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Review paper

Global Geodetic Observing System in Poland 2019–2022

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Abstract: This paper summarizes the contribution of Polish scientific units to the development of the Global Geodetic Observing System (GGOS) in recent years. We discuss the issues related to the integration of space geodetic techniques and co-location in space onboard Global Navigation Satellites Systems (GNSS) and Low Earth Orbiters (LEO), as well as perspectives introduced by the new European Space Agency's (ESA) mission GENESIS. We summarize recent developments in terms of the European Galileo system and its contribution to satellite geodesy and general relativity, as well as ESA's recent initiative – Moonlight to establish a satellite navigation and communication system for the Moon. Recent progress in troposphere delay modeling in Satellite Laser Ranging (SLR) allowed for better handling of systematic errors in SLR, such as range biases and tropospheric biases. We discuss enhanced tropospheric delay models for SLR based on numerical weather models with empirical corrections, which improve the consistency between space geodetic parameters derived using different techniques, such as SLR, GNSS, and Very Long Baseline Interferometry (VLBI). Finally, we review recent progress in the development of Polish GGOS scientific infrastructure in the framework of the European Plate Observing System project EPOS-PL+.

Keywords: GNSS, GGOS, SLR, space ties, GENESIS

1. Introduction

The Global Geodetic Observing System (GGOS) introduced a challenge to space geodesy requiring the accuracy of the realization of the terrestrial reference frame of 1 mm and 0.1 mm per year for its stability (Plug and Pearlman, 2009). These requirements are dictated by the need of moving the boundaries of knowledge about subtle phenomena occurring in the

Earth system, such as sea level rise, as well as changes in the cryosphere, land hydrology, and lithosphere. The current accuracy of the terrestrial reference frame realization exceeds about four times the GGOS requirements (Altamimi et al., 2022). Therefore, many efforts have been undertaken to accomplish the GGOS criteria by improving the global infrastructure in terms of the distribution of the stations, performance and accuracy, mitigation of systematic errors included in observations, modeling of geophysical and geodynamic background models, proposing new satellite missions and observation types to improve the space segment and orbit determination, as well as enhancing the connection of various space geodetic techniques by space ties, tropospheric ties, and global ties.

2. Co-location in space onboard GNSS satellites

Currently, local ties are used for the realization of the international terrestrial reference frames, e.g., ITRF2020 (Altamimi et al., 2022). Local ties are measured at the GGOS stations equipped with more than one space geodetic technique: VLBI, GNSS, SLR, and DORIS (Kallio et al., 2022). The measurements require a very high accuracy because all potential errors in local tie measurements may directly leak into the ITRF realization as an inconsistency between space geodetic techniques and affect the accuracy of the ITRF realization. Local ties are typically measured once over several years at GGOS stations because of the high costs and efforts required for the measurement process.

Instead of conducting laborious local tie measurements, the space ties onboard satellites can be used for the ITRF realization (see Fig. 1). A space tie link is possible whenever more than one space geodetic technique is targeted toward a common object. Bury et al. (2021a) showed that the space ties onboard Galileo and GLONASS can be used for the connection between SLR and GNSS techniques because all Galileo and GLONASS satellites are equipped with laser retroreflectors for SLR. The independent space tie is

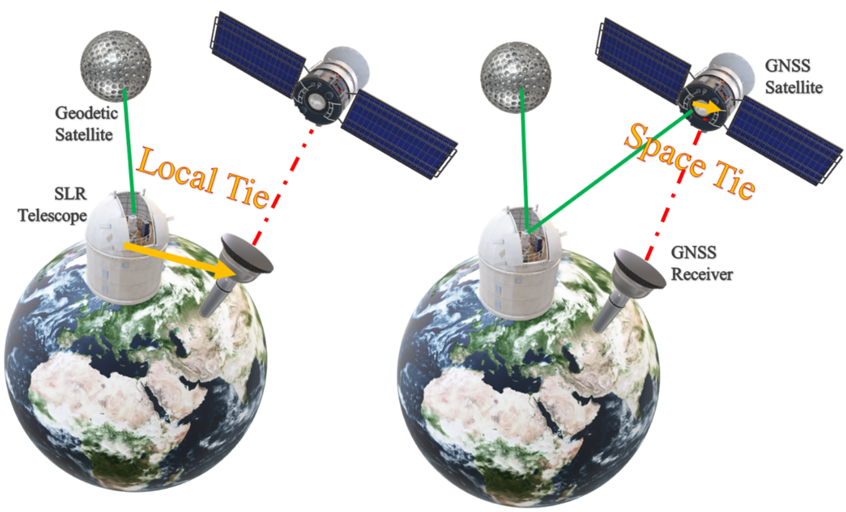

Fig. 1. SLR-GNSS co-location in space onboard GNSS satellites, after Bury et al. (2021a)

available whenever an SLR station tracks GNSS satellites and the GNSS receiver at the station provides observations to the same satellites. The quality of space ties on-board GNSS satellites in terms of the standard deviation of differences between GNSS and SLR solutions is about 40-50 mm in 1-day solutions for individual stations. However, the long-term mean of space ties agrees to 3–4 mm with local tie measurements (Bury et al., 2021a). The co-location in space requires proper handling of SLR range biases because biases and detector-specific signature effects constitute the major factors that limit the accuracy of SLR data processing. For flat laser retroreflectors installed onboard GNSS, only the correction between the satellite center-of-mass and the retroreflector centroid is considered when processing SLR data. The single-shot laser pulse can be reflected by any corner cube of the retroreflector array. Detectors installed at SLR stations may operate in single-photon, few-photon, or multi-photon regimes which results in different mapping of the GNSS retroreflector array depending on the incidence angle of the incoming laser pulse. Different SLR detectors' regimes result in systematic effects observed at SLR stations, which are called the signature effect (Strugarek et al., 2021b).

3. Co-location in space onboard LEO satellites

Due to the recent progress in GNSS data modeling, the accuracy of GNSS-based LEO orbits has essentially improved (Arnold et al., 2019). The largest improvement of LEO orbits emerges from 1) using satellite macromodels to account for the solar radiation pressure, albedo, and atmospheric drag, 2) resolving phase ambiguities, 3) enhanced LEO antenna calibrations, 4) and proper satellite attitude modeling (Strugarek 2019b; Montenbruck et al., 2022). Many LEO satellites requiring the highest quality of determined orbits are equipped with laser retroreflectors for SLR, GNSS receivers, and DORIS receivers. Therefore, LEO can be used as the platform for co-location in space. Strugarek et al. (2019a) used the SLR observations to GNSS-based Sentinel 3A and 3B orbits to derive global geodetic parameters. Such an approach allows for the deriving of global geodetic parameters and SLR station coordinates with comparable quality to that derived from LAGEOS observations. Strugarek et al. (2019a) tested different network constraints and different lengths of the solutions. However, 3-day and 5-day solutions turned out to be insufficient to derive global parameters due to missing observations from at least four continents, thus, 7-day solutions are optimum for SLR. Strugarek et al. (2019a) also proposed an SLR-based precise point positioning (PPP) solution, in which no network constraints are required because only station coordinates are estimated, whereas satellite orbits and Earth rotation parameters are derived from GNSS. Such a solution allows for deriving SLR station coordinates individually for each site. The concept of the SLR-PPP technique was further employed using the SWARM-A/B/C constellation (Strugarek et al., 2021b).

Sosnica et al. (2019) used integrated SLR observation to Galileo, GLONASS, BeiDou, GPS, and QZSS for deriving global geodetic parameters. Strugarek et al. (2021a) extended the possibilities of deriving SLR station coordinates and geodetic parameters by integrating SLR observations to active satellites at different heights: LEO and Galileo, as well as passive geodetic satellites: LARES and LAGEOS (see Fig. 2). Such a solution, allowed for deriving SLR station coordinates of superior quality when compared to LAGEOS-based products provided that proper weighting is employed. Using equal weights for all SLR targets may result in solution deterioration (Strugarek et al. 2021a).

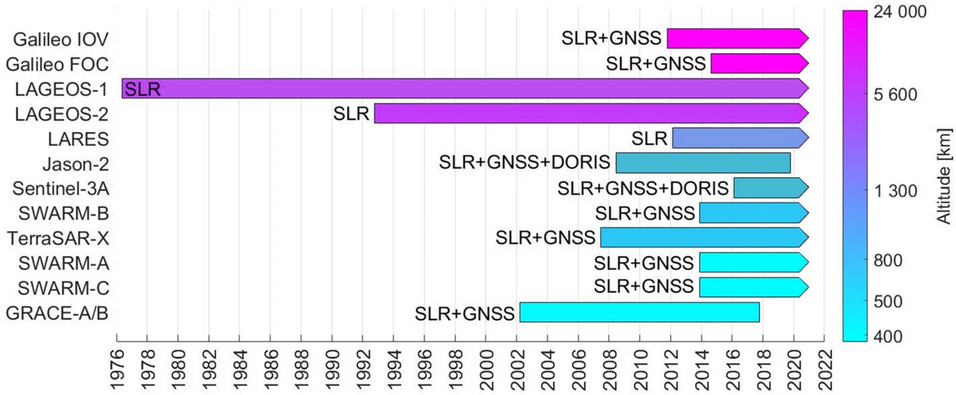

Fig. 2. Satellite missions allowing for the co-location in space as described in the paper by Strugarek et al. (2021a)

One of the errors affecting the SLR observations is the blue-sky effect caused by the atmospheric pressure loading because the dominating SLR observations are collected during cloudless weather conditions when the Earth's crust is deformed by high atmospheric pressure. Bury et al. (2019c) assessed the impact of the blue-sky effect based on SLR observations to GNSS satellites. The missing loading corrections can be reconstructed a posteriori by translating the SLR network. However, a considerable part of the loading effect affects not only the network origin but also all estimated parameters, such as orbits, pole coordinates, and length of day; thus, loading corrections should be applied a priori at the observation level to ensure the highest solution accuracy (Bury et al., 2019c).

The Synthetic Aperture Radar (SAR) satellites together with active transponders have been tested in terms of the height system unification and sea level research for the countries near the Baltic Sea (Gruber et al., 2020). The SAR transponders were co-located with GNSS receivers and the tide gauges, resulting in the agreement at the several-centimeter level between different techniques (Czikhardt et al., 2021; Gruber et al., 2022). Hence, the SAR technique introduces a novel opportunity for co-location in space geodesy, however, the SAR applicability for the reference frame realization requires further studies.

4. Co-location in space onboard GENESIS

So far, VLBI was the only technique missing for the successful co-location onboard artificial Earth satellites. Some tests of tracking CubeSat LEO using VLBI have been conducted (Hellerschmied et al., 2018), but the results remained unsatisfactory for geodetic purposes. In 2022, ESA decided to fund a mission dedicated to space geodesy (see Fig. 3). The GENESIS platform will carry onboard all the geodetic instruments referenced to one another through carefully calibrated space ties. The co-location of the techniques in space will solve the inconsistencies and biases between the different geodetic techniques, and pave new opportunities for reference frame realization to bring us closer to the fulfillment of the GGOS goals (Delva et al., 2023).

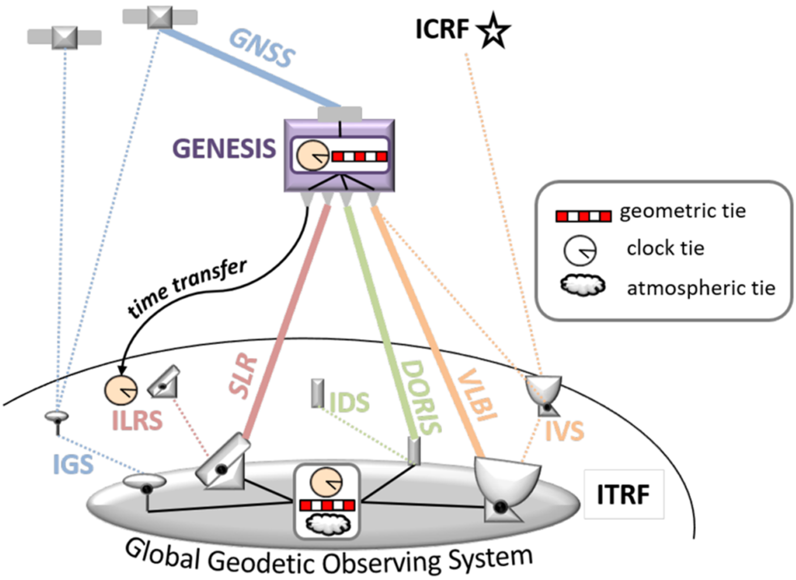

Fig. 3. Concept of the GENESIS mission for the SLR, GNSS, DORIS, and VLBI co-location in space, after Delva et al. (2023)

5. GNSS orbit modeling

Precise GNSS orbits are a prerequisite for obtaining all derivative products – geodetic parameters based on GNSS. A huge progress in the precise orbit determination of Galileo was possible due to the publication of satellite metadata. The Galileo metadata included indispensable information for orbit determination, e.g., satellite components' size and surface properties – reflection, absorption and dispersion coefficients, modified yaw-steering law, laser retroreflector offsets, as well as antenna offsets and variations based on calibrated data.

Bury et al. (2019a) developed a box-wing model for Galileo In-Orbit Validation (IOV) and Full Operational Capability (FOC) satellites based on published satellite metadata. To fully exploit the potential of the box-wing model, the number of empirical orbit parameters had to be reduced excluding the twice-per-revolution and quadruple terms proposed by Arnold et al. (2015) for the new Empirical CODE orbit model (ECOM). The box-wing model improves the Galileo orbits, especially for the eclipsing periods – the standard deviation of SLR residuals decreases from 37 to 25 mm between the solution based on the extended empirical ECOM with twice-per-rev parameters and the solution based on the box-wing model and a reduced number of ECOM parameters to the five main terms.

Bury et al. (2020) assessed the impact of the non-gravitational force modeling on Galileo satellites, including the direct solar radiation pressure, albedo, Earth infrared radiation, and navigation antenna thrust. The authors concluded that the published Galileo metadata are capable of absorbing about 97% of the total non-gravitational perturbing forces, whereas the remaining part must be absorbed by additionally estimated empirical orbit parameters.

Further improvement of the orbit determination can be obtained by integrating SLR and GNSS data. Bury et al. (2021b) showed that the orbits in the periods when the Sun is almost perpendicular to the orbital plane, resulting in orbit modeling issues due to large correlations between orbit parameters, are improved when combining SLR with GNSS for precise orbit determination (see Fig. 4). However, the SLR and GNSS observations require proper weighting because assuming that the SLR observations and phase GNSS data are of the same quality introduces spurious effects in determined orbits. Therefore, down-weighting of the SLR by a factor of four for Galileo (Bury et al., 2021b) and satellite-dependent weighting for GLONASS with even further reduced weights (Bury et al., 2022) is indispensable for obtaining high-quality combined orbits.

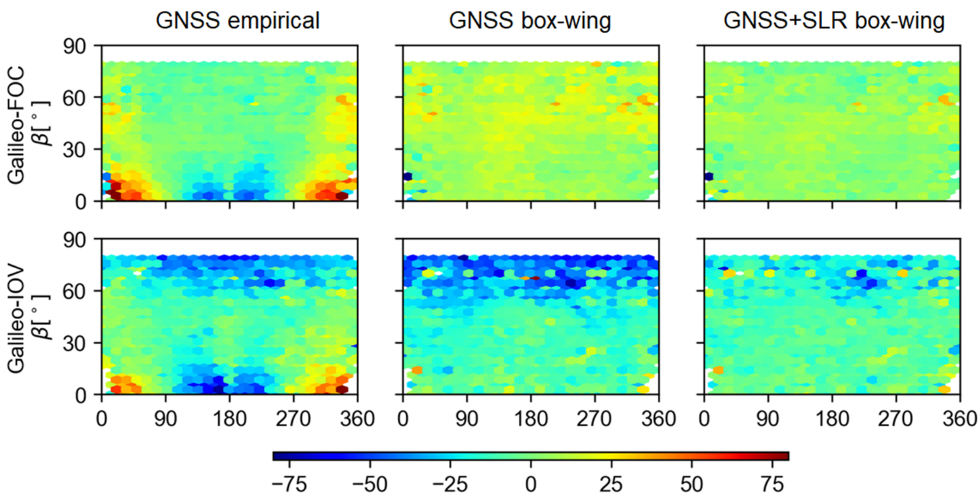

Fig. 4. Progress in Galileo orbit modeling and reducing systematic patterns – SLR residuals to Galileo orbits for the GNSS-based empirical orbit solution (left), GNSS-based box-wing orbit model solution with estimating five ECOM parameters (middle), and the combination of GNSS and SLR data with the box-wing model and estimating five ECOM parameters (right). All values are in millimeters. After Bury et al. (2021b)

SLR observations to GNSS satellites can also be used for deriving their orbits, however, the cross-track component is poorly observed by SLR, whereas the orbits of cm-level quality require SLR observations collected from different continents for each satellite arc, which occurs only during intensive SLR tracking campaigns (Bury et al., 2019b). Therefore, the combination of SLR and GNSS data is preferable for GNSS precise orbit determination.

For the Galileo satellites of the second generation, the inter-satellite links are considered which would increase the independence of the system with respect to the ground-based control segment. Kur et al. (2021), and Kur and Kalarus (2021) studied different configurations of inter-satellite links and their impact on the accuracy of satellite orbits, clocks, and geodetic parameters. The authors employed the variance component estimation for relative weighting of simulated inter-satellite links and GNSS measurements to further benefit from new observation types for precise orbit determination (Kur and Liwosz, 2022).

The current ITRF realizations struggle with the increasing number of contributing stations and longer time series, and thus, the increasing number of discontinuities in the station coordinate time series caused by equipment changes, earthquakes, electromagnetic interference, and other reasons. Najder (2020) studied the possibility of using automatic algorithm of detecting discontinuities and velocity changes in GNSS data and compared those to the events considered in the ITRF realization. Baselga and Najder (2022) employed similar automatic tools for detecting EUREF permanent GNSS network stations' discontinuities due to earthquake events. Although the automatic tools for the analysis of the station coordinates still require manual adaptation of the threshold levels for significant events, these automated tools are very useful for processing large-scale GNSS networks.

6. Realization of the reference frame scale based on GNSS

The ITRF is the basis for almost all applications in geosciences by providing the reference for observations, and the monitoring of geophysical phenomena occurring in the Earth system. In the ITRF history, the scale was realized in several ways: from SLR or VLBI observations only, as a combination of selected periods from SLR, VLBI and GPS solutions, or by an alignment to the previous ITRF solution. Throughout the ITRF history, the scale differences between consecutive ITRF solutions reach up to 1 ppb. Most commonly, these could be explained by modeling errors and inter-technique inconsistencies. For ITRF2014, the individual solutions from SLR and VLBI had a corresponding offset of 0.4 and −0.4 ppb, respectively. Meanwhile, thanks to the improved procedure of the SLR range bias handling, the ITRF2020 results show a substantial scale consistency improvement, as the level of agreement between SLR and VLBI intrinsic scales is now at the level of 0.15 ± 0.05 ppb (Altamimi et al., 2022).

Antenna calibrations provided in Galileo metadata allow for the realization of the global scale. In the framework of the ITRF2020 realization, Galileo has been processed for the first time together with GPS and GLONASS data. However, due to the inconsistencies in the scale realization between GNSS, SLR and VLBI, the official ITRF2020 realization does not employ the Galileo-based scale (Altamimi et al., 2022) and the scale is based only on VLBI and SLR. Interestingly, the DTRF2020, that is the DGFI-TUM realization of the terrestrial reference frame, incorporates the Galileo-based scale together with the VLBI-based scale (Seitz et al., 2022).

The two following GNSS contributors allow for the independent GNSS-based contribution to the ITRF scale realization. Both GPS-III and BDS-3 manufacturers released information about the satellite antenna calibrations. Zajdel et al. (2022b) tested different combinations of frequencies for the BeiDou-3 system, for which the antenna calibrations have been provided, in terms of their applications to the global scale realization. Zajdel et al. (2022b) found that the GNSS-based scale realization can be frequency-dependent and is strongly vulnerable to orbit modeling. Therefore, the issue of the GNSS scale realization requires further investigation.

7. Deriving global geodetic parameters based on multi-GNSS data

Galileo provides superior global geodetic parameters due to the recent developments in orbit modeling, advanced technology employed, available metadata, and the characteristics of the satellite orbits. Due to the deep resonance 1:2 between the Earth rotation and satellite revolution for GPS, some diurnal and semidiurnal parameters cannot be reliably derived, whereas the GPS-based length-of-day data typically result in an offset which translates into a secular drift of UT1-UTC values. Galileo satellites are not affected by a deep orbit resonance with the Earth rotation (Zajdel et al., 2021b), therefore, the diurnal and semidiurnal signals can be derived with superior quality when compared to GPS. Zajdel et al. (2020) tested the Earth rotation parameters derived from GPS, GLONASS, and Galileo data and found that the accumulated length-of-day values based on Galileo have a secular rate up to fourteen times smaller than GPS-based values. The GLONASS-based pole coordinates are strongly affected by the orbit modeling issues and thus are not as reliable as the GPS and Galileo results (see Fig. 5).

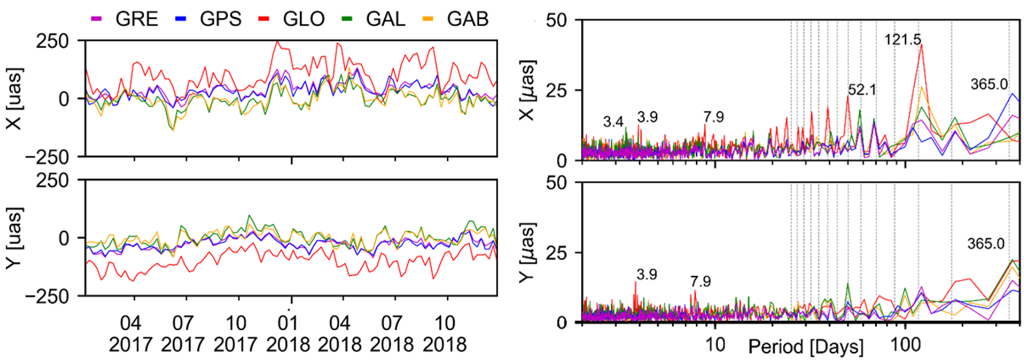

Fig. 5. Pole coordinates derived from GPS, GLONASS (GLO), Galileo based on empirical orbit model (GAL), Galileo based on box-wing model (GAB), and GPS+GLONASS+Galileo (GRE) combination as a difference with respect to IERS-14-C04 series (left) with a corresponding spectrum analysis (right), after Zajdel et al. (2021b)

Zajdel et al. (2021a) studied the impact of solar radiation pressure modeling on GNSS-based geocenter coordinates. The authors found that six orbital planes of the GPS system stabilize the geocenter motion recovery. The largest orbit modeling issues for GNSS systems including three orbital planes take place when the Sun illuminates one orbital plane almost perpendicularly (i.e., the Sun elevation angle above the orbital plane is maximum) and the Sun elevation angle above two other orbital planes is similar. Such a configuration results in substantial correlations between empirical orbit parameters and the Z component of the geocenter motion. Zajdel et al. (2021a) found that this phenomenon is strengthened for the new ECOM model with additional twice-per-revolution terms when compared to the classical ECOM model. Therefore, estimating the minimum number of empirical orbit parameters is preferable.

GLONASS-based geocenter motion is unreliable due to three orbital planes and orbit modeling issues. However, despite that the Galileo system nominally consists of three orbital planes, the E14 and E18 Galileo FOC satellites, accidentally launched into eccentric orbits, form the fourth orbital plane stabilizing the Galileo solutions. Therefore, the geocenter motion provided by the Galileo system is only slightly worse when compared to that provided by GPS, whereas the GPS+Galileo combination provides superior results (Zajdel et al., 2021a).

Zajdel et al. (2019b) tested the reliability of the GNSS-based geocenter estimates and compared the GNSS station coordinates between the solution with and without imposing the no-net-translation constraint on the GNSS network. The errors of station heights increase by a factor of three when the no-net-translation constraint is not imposed on the GNSS network, despite not estimating the geocenter coordinates as an additional parameter. Therefore, the GNSS network solution based on double differences has a limited sensitivity to the network origin and the GNSS-based geocenter motion includes not only the geophysical signals but also the limitations of the global GNSS solutions to sense the Earth's center-of-mass. Zajdel et al. (2019b) recommend that the not-net-translation constraint should always be imposed on the global GNSS solution despite the lack of direct solution singularity. A different situation occurs in the SLR solutions based on LAGEOS observations (Zajdel et al., 2019b). When imposing the no-net-translation constraint, the estimated geocenter parameter includes the geocenter motion; whereas when not imposing no-net-translation, estimated SLR station coordinates fully absorb the geocenter motion, and the formal errors of station heights are not increased. Therefore, the no-net-translation constraint is not obligatory in the SLR global solutions; and thus, one can choose whether the SLR-based results should be provided in the center-of-mass frame (without no-net-translation) or the center-of-network frame (with no-net-translation constraint). Such a prospect is not possible in GNSS solutions, which always require the no-net-translation constraint.

8. Orbital signals in global geodetic parameters

The time series of geodetic parameters typically contain spurious signals that are related to: (1) orbital resonances between the satellite revolution period and Earth rotation, (2) aliasing between the sub-daily background models and resulting parameter sampling,

(3) draconitic errors due to the orbit modeling issues. These errors have been found in GNSS-based Earth rotation parameters (Zajdel et al., 2020), sub-daily polar motion (Zajdel et al., 2021b), geocenter coordinates (Zajdel et al., 2021a), sub-daily station coordinates derived from PPP (Zajdel et al., 2022a), and tropospheric parameters (Hadas and Hobiger, 2021; Zajdel et al., 2022a). Moreover, the troposphere parameters and station coordinates based on different GNSS may result in an inter-system bias (Wilgan et al. 2022, 2023).

Zajdel et al. (2020, 2022a) found that the orbital resonances can be mitigated by the multi-satellite combinations (see Fig. 6). In the multi-satellite solutions, satellites with different revolution periods are employed, resulting in the de-correlation between global geodetic parameter estimation intervals and satellite ground track repeatabilities. The aliasing issues must be mitigated by improving the background models of high-frequency phenomena, e.g., better sub-daily Earth rotation models based on geophysical ocean tide models with libration corrections or empirical models based on space geodetic data (Zajdel et al., 2021b). The draconitic errors can be reduced by improved orbit modeling, e.g., by using satellite macromodels for mitigating the impact of solar radiation pressure with the minimum number of estimated empirical orbit parameters (Zajdel et al., 2020, 2021a). However, GLONASS has been found to provide station coordinates of inferior quality, therefore, its contribution had to be down-weighted to avoid the degradation of multi-GNSS PPP solutions (Zajdel et al., 2022a).

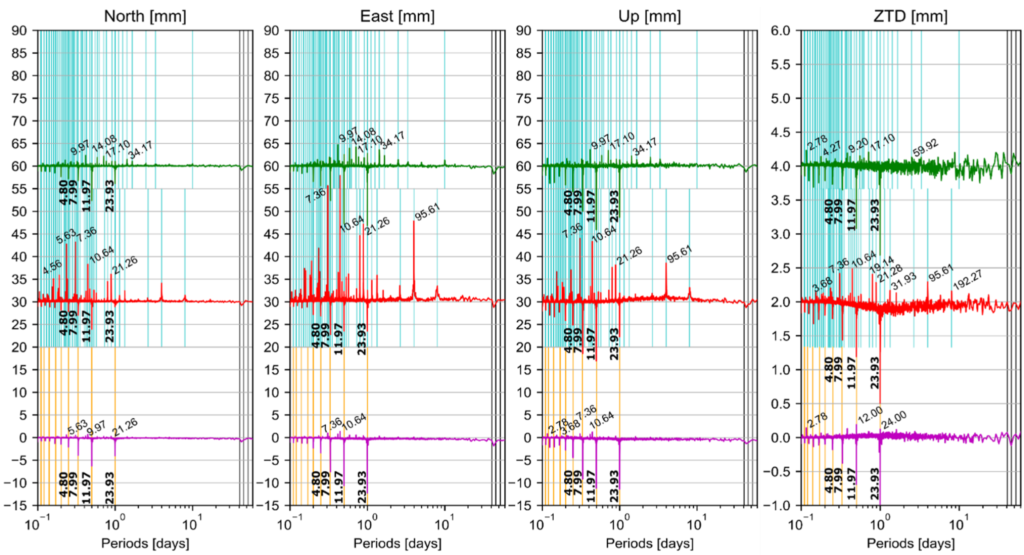

Fig. 6. Stacked differential periodograms of station coordinates for the North, East, and Up components and zenith total delay correction (ZTD). Top: the difference between Galileo and GPS, middle: the difference between GLONASS and GPS, bottom: the difference between multi-GNSS and GPS. Positive values denote that the signals have larger amplitudes in system-specific solutions than in GPS, and negative values denote a reduction of the signals that occurred in GPS-only solutions. Blue lines denote orbital signals for Galileo and GLONASS, whereas orange lines denote the harmonics of the sidereal day (orbital signals for GPS). Labels are in hours. After: Zajdel et al. (2022a)

9. New perspectives for Galileo and BeiDou

Galileo and BeiDou are the new GNSS systems, for which the metadata have been released allowing for advanced orbit modeling and scale realization. However, some parameters provided for BeiDou are still incomplete, e.g., satellite surface properties, whereas some antenna offset parameters seem to be invalid for some BeiDou-3 satellites (Zajdel et al., 2022b).

The International GNSS Service (IGS) provided an initial orbit product by combining GPS, GLONASS, Galileo, BeiDou, and QZSS orbits provided by different IGS analysis centers, including those contributing to the multi-GNSS experiment (MGEX). The initial orbit combination service was evaluated by Sosnica et al. (2020) showing that substantial efforts must be undertaken by MGEX centers to reach the same quality of orbits for new systems as currently obtained for the best-performing systems.

Despite that all BeiDou-3 satellites are equipped with laser retroreflector arrays, only three of them are being tracked by SLR stations. The SLR tracking of BeiDou-3 requires orbit predictions of high reliability and quality (Najder and Sosnica, 2021). The International Laser Ranging Service plans to track 20 out of 30 BeiDou-3 satellites in the future instead of GLONASS satellites, whose tracking stopped after the Russian invasion on Ukraine in 2022.

Kazmierski et al. (2020) evaluated the real-time orbits and clocks provided by the CNES IGS analysis center (Katsigianni et al., 2019). The authors found that despite modeling issues included in the Galileo orbits, some errors in the orbit radial direction are absorbed and compensated by clock corrections. This is only possible in the GNSS systems that are equipped with superior clocks, such as Galileo with pairs of hydrogen masers compensated by rubidium clocks (Kazmierski et al., 2020). The time transfer based on Galileo is of similar quality to GPS results or even better despite that the Galileo system still did not reach its full operational capability (Mikos et al., 2023). Galileo satellites are homogeneous as opposed to GPS satellites employing different technologies and frequencies for different blocks. Moreover, the broadcast messages of Galileo satellites are being updated more frequently than in the case of GPS, GLONASS, and BeiDou. Therefore, the PPP based on Galileo broadcast data with no further corrections allows for the positioning with decimeter-level accuracy (Hadas et al., 2019) – more than a factor of three better than those based on GPS.

High-quality orbits allow for the validation of effects emerging from general relativity, such as the Schwarzschild, Lense-Thirring, and De Sitter (geodetic precession) effects. Sosnica et al. (2021) derived formulas of theoretical changes in Keplerian parameters and satellite revolution periods due to three main effects emerging from general relativity. The authors calculated the magnitude of periodical and secular orbit perturbations for GNSS, LAGEOS, LARES, and geostationary orbits. The periodical variations of the semi-major axis due to the Schwarzschild effect and the secular rates of the ascending node due to Lense-Thirring and De Sitter turned out to be measurable using GNSS orbits as they reach the centimeter level within 3-day arcs. Accumulating the long-term GNSS solutions may even further improve the confirmation of general relativistic effects.

Sosnica et al. (2022) used GPS, GLONASS, and Galileo orbits to detect the impact of the Schwarzschild effect on the semi-major axis and eccentricity of GNSS orbits. The Galileo satellites in eccentric orbits provided a very good agreement with theoretically derived values. The change of the satellite semi-major axis equaled +28.3 and –7.8 mm when eccentric Galileo satellites are in their perigees and apogees, respectively. When considering the full constellation of GPS, GLONASS, and Galileo, the mean observed semi-major offset is −17.41 mm, which gives a relative error versus the expected value from the theory of 0.36% (Sosnica et al. 2022). Therefore, GNSS satellites with enhanced orbit modeling considerably contribute to fundamental physics.

10. Progress in SLR data modeling

Some of the global geodetic parameters can be derived entirely reliably only from the SLR technique, e.g., Earth's oblateness term (Yu et al., 2021b), geocenter coordinates (Zajdel et al., 2019b; Kosek et al., 2020; Yu et al., 2021a) or the standard gravitational product GM (Perlman et al., 2019). Moreover, the combination of GNSS-based LEO kinematic orbits and SLR data can be used for deriving the low-degree gravity field parameters and fill up the gap between GRACE and GRACE Follow-On missions (Meyer et al. 2019; Zhong et al., 2021). Despite significant progress in SLR data processing, the SLR-based parameters are still affected by systematic errors.

One of the major systematic error sources in SLR data is the modeling of the troposphere delay. SLR stations rely on the meteorological data collected at the SLR stations to derive the corrections for the slant tropospheric delays. For the delay in the zenith direction, the barometer with water vapor data are employed, whereas, for the mapping function, the temperature records collected at the station are used. Due to the point meteorological measurements, the full symmetry of the atmosphere is assumed for the SLR tropospheric delay modeling.

Drozdzewski et al. (2019) proposed employing numerical weather models to account for the asymmetry of the atmosphere above the SLR stations. The horizontal gradients and mapping functions based on numerical models improved the SLR solutions, however, the zenith delays turned out to be more accurate when based on direct meteorological data collected at SLR stations than numerical weather models. Using the hybrid approach with barometer data and horizontal gradients and mapping functions from numerical models, the SLR-based pole coordinates improved by about 20 μas (Drozdzewski et al., 2019) and became more consistent with the results obtained from other space geodetic techniques, especially GNSS.

Despite the calibrations, some SLR stations seemed to be affected by barometer biases resulting in tropospheric biases (Drozdzewski and Sosnica, 2021). Therefore, the estimation of tropospheric biases has been proposed for SLR. The estimation of tropospheric biases improves the repeatability of SLR station coordinates, changes the geocenter mean offset at the millimeter level (Drozdzewski and Sosnica, 2021), and substantially reduce the SLR residuals to LEO satellites – from the level of 10 to 6 mm for high-performing SLR stations (Strugarek et al., 2022). Due to the elevation-dependency of tropospheric biases, they are much better suited to account for systematic errors in SLR data than range biases, which are independent of the elevation angle (see Fig. 7). Therefore, estimating tropospheric biases is beneficial for SLR solutions, whereas estimating range biases may result of biased SLR-based parameters, especially the height component of station coordinates and the global scale (Drozdzewski and Sosnica, 2021).

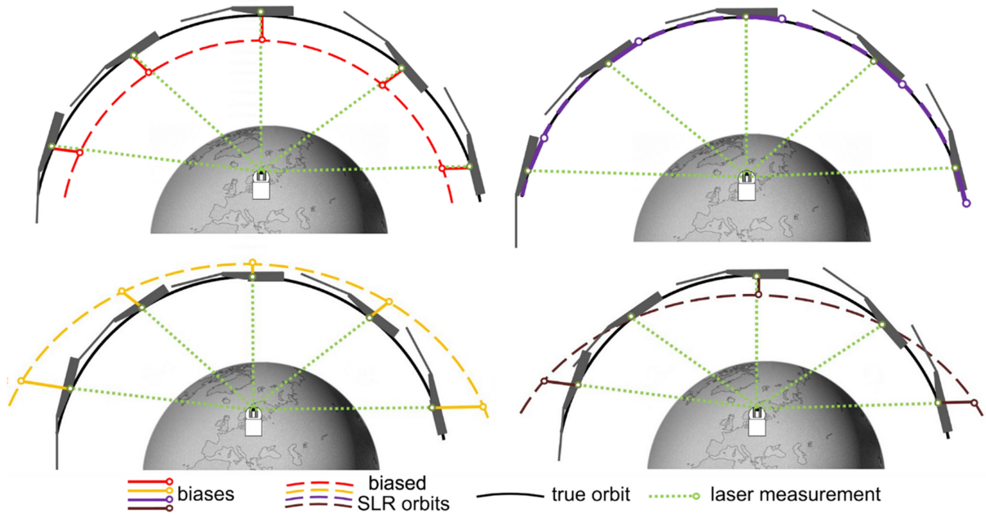

Fig. 7. Geometry of systematic errors in SLR. Range bias (top-left, red), time bias (top-right, purple), tropospheric bias (bottom-left, yellow), and sum of errors (bottom-right, brown), after Otsubo et al. (2019) and Strugarek et al. (2022)

11. ESA's new initiatives

Besides the GENESIS initiative, ESA will support a new mission in the framework of the Moonlight program. For future lunar missions, the satellite navigation and communication system is indispensable. Navigation and positioning on the Moon using a satellite system require a high-accuracy lunar reference frame realization, connection to the terrestrial reference frame, lunar-specific time system definitions, and time transfer between the UTC time on the Earth and lunar satellites and receivers. The high-quality lunar reference frames can be provided by the laser retrorefectors on the Moon installed by Apollo and Luna missions, as well as future Arthemis missions (Iess et al., 2022). The high-quality orbits of lunar orbiters can be provided by range, range-rate, and Doppler observations by a dedicated ESA network as well as by GNSS receivers that are planned to be placed on the lunar orbiters (Sesta et al., 2023). ESA funded the project ATLAS (Fundamental techniques, models and algorithms for a Lunar Radio Navigation system) to define the requirements and technologies needed to establish the navigation system (Iess et al., 2022). The role of the Polish partner in the ATLAS project is to define the structure of the broadcast navigation message with orbit representation, to evaluate the impact of orbit perturbations for eccentric lunar orbiters, simulate the orbits with extended gravitation and non-gravitational orbit perturbations, to analyze the visibility of the satellites, to assess possible inconsistencies in the origin, rotation, and translation of the lunar reference frame realizations with their impact on positioning, and to analyze the possibility of receiving faint GNSS signals at lunar distances (Di Benedetto et al., 2022; Sosnica et al., 2023).

12. New GGOS infrastructure in Poland

Two GGOS observatories in Poland have been recently supported by new infrastructure in the framework of the European Plate Observing System – EPOS-PL+. The Astrogedynamical Observatory in Borowiec belonging to the Space Research Center of the Polish Academy of Sciences bought the tidal gravimeter gPhone-X that shall support the routine SLR and GNSS observations and provide corrections to high-accuracy clocks, such as cesium fountain. The local tidal parameters can be derived from SLR data (Jagoda et al., 2020) and then compared with those directly obtained from gPhone-X gravimeter. The Borowiec SLR Observatory continues tracking geodetic targets (Schillak et al., 2021, 2022) and contributes to new initiatives dedicated to space debris tracking (Smaglo et al., 2021). The new, independent laser system is planned to be installed in the near future (Suchodolski, 2022), whereas the legacy SLR system will be supported by a new detector – compensated single photon avalanche diode (CSPAD) and kilohertz laser (Smaglo et al., 2021), which allows for the spin determination of geodetic satellites and time transfer based on laser observations (Kucharski et al., 2019).

The GGOS infrastructure at the Institute of Geodesy and Geoinformatics UPWr has been recently supported by the gravimeter CG-6, which is also used as a tidal gravimeter parallel to gPhone-X when not employed for field measurements. Besides the existing GNSS stations, such as WROC and WROE, a number of GNSS receivers based on low-cost and geodetic-grade antennas and chipsets have been tested. The WROC IGS station has been operating for 26 years and since 2017 has been supported by a microwave radiometer (Sosnica and Bosy, 2019). Soon, the link via a black optical fiber between Wroclaw and Borowiec is planned which will allow for the connection of the WROC and WROE stations to a hydrogen maser or a cesium fountain. The optical link will allow for the time transfer using a direct connection as well as multi-GNSS observations (Mikos et al., 2023). Finally, the robot acquired in the EPOS-PL+ will provide antenna calibrations for low-cost antennas increasing their accuracies and reliabilities for high-accuracy geodetic applications.

13. Conclusions and Outlook

We provided a review of the recent contribution of Polish scientific units to GGOS in terms of the development of models and processing procedures, as well as new geodetic infrastructure. Considerable progress in GNSS data processing was possible due to metadata release for Galileo and BeiDou-3 systems allowing for improved satellite orbit models, and thus, also global geodetic parameters. Thanks to multiple satellites distributed on different orbital planes and characterized by different orbital revolution periods, one can derive station coordinates, tropospheric parameters, pole coordinates, and length-of-day excess values with unprecedented quality. Antenna calibrations provided for Galileo allow for the scale realization of reference frames and were employed in DTRF2020 along with the VLBI for the scale realization. Two techniques of space geodesy co-located onboard Galileo, GLONASS, and BeiDou – SLR and GNSS – allow for co-location in space. However, only four BeiDou-3 satellites are tracked by SLR stations, and since 2022 the stations ceased to track GLONASS. Therefore, a successful co-location is currently possible only via Galileo satellites. Co-location in space of GNSS and SLR can be conducted onboard LEO missions, such as GRACE, GOCE, and SWARM, whereas Sentinel-6A, Sentinel-3A/B, and Jason-3 offer the co-location of three techniques, as they track the signals from DORIS beacons in addition. The future ESA's GENESIS mission will provide X-band and S-band signals for VLBI tracking, allowing for the co-location in space of all four space geodetic techniques for the first time.

Better orbit models reduced the draconitic errors embedded in GNSS-based global geodetic parameters, such as station coordinates and Earth rotation parameters. Estimating tropospheric biases in SLR solutions improved the station height estimates and the SLR residuals to GNSS-based LEO orbits, whereas the horizontal gradients based on numerical weather models improved the SLR-based polar motion estimates and enhanced the consistency between SLR and other space geodetic techniques.

Future progress in quality improvement of the global geodetic parameters is expected from the full exploitation of high-quality clocks onboard GNSS satellites and on the ground via stochastic modeling, proper integration of all GNSS systems with understanding the sources of inter-system biases, reducing systematic errors, such as SLR signature effects and tropospheric biases, better modeling of geodynamic phenomena, such as tides and non-tidal loading effects. More consistent antenna calibrations and more complete information about satellite surface properties will entail better orbit models and translate into a superior quality of geodetic parameters and confirmation of general relativity effects with smaller uncertainties. Finally, new observation types, such as inter-satellite links or direct connections to lunar orbiters will pave novel opportunities not only for Earth sciences but also for better understanding processes in the entire Earth-Moon system.

Author contributions

Conceptualization: K.S., J.B.; literature review: K.S, R.Z.; writing – original draft preparation: K.S., R.Z.; writing – review and editing: J.B.; funding acquisition: K.S., J.B.

Data availability statement

No datasets were used in this research.

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