgosz, P., Garcia-Rigo, A., Kaźmierski, K., Sośnica, K., Kwaśniak, D., Sierny, J., Bosy, J., Puciłowski, M., Szyszko, R., Portasiak, K., Olivares-Pulido, G., Gulyaeva, T. and Orus-Perez, R. (2017a). Impact and Implementation of Higher-Order Ionospheric Effects on Precise GNSS Applications. *J. Geophys. Res.: Solid Earth*, 122(11), 9420–9436. DOI: 10.1002/2017JB014750.

Hadas, T., Teferle, F.N., Kazmierski, K., Hordyniec, P. and Bosy, J. (2017b). Optimum stochastic modeling for GNSS tropospheric delay estimation in real-time. *GPS Solut.*, 21(3), 1069–1081. DOI: 10.1007/s10291-016-0595-0.

Hellerschmied, A., McCallum, L., McCallum, J., Sun, J., Böhm, J. and Cao, J. (2018). Observing APOD with the AuScope VLBI Array. *Sensors*, 18(5), 1587. DOI: 10.3390/s18051587.

Hernández-Pajares, M., Wielgosz, P., Paziewski, J., Krypiak-Gregorczyk, A., Krukowska, M., Stępniak, K., Kapłon, J., Hadaś, T., Sośnica, K., Bosy, J., Orus-Perez, R., Monte-Moreno, E., Yang, H., Garcia-Rigo, A. and Olivares-Pulido, G. (2017). Direct MSTID mitigation in precise GPS processing. *Radio Sci.*, 52(3), 321–337. DOI: 10.1002/2016RS006159.

Jagoda, M., Rutkowska, M., Kraszewska, K. and Suchocki, C. (2018). Time changes of the potential Love tidal parameters k2 and k3. *Stud. Geophys. Geod.*, 62(4), 586–595. DOI: 10.1007 s11200-018-0610-8.

Jagoda, M. (2019). Influence of use of different values of tidal parameters h2, l2 on determination of coordinates of SLR stations. *Stud. Geophys. Geod.*, 1–12. DOI: 10.1007/s11200-018-1174-3.

Jäggi, A., Meyer, U., Jean, Y., Flechtner, F., Mayer-Gürr, T. and Lemoine, J.-M. (2018). Combination Service for Time-Variable Gravity Field Solutions (COST-G): Transition from an EGSIEM prototype service into a product center of the IGFS. In 42. COSPAR Scientific Assembly, Pasadena, CA, USA, 14–22 July, 2018.

Kalarus, M., Wielgosz, A., Liwosz, T., Sośnica, K. and Zieliński, J. (2016). Possible advantages of equipping the GNSS satellites with on-board accelerometers. In Proceedings of the IAG commission 4 positioning and applications symposium, Wroclaw, Poland, September 4–7, 2016.

Katsigianni, G., Loyer, S., Perosanz, F., Mercier, F., Zajdel, R. and Sośnica, K. (2019). Improving Galileo orbit determination using zero-difference ambiguity fixing in a Multi-GNSS processing. *Adv. Space Res.* DOI: 10.1016/j.asr.2018.08.035.

Kaźmierski, K., Sośnica, K. and Hadaś, T. (2018a). Quality assessment of multi-GNSS orbits and clocks for real-time Precise Point Positioning. *GPS Solut.*, 22:11. DOI: 10.1007/s10291-017-0678-6.

Kaźmierski, K., Hadaś, T. and Sośnica, K. (2018b). Weighting of Multi-GNSS Observations in Real-Time Precise Point Positioning. *Remote Sens.*, 10(84), 1–15. DOI: 10.3390/rs10010084.

Kaźmierski, K. (2018c). Performance of Absolute Real-Time Multi-GNSS Kinematic Positioning. *Artificial Satellites. Journal of Planetary Geodesy*, 53(2), 75–88. DOI: 10.2478/arsa-2018-0007.

Kucharski, D., Kirchner, G., Bennett, J.C., Lachut, M., Sośnica, K., Koshkin, N., Shakun, L., Koidl, F., Steindorfer, M., Wang, P. et al. (2017). Photon pressure force on space debris TOPEX/Poseidon measured by Satellite Laser Ranging. *Earth Space Sci.*, 4(10), 661–668. DOI: 10.1002/2017EA000329.

Kuczynska-Siehien, J., Lyszkowicz, A. and Birylo, M. (2016). Geoid determination for the area of Poland by the least squares modification of Stokes' formula. *Acta Geodyn. Geomater.*, 13(1), 19–26. DOI: 10.13168/AGG.2015.0041.

Lejba, P., Suchodolski, T., Michałek, P., Bartoszak, J., Schillak, S. and Zapaśnik, S. (2018a). First laser measurements to space debris in Poland. *Adv. Space Res.*, 61(10), 2609–2616. DOI: 10.1016/j.asr.2018.02.033.

Lejba, P., Suchodolski, T., Michałek, P., Bartoszak, J., Zapaśnik, S. and Schillak, S. (2018b). Laser activity of the Borowiec laser station in years 2017–2018. In: 21 ILRS Workshop on Laser Ranging. Canberra, 5–9 November 2018.

Lucchesi, D. M., Santoli, F., Peron, R., Fiorenza, E., Lefevre, C., Lucente, M., Kalarus M. and Zielinski, J. (2016). Non-gravitational accelerations measurements by means of an on-board accelerometer for the Second Generation Galileo Global Navigation Satellite System. In: *Metrology for Aerospace (MetroAeroSpace)*, 2016 IEEE, 423–433. DOI: 10.1109/MetroAeroSpace.2016.7573253,

Männel, B. (2016). *Co-location of Geodetic Observation Techniques in Space*. Geodätisch-geophysikalische Arbeiten in der Schweiz, 97, SGC ETH Zürich, Switzerland. ISBN 978-3-908440-43-7.

Meyer, U., Sośnica, K, Andritsch, F., Dach, R., Jäggi, A., König, D. and Thaller, D. (2018). SLR, GRACE and SWARM gravity field determination and combination. In: 21 ILRS Workshop on Laser Ranging. Canberra, 5–9 November 2018.

Montenbruck, O., Steigenberger, P., Prange, L., et al. (2017). The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges. *Adv. Space Res.*, 59(7), 1671–1697. DOI: 10.1016/J.ASR.2017.01.011.

Osada, E., Sośnica, K., Borkowski, A., Owczarek-Wesołowska, M. and Gromczak, A. (2017a). A Direct Georeferencing Method for Terrestrial Laser Scanning Using GNSS Data and the Vertical Deflection from Global Earth Gravity Models. *Sensors*, 17(7), 1489. DOI: 10.3390/s17071489.

Osada, E., Owczarek-Wesołowska, M., Ficner, M. and Kurpiński, G. (2017b). TotalStation/GNSS/EGM integrated geocentric positioning method. *Surv. Rev.*, 49(354), 206–211. DOI: 10.1080/00396265.2016.1151969.

Otsubo, T., Müller, H., Pavlis, E.C., Torrence, M.H., Thaller, D., Glotov, V.D., Wang, X., Sośnica, K., Meyer, U. and Wilkinson, M.J. (2019). Rapid response quality control service for the laser ranging tracking network. *J. Geod*. DOI:10.1007/s00190-018-1197-0.

Paziewski, J., Sieradzki, R. and Wielgosz, P. (2018). On the Applicability of Galileo FOC Satellites with Incorrect Highly Eccentric Orbits: An Evaluation of Instantaneous Medium-Range Positioning. *Remote Sens.*, 10(2), 208. DOI: 10.3390/rs10020208.

Pearlman, M., Degnan, J. and Bosworth, J. (2002). The International Laser Ranging Service. *Adv. Space Res.*, 30(2), 135–143. DOI: 10.1016/S0273-1177(02)00277-6.

Pearlman, M., Arnold, D., Davis, M., Barlier, F., Biancale, R., Vasiliev, V., Ciufolini, I., Paolozzi, A., Pavlis, E., Sośnica, K. and Bloßfeld, M. (2019). Laser geodetic satellites: a high accuracy scientific tool. *J. Geod.* DOI: 10.1007%2Fs00190-019-01228-y.

Plag, H.P. and Pearlman, M. (2009). *Global Geodetic Observing System, Meeting the Requirements of a Global Society on a Changing Planet in 2020*. Springer-Verlag Berlin Heidelberg, 2nd edition. DOI: 10.1007/978-3-642-02687-4.

Rothacher, M. (2003). The Special Role of SLR for Inter-Technique Combinations. In: ILRS Workshop 2003, October 28–31, 2003, Bad Koetzing, Germany.

Schillak, S., Lejba, P. and Michałek, P. (2018). Determination of the coordinates of SLR stations from the LARES satellite. In: 21 ILRS Workshop on Laser Ranging. Canberra, 5-9 November 2018.

Schlüter, W. and Behrend, D. (2007). The International VLBI Service for Geodesy and Astrometry (IVS): current capabilities and future prospects. *J. Geod.*, 81(6-8), 379–387. DOI: 10.1007/s00190-006-0131-z.

Sośnica, K., Jäggi, A., Meyer, U., Thaller, D., Beutler, G., Arnold, D. and Dach, R. (2015a). Time variable Earth's gravity field from SLR satellites. *J. Geod.*, 89(10), 945–960. DOI: 10.1007/s00190-015-0825-1.

Sośnica, K. (2015b). *Determination of precise satellite orbits and geodetic parameters using satellite laser ranging*. Geodätisch-geophysikalische Arbeiten in der Schweiz, 93, SGC ETH Zürich, Switzerland, ISBN 978-3-908440-38-3.

Sośnica, K., Thaller, D., Dach, R., Steigenberger, P., Beutler, G., Arnold, D. and Jäggi, A. (2015c). Satellite laser ranging to GPS and GLONASS. *J. Geod.*, 89(7), 725–743. DOI: 10.1007/s00190-015-0810-8.

Sośnica, K., Bury, G. and Zajdel, R. (2018a). Contribution of Multi-GNSS Constellation to SLR-Derived Terrestrial Reference Frame. *Geophys. Res. Lett.*, 45(5), 2339–2348. DOI: 10.1002/2017GL076850J.

Sośnica, K., Prange, L., Kaźmierski, K., Bury, G., Drożdżewski, M., Zajdel, R. and Hadaś, T. (2018b). Validation of Galileo orbits using SLR with a focus on satellites launched into incorrect orbital plane. *J. Geod.*, 92(2), 131–148. DOI: 10.1007/s00190-017-1050-x.

Sośnica, K., Rohm, W., Bosy, J., Zajdel, R., Hadas, T., Kapłon, J., Kudlacik, I., Pawluszek, K., Sierny, J., Ilieva, M., Borkowski, A., Krynski, J., Dykowski, P., Mutke, G., Kotyrba, A. and Olszewska, D. (2018c). Monitoring of Earth surface displacements using integrated multi-GNSS, gravity, seismic, and InSAR data in the framework of GGOS-PL++. In: 42. COSPAR Scientific Assembly, Pasadena, CA, USA, 14–22 July, 2018.

Strugarek, D., Sośnica, K. and Jaeggi, A. (2019). Characteristics of GOCE orbits based on Satellite Laser Ranging. *Adv. Space Res.*, 63(1), 417–431. DOI: 10.1016/j.asr.2018.08.033.

Tercjak, M. and Brzeziński, A. (2017). On the Influence of Known Diurnal and Subdiurnal Signals in Polar Motion and UT1 on Ring Laser Gyroscope Observations. *Pure Appl. Geophys.*, 174(7), 2719–2731. DOI: 10.1007/s00024-017-1552-8.

Trojanowicz, M., Osada, E. and Karsznia, K. (2018). Precise local quasigeoid modelling using GNSS/levelling height anomalies and gravity data. *Surv. Rev.*, 1–8. DOI: 10.1080/00396265.2018.1525981.

Wielgosz, A., Tercjak, M. and Brzeziński, A. (2016). Testing impact of the strategy of VLBI data analysis on the estimation of Earth Orientation Parameters and station coordinates. *Reports on Geodesy and Geoinformatics*, 101(1), 1–15. DOI: 10.1515/rgg-2016-0017.

Willis, P., Fagard, H., Ferrage, P., Lemoine, F.G., Noll, C.E., Noomen, R. and Tavernier, G. (2010). The international DORIS service (IDS): toward maturity. *Adv. Space Res.*, 45(12), 1408–1420. DOI: 10.1016/j.asr.2009.11.018.

Wińska, M., Nastula, J. and Salstein, D. (2017). Hydrological excitation of polar motion by different variables from the GLDAS models. *J. Geod.*, 91(12), 1461–1473. DOI: 10.1007/s00190-017-1036-8.

Wińska, M. and Śliwińska, J. (2018). Assessing hydrological signal in polar motion from observations and geophysical models. *Stud. Geophys. Geod.*, 1–24. DOI: 10.1007/s11200-018-1028-z.

Zajdel, R., Sośnica, K. and Bury, G. (2017). A New Online Service for the Validation of Multi-GNSS Orbits Using SLR. *Remote Sens.*, 9(10), 1049. DOI: 10.3390/rs9101049.

Zajdel, R., Sośnica, K., Dach, R., Bury, G., Prange, L. and Jaeggi, A. (2019). Network effects and handling of the geocenter motion in multi-GNSS processing. *J. Geophys. Res.* (in review)

Zieliński, J. (2015). Pure gravitational orbits of GNSS – The tool for the relativistic space geodesy. In: *Metrology for Aerospace (MetroAeroSpace)*, 2015 IEEE. DOI: 10.1109/MetroAeroSpace.2015.7180644.

Zieliński, J. and Wielgosz, A. (2018). High Precision GNSS – Prospects for Science and Applications. In: Cefalo R., Zieliński J., Barbarella M. (Eds.), *New Advanced GNSS and 3D Spatial Techniques. Lecture Notes in Geoinformation and Cartography*. Springer, Cham.